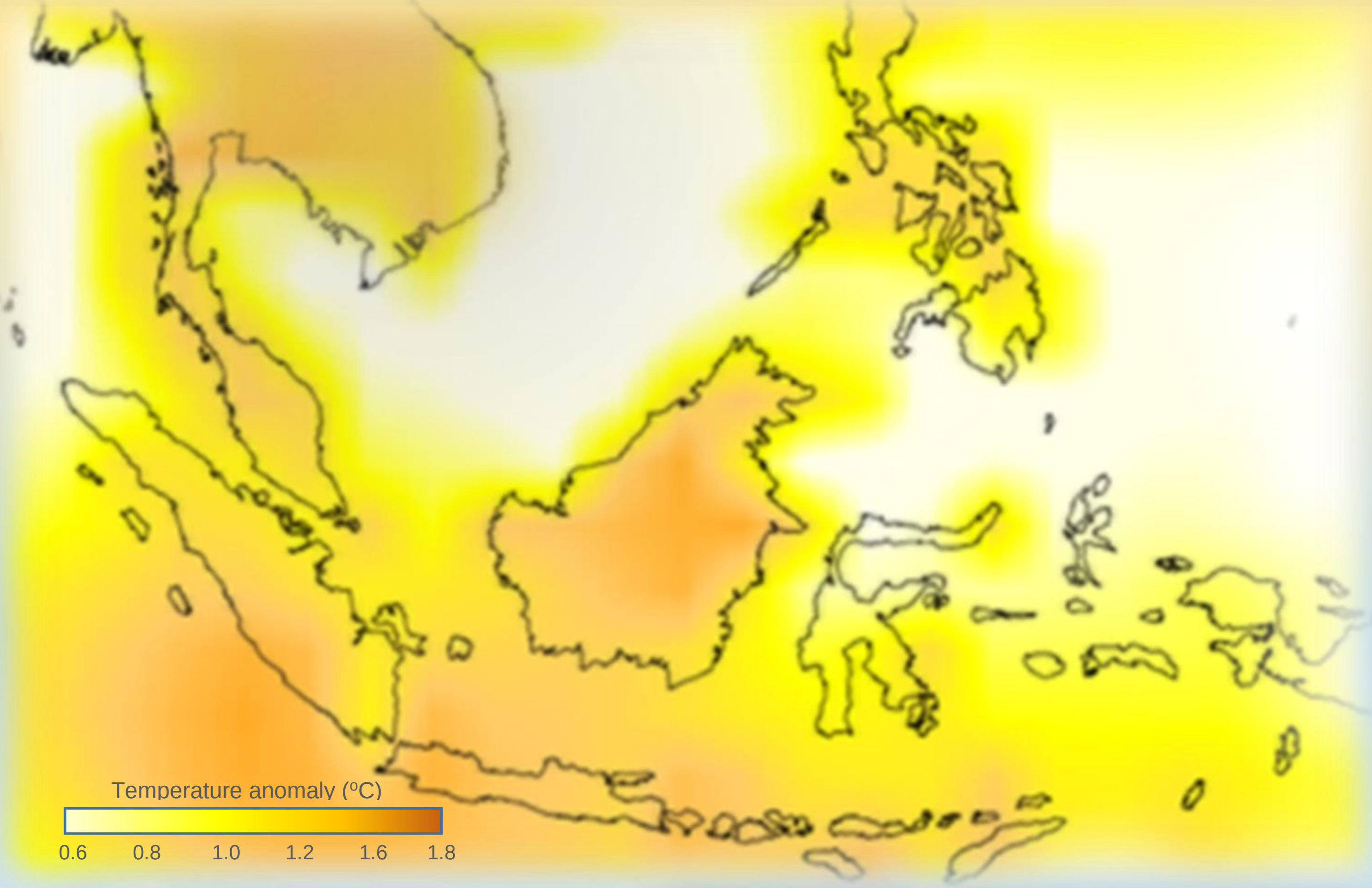
ANNUAL CLIMATE ASSESSMENT 2016

SINGAPORE

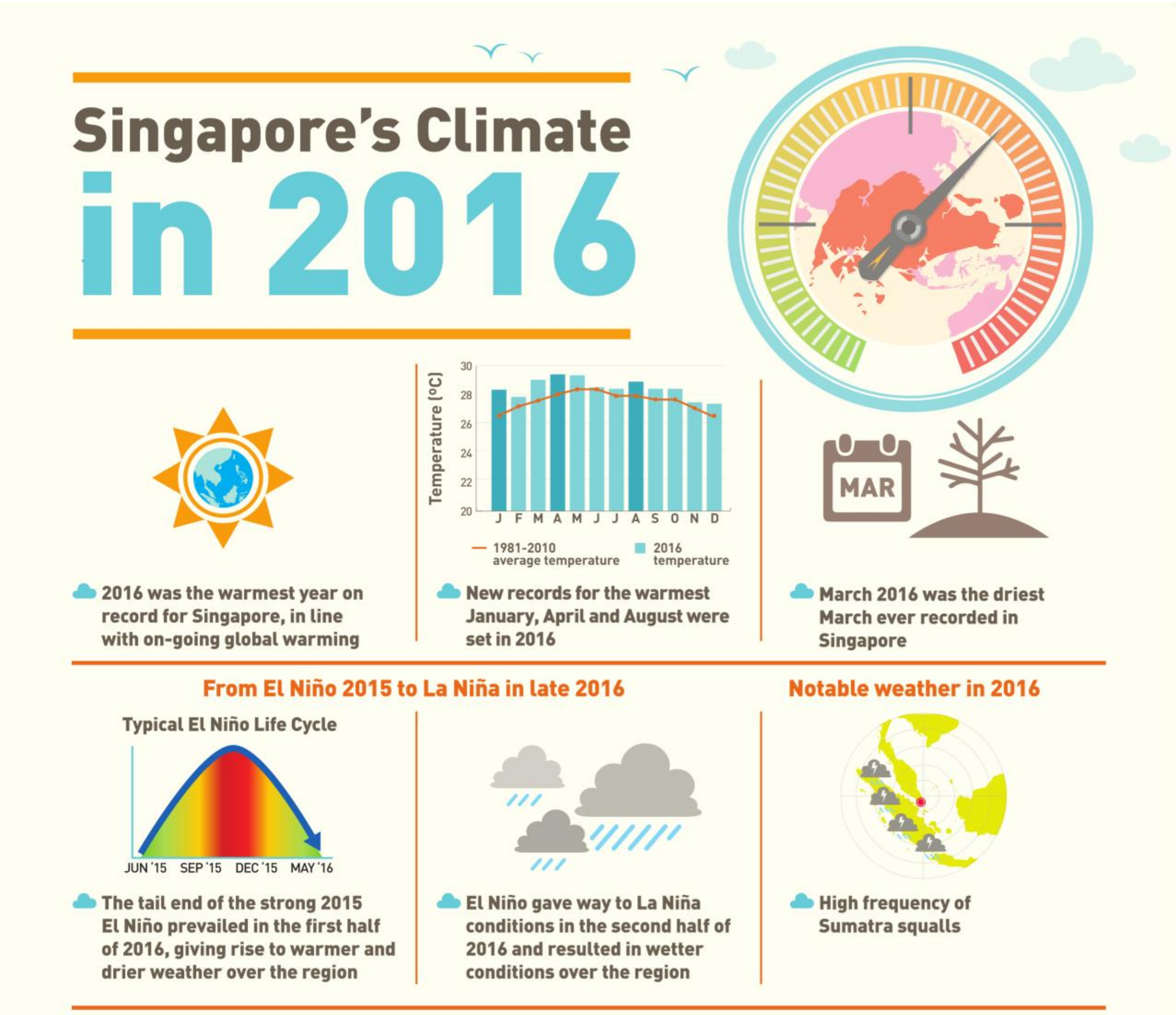


METEOROLOGICAL SERVICE SINGAPORE
Centre for Climate Research Singapore

Introduction

The climate influences many aspects of our lives; how last year's climate compares with historical records and how our climate is changing is a topic of interest for many stakeholders.

The annual Climate Assessment Report provides a description of the key climatic features and notable weather events that have affected Singapore during 2016. It aims to provide the necessary information to appreciate the state of the current climate of Singapore, place it within a historical perspective of past and future climate trends over Singapore



Singapore Climate in 2016

2016, with a mean annual temperature of 28.4°C, is Singapore's warmest year on record since 1929. This is 0.1°C higher than the previous joint record set in the years 2015, 1998 and 1997. All months in 2016 recorded mean temperatures above the 1981-2010 climate normal. With on-going global warming, new record temperatures for Singapore are increasingly more likely. Apart from this factor, the new record for 2016 can be attributed in part to a strong El Niño event which developed in mid-2015 and started to decay in early 2016. During this event, seven records for the warmest calendar month were either broken or tied: July, October, November, December in 2015 and January, April and August in 2016.

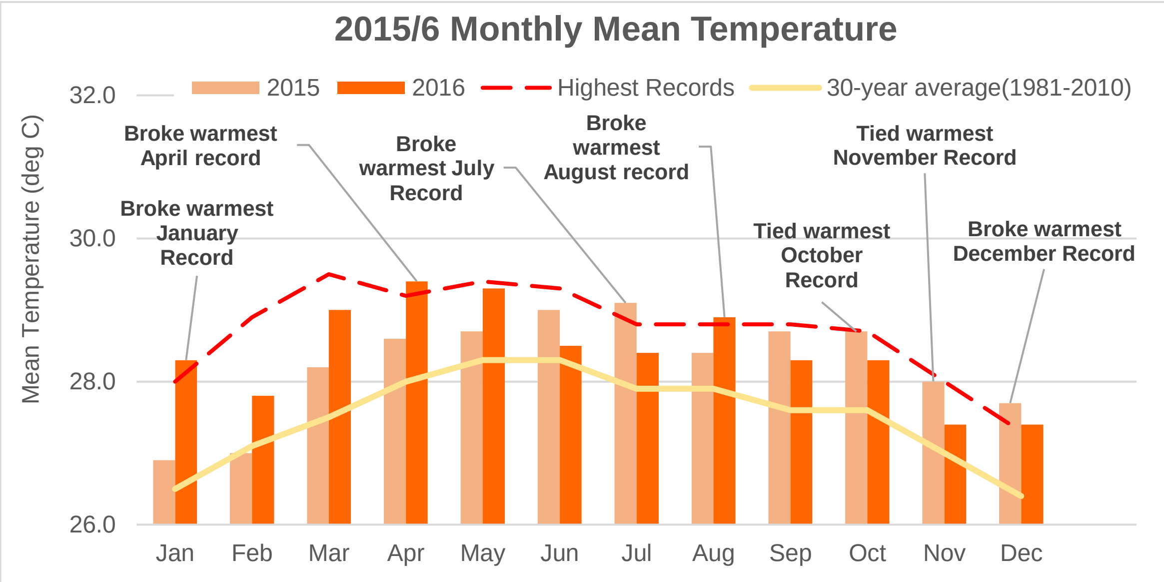


Figure 1: Monthly mean temperatures in 2015 and 2016 compared with the corresponding long-term average and highest values on record.

The strong El Niño of 2015-16 gave way to La Niña conditions in the second half of 2016. Accordingly, rainfall in the beginning of the year was mostly below normal (-29 per cent on average from January to May), consistent with El Niño conditions. Notably, March 2016 set a new record for the driest March, with only 6.2mm of rainfall recorded at the climate station. Rainfall during the second half of the year was mostly near average. Although the surrounding region experienced above average rainfall as expected during a La Niña episode, such positive rainfall anomalies were not consistently observed across Singapore.

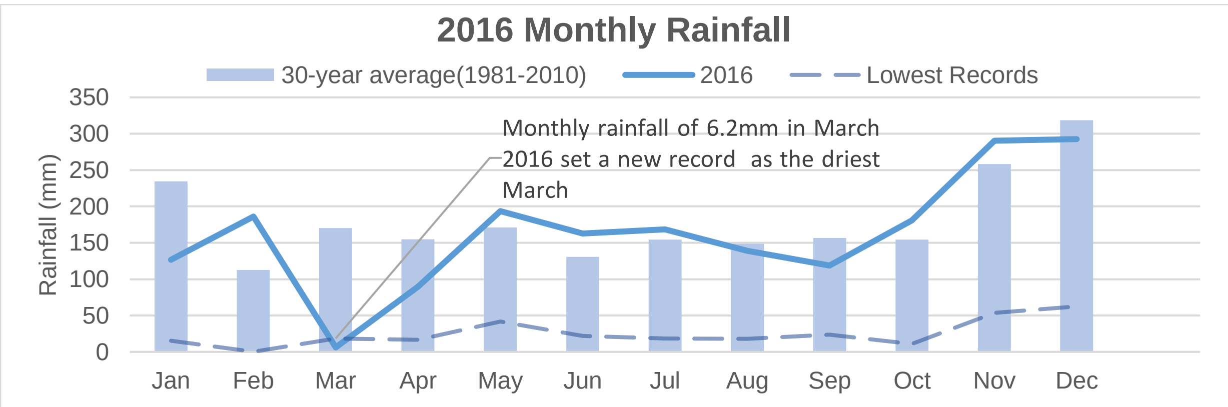


Figure 2: Monthly rainfall in 2016 compared with the corresponding long-term average and lowest values on record.

El Niño Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD) and their role in 2016

As reported in the Annual Climate Assessment 2015, a strong El Niño event emerged in the second half of 2015. Following its peak in late 2015, the El Niño gradually weakened to a neutral state towards mid-2016. At its most intense (based on oceanic and atmospheric indicator values), the event was ranked as one of the top three strongest El Niños since 1950 (the two other large events being the 1982-83 and 1997-98 episodes). From mid-2016 onwards, model runs from international climate centres favoured the development of La Niña (the opposite of El Niño; see Box 1) for the rest of the year.

As the second half of 2016 progressed, signs of La Niña conditions gradually emerged. However, masked by the long-term warming trend over the global oceans, the sea-surface temperature (SST) anomalies indicated only weak La Niña intensity. As ENSO evolved through the different stages in 2016, the Indian Ocean Dipole (IOD; see Box 1) entered a negative state and peaked in June and July.

Box 1: El Niño Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD)

During El Niño events, the sea-surface temperature (SST) over the central-eastern equatorial Pacific Ocean is warmer than average and the atmospheric response over the Southeast Asia region usually leads to warmer and drier conditions especially during the June to October period. For La Niña, which is the opposite of El Niño, the SST over the central-eastern equatorial Pacific is cooler than average and the atmosphere typically responds with wetter conditions during the same period. For the IOD, in its negative state as seen in 2016, wetter conditions in the southern and western parts of the Southeast Asia region are often experienced.

The Evolution of ENSO and IOD Indices in 2016

A commonly used indicator of an El Niño or La Niña event is SST departures from average values in the Nino3.4 region situated in the central-eastern equatorial Pacific Ocean. The Indian Ocean Dipole Mode Index (DMI), which is a measure of the strength of the IOD, measures the difference in SST between the western Indian Ocean and the eastern Indian Ocean. Figure 3 shows the SST boxes used to calculate the Nino3.4 index and the DMI. These SST boxes are used widely by scientists as they contain SST changes that bear the strongest signals representing ENSO and IOD variability.

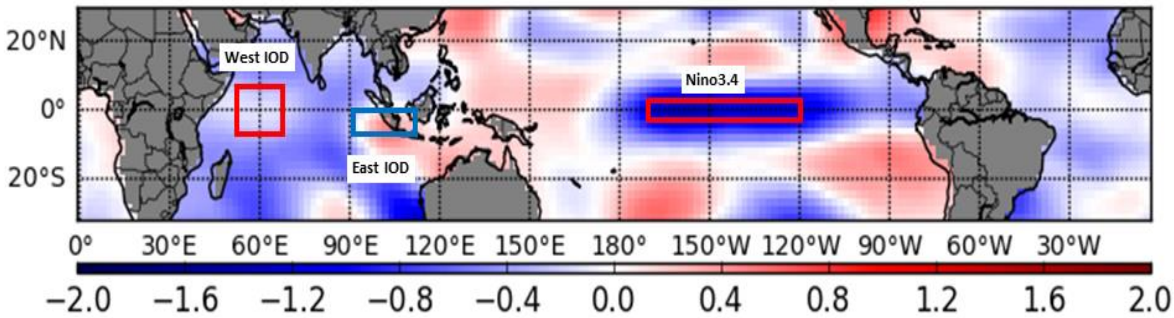


Figure 3: Commonly used SST boxes to monitor tropical modes of variability are indicated on the map: Nino3.4 (5°N to 5°S, 170°W to 120°W), the Indian Ocean Dipole is the difference between the Western (10°N to 10°S, 50°E to 70°E) and Eastern (0° to 10°S, 90° to 110°E) boxes.

La Niña conditions gradually developed from June-August (JJA) 2016, when the Nino3.4 index became negative (Figure 4). Long-term global warming across the oceans partly reduces the magnitude of the SST cold anomalies during a La Niña episode (while increasing the anomalies during an El Niño episode). Detrended Nino3.4 values (Figure 4) indicate that a stronger La Niña could have been identified earlier if not for the warming trend (see Box 2 for explanation of detrending). The DMI was negative for much of 2016 and peaked in the middle of the year (Figure 5). A coincidence of La Niña and negative IOD events tends to bring wetter conditions to the Southeast Asia region. Unlike Nino3.4, the detrending of DMI is not required as it is based on the differences of two boxes over the Indian Ocean and the subtraction removes the long-term warming affecting both boxes.

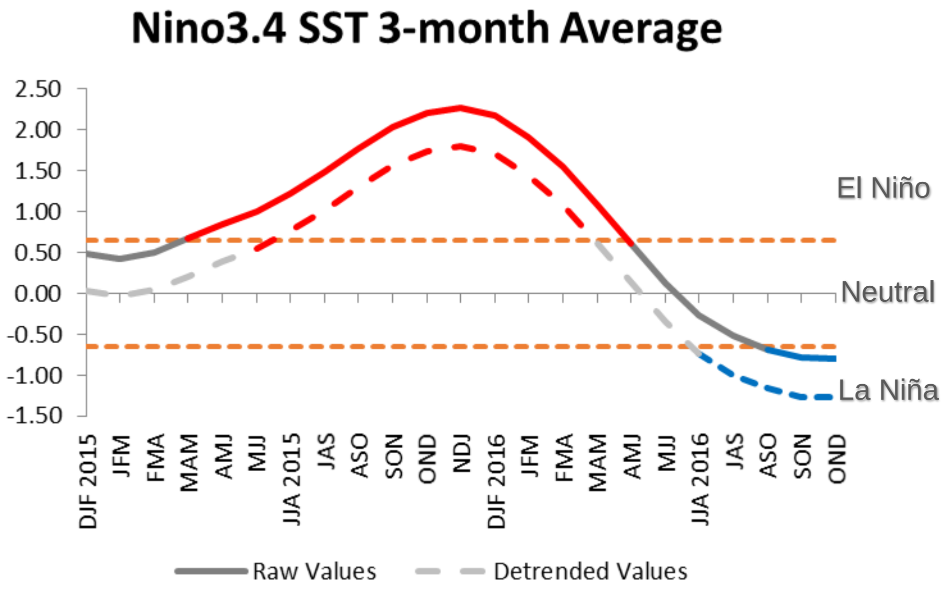


Figure 4: The Nino3.4 index based on raw (full line) and detrended (dashed line) data, using three-month running mean of SST anomalies in the Nino3.4 region bounded by 5°N to 5°S and 170°W to 120°W. Warm anomalies (red line) correspond to an El Niño event while cold anomalies (blue line) correspond to a La Niña event. (Data source: ERSSTv4 from NOAA). The horizontal axis is labelled with the first letters of the 3-month seasons, e.g. JFM refers to January, February and March seasonal average.

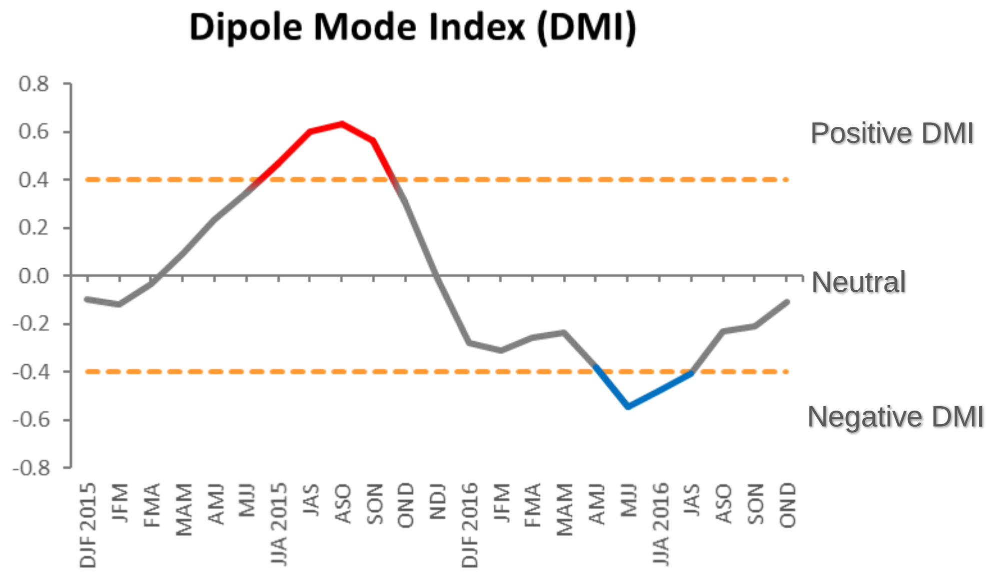
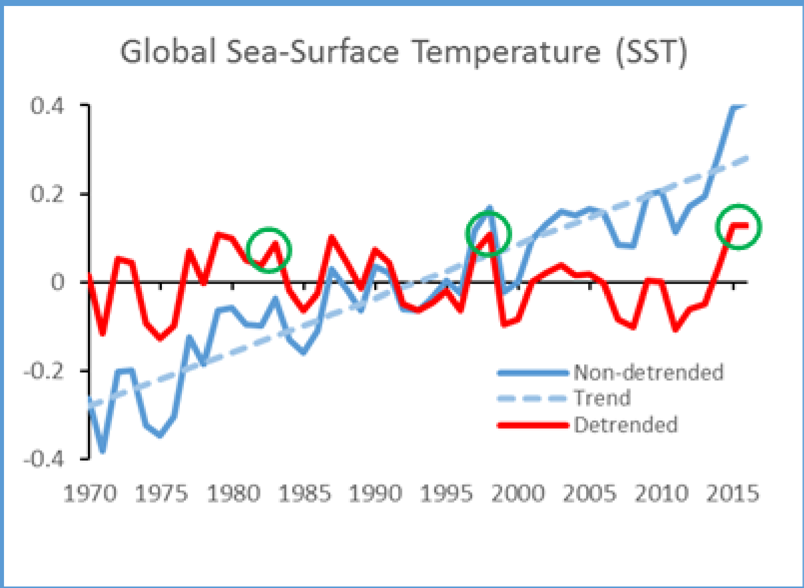


Figure 5: The Dipole Mode Index (DMI) measures the difference in the western Indian Ocean SST (10°N to 10°S, 50°E to 70°E) and the eastern Indian Ocean SST (0° to 10°S, 90°E to 110°E). Warmer than average SSTs in the eastern Indian Ocean, relative to the western Indian Ocean, translates to a negative value in the DMI and bring about wetter conditions to the southern and western parts of the Southeast Asian region. (Data source: ERSSTv4 from KNMI).

Box 2: Detrending of SST Indices

The sea-surface temperatures (SSTs) of the world's oceans have gradually warmed over the last century under the influence of climate change. Against this background warming trend, the SST values over the Nino3.4 will increasingly be magnified with time, and hence appear warmer than they should be. Detrending is needed to adjust for this effect.

As an example, the time series of the original annual SST anomaly over the global ocean is plotted below (blue curve) including the linear trend fitted to the data (dotted blue line). To better display how the SST are evolving on year to year basis, first the warming trend is removed from the time series (i.e. the time series is "detrended"). With the removal of the background warming trend in the final plot (resultant red line), it is therefore easier to identify warm years due to naturally occurring climate variability i.e. the three green circles identify 1982-1983, 1997-1998 and 2015-16 which correspond to the three very large El Niño events witnessed during this period. Their impact on the global SST is more clearly noted on the detrended time series.



Impact of El Niño/La Niña on Rainfall and Temperature

Despite the decline of the 2015 El Niño event in the first half of 2016, it still had significant impact on rainfall and temperature conditions over Singapore and the nearby region. Notably, hot and dry weather spells affected the Malay Peninsula[1], stretching from early March to April 2016 (Figure 6). The higher temperatures during these spells were likely due to a combination of factors on different timescales: El Niño itself combining with global warming during the traditionally drier time of the year for Singapore and the nearby region. Although the exact contribution of each factor cannot be determined, El Niño was considered a major factor for the warmer conditions during this period. Studies have shown that El Niños tend to have maximum impact on the temperature in the region about four to five months following its peak, and what happened in 2015-2016 reflects this.

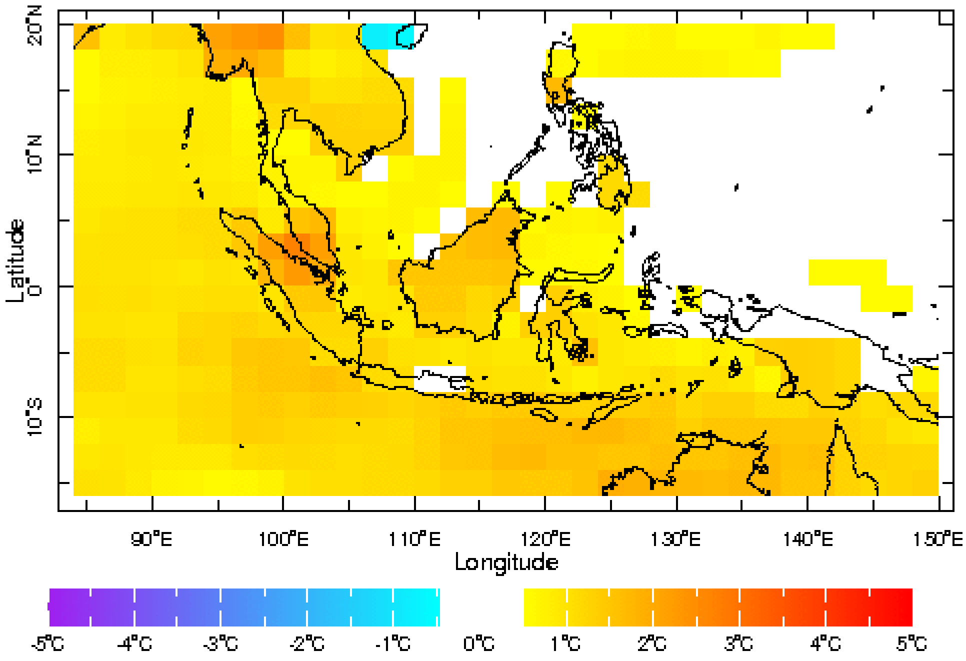


Figure 6: Temperature anomalies during Feb-Apr 2016 compared to the 1971-2000 average for the same season. Yellow to red shades on the map show areas with increasingly warmer than usual temperatures, while blue shades show cooler than usual temperatures. (Data source: CAMS from NOAA)

While the strongest impact of the El Niño on rainfall is during the June to October period, it also affects rainfall patterns over the region in other months such as February to April, although this impact may not be as strong. For the February to April 2016 period, the rainfall pattern displayed a strong El Niño signature for much of the region and in particular the Malay Peninsula (with the exception of Sumatra Island and Borneo) (Figure 7).

The large-scale temperature and rainfall responses to El Niño over the region were largely similar for both the 2015-16 and 1997-98 events. The significantly drier conditions notably affected water supply sources in some parts of the region.

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[1] The Malay Peninsula is a peninsula in Southeast Asia with the land mass running approximately north-south. It is flanked by the Malacca Straits and Andaman Sea to its west and Gulf of Thailand and the South China Sea to its east.

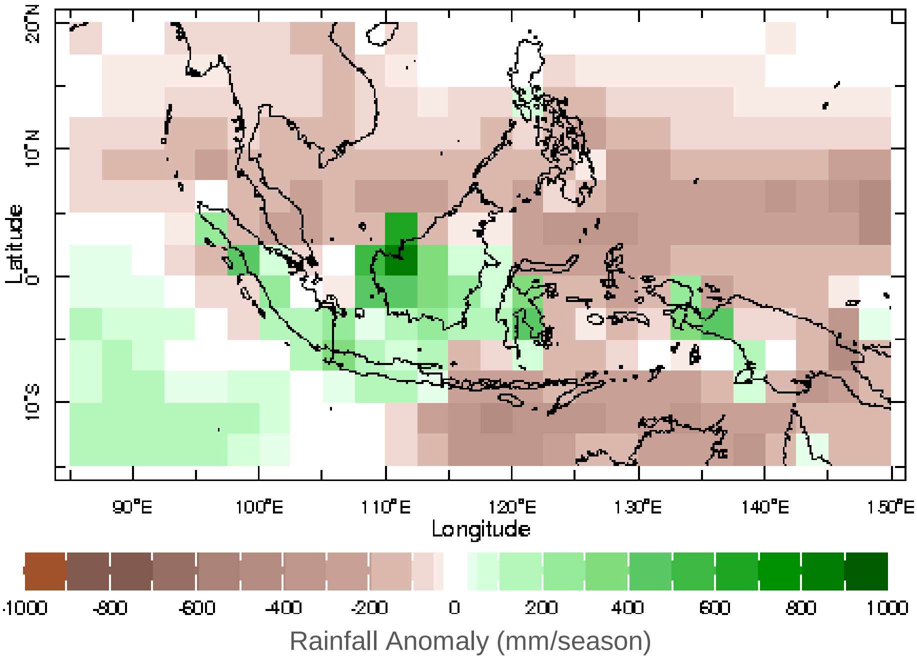


Figure 7: Rainfall anomalies during Feb-Apr 2016 compared to the 1971-2000 average for the same season. Green shades on the map show areas with wetter than usual rainfall conditions, while brown shades show drier than usual rainfall conditions. (Data source: CAMS_OPI from NOAA)

As La Niña conditions gradually developed in the second half of 2016 (based on the detrended Nino3.4 data in Figure 4), the atmosphere responded with wetter-than-normal rainfall patterns over the region from July to September 2016 (Figure 8).

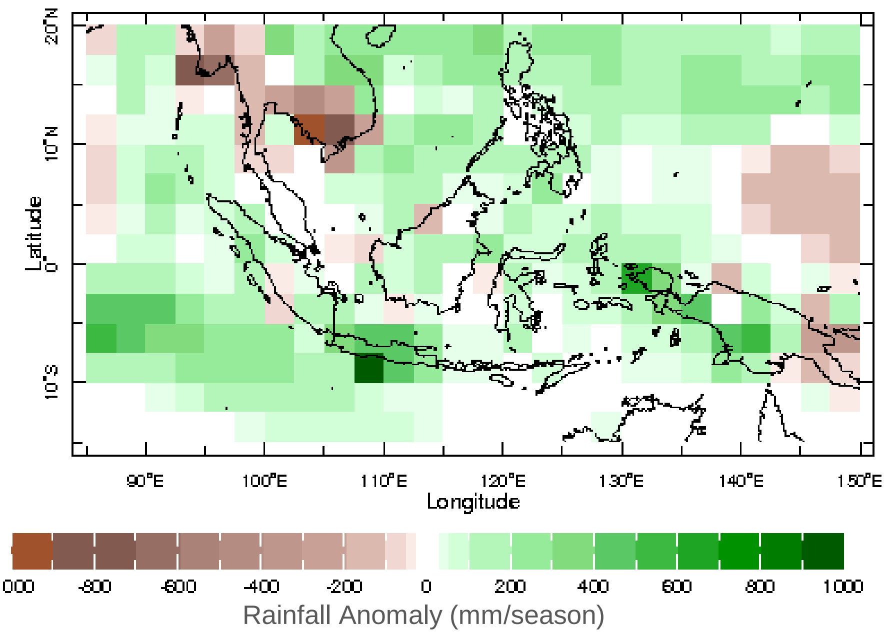


Figure 8: Rainfall anomalies during Jul-Sep 2016 compared to the 1971-2000 average for the same season. Green shades on the map show areas with wetter than usual rainfall conditions, while brown shades show drier than usual rainfall conditions. (Data source: CAMS_OPI from NOAA)

Temperature

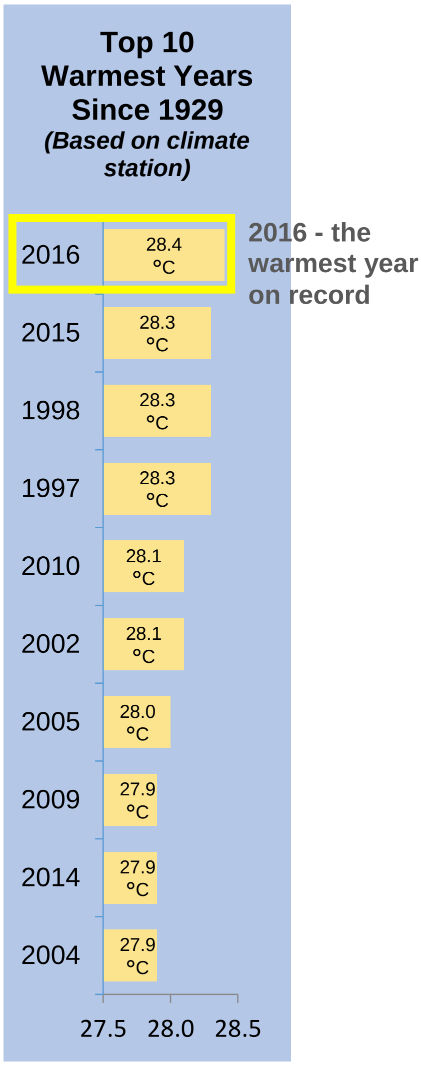


Figure 9: Annual mean temperature across Singapore in 2016.

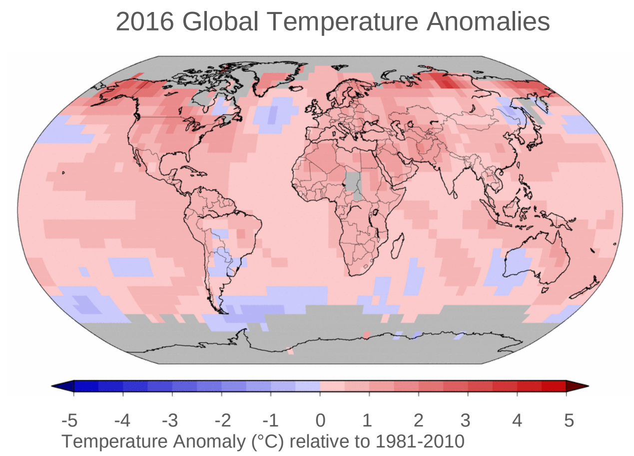


Figure 10: Global annual temperature anomalies in 2016 compared with the corresponding long-term average. (Source: NOAA, GHCN-M version 3.3.0 & ERSST version 4.0.0)

2016 set a new record for the warmest year in Singapore with an annual mean temperature of 28.4°C. This is 0.1°C higher than the previous joint warmest record in 2015, 1998 and 1997. Eight of the 10 warmest years in Singapore have occurred in the 21st century and all have occurred since 1997, consistent with global warming. Natural climate variability also played a major part in these record warmest years, with all the 10 warmest years connected to an El Niño event: either the warm phase started during the year or these conditions were established earlier in the year giving way to a cold phase (La Niña conditions) later in the year. A typical ENSO episode (either positive or negative) is not aligned with a calendar year but starts in mid-year and concludes in the first half of the following calendar year, thus impacting the temperature over a two-year period. The temperatures in the top warmest years of 1997, 1998, 2015 and 2016 in Singapore were influenced by two of the strongest El Niño events on record.

Globally, the year 2016 is also the warmest year on record, exceeding the previous record that was set in 2015 by 0.05°C. The global average surface temperature in 2016 was about 0.82°C above the 1961-1990 average. The next three warmest years are 2015 (0.77ºC), 2014 (0.61°C) and 2010 (0.58°C), all within the past 10 years. Most parts of the world experienced above normal temperatures (see Figure 10) and many countries observed a record or near record warm year.

From 2014 to 2016, the world experienced a strong acceleration of the global warming with the mean temperature increasing by 0.21ºC, largely due to the strong El Niño experienced in 2015-16. This is not unprecedented; during the 1997-98 El Niño episode, the global temperature also rose by 0.32ºC (from 1996 to 1998). The larger rise of global temperature in that previous episode is a testimony that the 1997-98 El Niño was very likely a bigger episode than the 2015-16 episode. In the meantime, the global temperature continues to gradually rise; the El Niño related acceleration episode brought the global temperature anomalies from 0.21ºC to 0.53ºC while the 2015-16 episode raised the global temperature anomalies from 0.61ºC to 0.82ºC. In between these two accelerations of the global warming, from 1998 to 2014, the increase was more moderate from 0.53ºC to 0.61 ºC. These episodes of acceleration of the warming and slower warming pace are due to naturally occurring variability within the climate system (when El Niño episodes occurs). The overall underlying warming trend is in response to human influences and the increase in greenhouse gases.

In Singapore, when El Niño prevailed from 2015 to 2016, the highest 12-month mean temperature recorded was 28.6°C (June 2015 - May 2016). This is slightly lower than the highest 12-month mean temperature of 28.7°C ever recorded in Singapore (June 1997 - May 1998 during the 1997/8 strong El Niño event).

The mid-points of the periods of highest 12-month mean temperatures are roughly around the peak of the El Niño events (Figure 11), illustrating the effects of El Niño on the temperatures over Singapore (and globally) across two consecutive years.

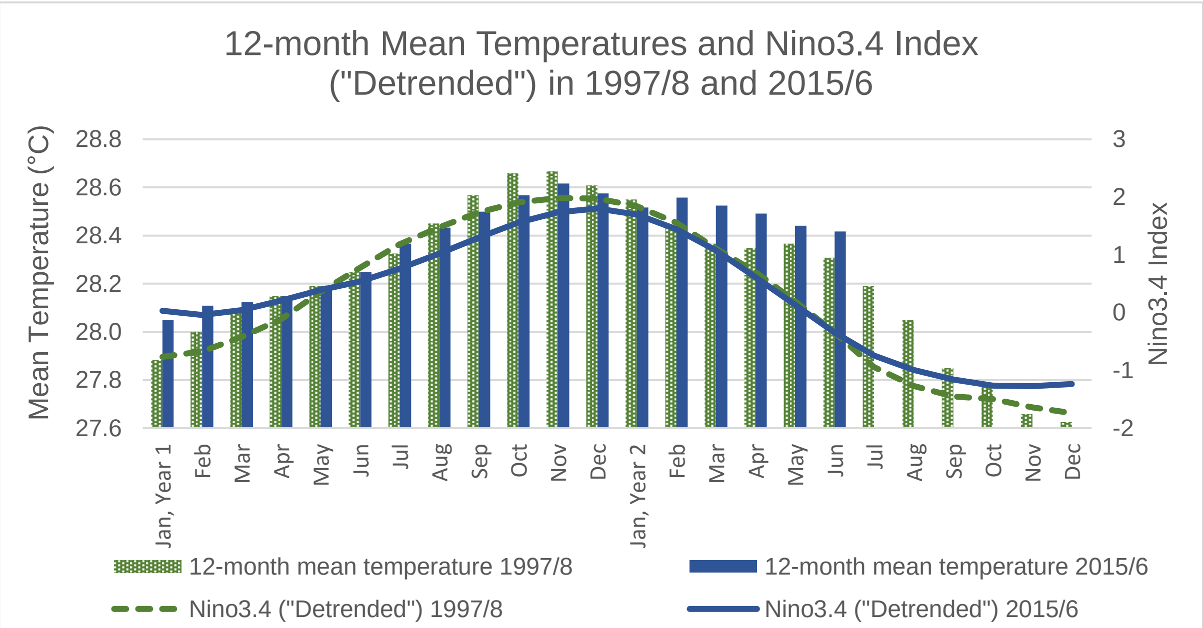


Figure 11: 12-month mean temperatures (Changi climate station) and Nino3.4 indices ("detrended") during the El Niño events in 1997/8 and 2015/6. The 12-month mean temperature plot is for the period from -5 months to +6 months of the month indicated in the horizontal axis.

Past Temperature Trends

Analysis of the annual mean temperature from the climate station (refer to last page for more information on Singapore's climate station) shows that there was an average rise of 0.25ºC per decade from 1948 to 2016. The rate of increase in temperature is greater than the global temperature trend (e.g. global warming). Figure 12 shows the comparison of Singapore and global temperature anomalies separated according to land and ocean globally.

A part of the higher temperature rise over Singapore is due to global warming being larger over land than over the ocean (the difference between land and ocean globally is noticeable in Figure 12). However, the rate of temperature increase over Singapore is higher than the global temperature trend over land; in contrast, local sea surface temperatures (SSTs) in the vicinity of Singapore (within the region 1°S – 3°N, 105°E-107°E) show a warming trend consistent with the warming of the global oceans.

Both the Singapore temperature and local SSTs show more year to year variability than global temperature (which smooth out local anomalies), but more importantly Singapore's temperature displays a stronger long-term warming beyond average global land temperature. Being a city state, Singapore has been impacted by other human activities influencing the local climate. For example, urbanization cannot be easily identified as it is not possible to measure what the temperature increase would be without the urbanisation effect which is contained within the station network observations. Thus, although greenhouse warming has contributed to the rise in temperature over Singapore, it does not account for all of the increase; urbanization has played a role in the warming over Singapore as well, as measured by MSS' network of instruments. Most of the additional warming however (when compared to the global warming over land) appears to have occurred in the 1980s and early 1990s.

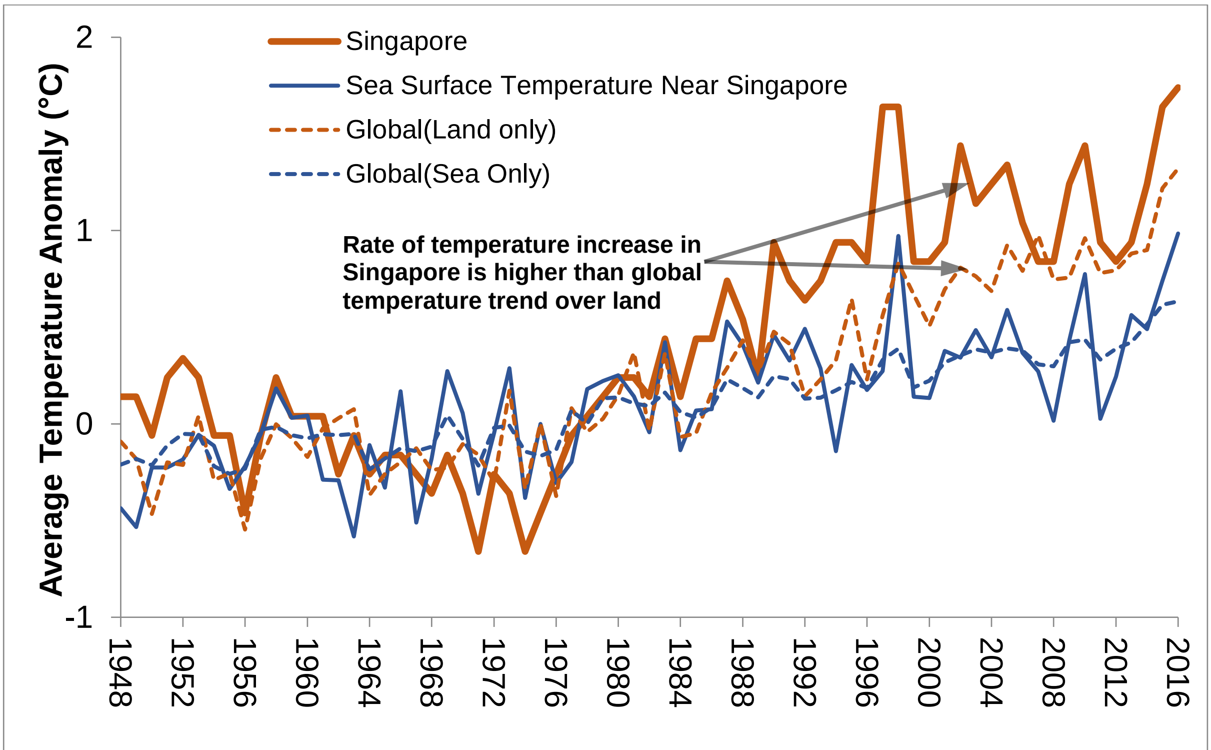


Figure 12: Global vs Singapore temperature anomalies (relative to 1961-1990 average) from 1948 to 2016. Global temperatures are from the NOAAGlobalTemp dataset produced by the National Oceanic and Atmospheric Administration, USA. Singapore temperature is from the Changi climate station.

Overall, the warming measured by the MSS temperature station network is generally indicative of the impact of human induced climate change, both through local urbanization as well as the increase in greenhouse gases globally. The warming is mostly felt through changes of the most extreme conditions either at night or during the day. Since 1972, Singapore has experienced an increase in the number of warm days and warm nights and a decrease in the number of cool nights (Figure 13 and Figure 14). As with average temperatures, the increase in frequency of warm days and nights occurs against a background of year-to-year climate variability, mostly associated with ENSO variability (El Niño and La Niña events).

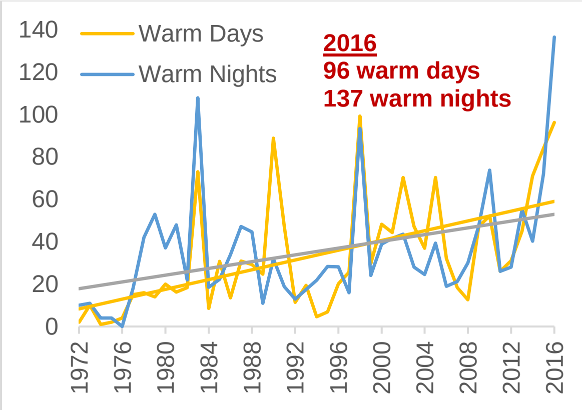


Figure 13: Increasing frequency of warm days/nights in Singapore since 1972.

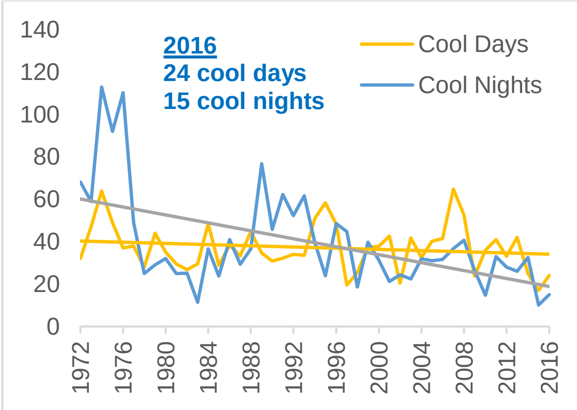


Figure 14: Decreasing frequency of cool days/nights in Singapore since 1972.

Rainfall

There was a mix of positive and negative precipitation anomalies globally in 2016, with the shift during the first six months of the year between the termination of the El Niño and the start of La Niña-like conditions, and a negative phase of the Indian Ocean Dipole (IOD) from May to August 2016, playing a significant role in our region (see Figure 5 in section on ENSO/IOD). Most parts of Southeast Asia received below average rainfall in the first half of the year and above normal rainfall in second half of the year, consistent with El Niño conditions in the beginning of the year and La Niña conditions alongside a negative phase of the IOD towards the later parts of 2016.

Locally over Singapore, the annual rainfall in 2016 was below normal. Most parts of the island received below normal rainfall (Figure 16) compared to the 1981-2010 average, but there was a mix of below and above normal rainfalls in the individual months. (Figure 17 next page).

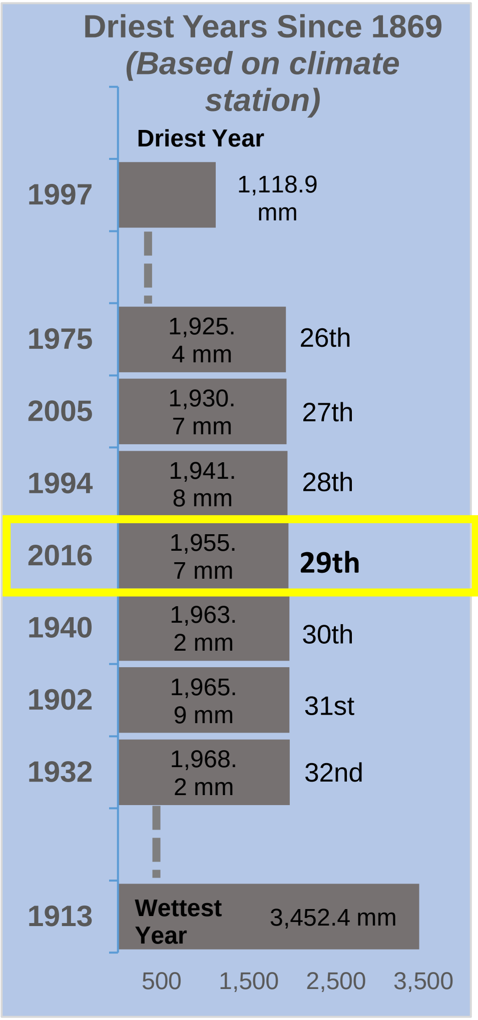


Figure 15: Annual total rainfall distribution across Singapore in 2016.

Figure 16: Annual rainfall anomalies across Singapore (relative to 1981-2010 average) in 2016.

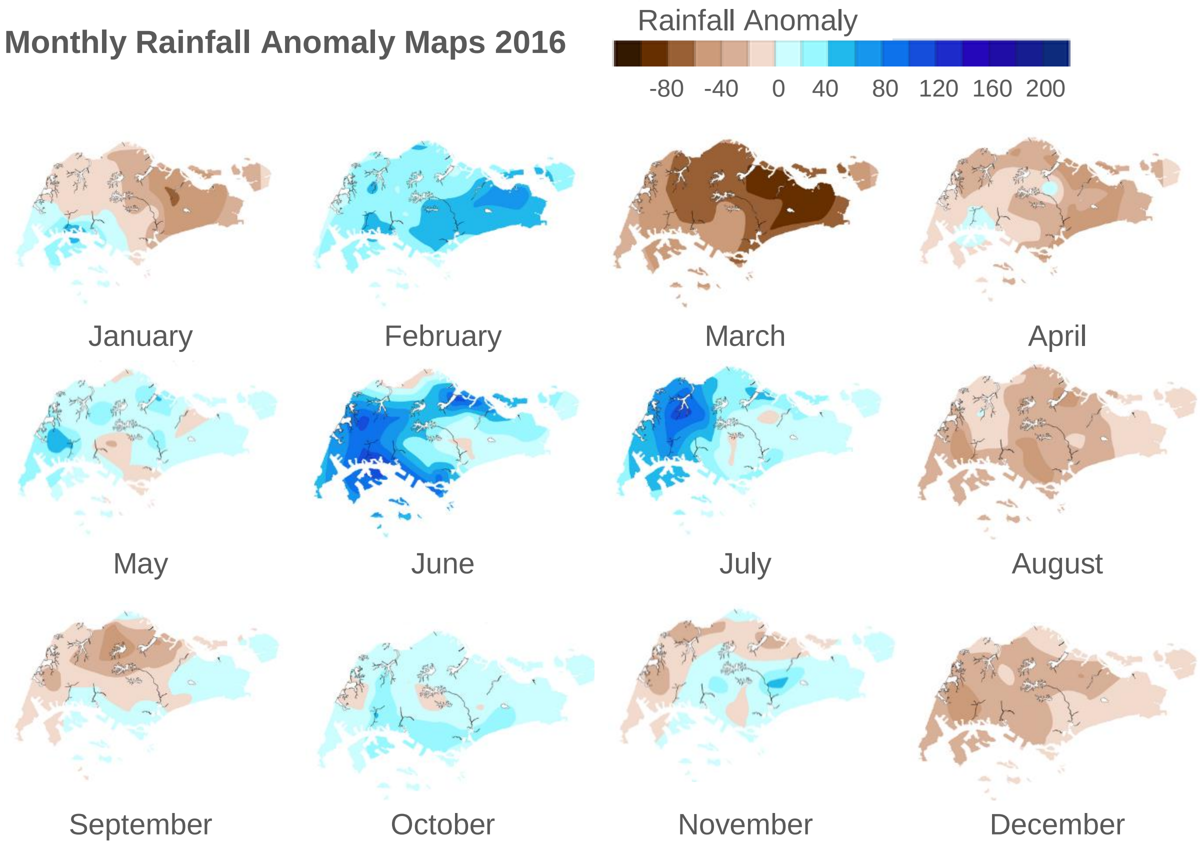


Figure 17: Monthly rainfall anomaly maps for 2016.

Past Rainfall Trends

Singapore rainfall records began in 1869. Prior to the 1970s, the network of rainfall stations was relatively sparse and the rainfall records were limited to only daily and monthly rainfall totals. Since the 1970s, the rainfall station network has gradually grown. There are now 28 rainfall stations island-wide with a sufficiently long period (since 1980) of continuous hourly rainfall records to enable the analysis of rainfall trends.

In the last thirty-seven years, the average annual rainfall totals recorded at the 28 rainfall stations increased at a rate of 10.1mm per year (Figure 18). The spatial variation in the trends in annual rainfall totals since 1980 is depicted in Figure 19 (next page). Generally, there are consistent rainfall trends across Singapore since 1980, with 20 per cent of the rainfall stations showing a statistically significant upward trend in the annual rainfall total, ranging from +14.5mm to +25.6mm per year.

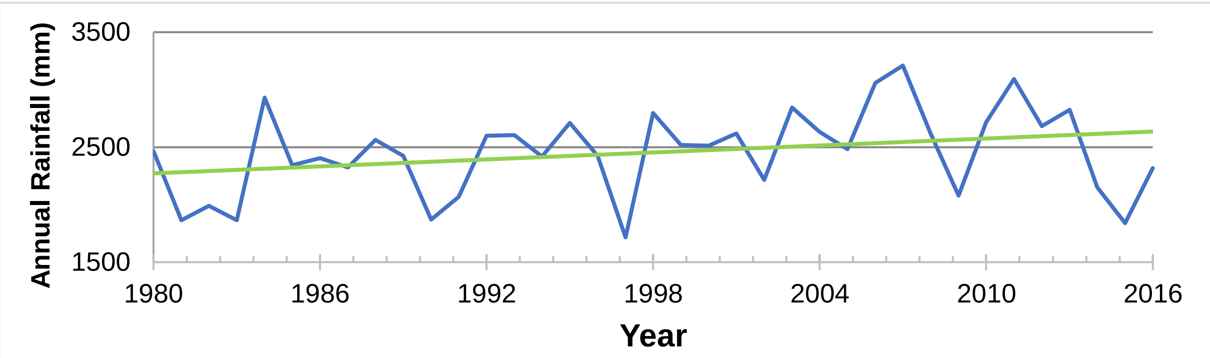


Figure 18: Time series of annual rainfall total in Singapore shows an upward trend of 10.1mm per year on average, based on linear fit, from 1980 to 2016.

Trends in the annual number of days with hourly rainfall totals exceeding 40mm (95th percentile hourly rainfall i.e. heavy rain) vary across the island (Figure 20). There are statistically significant upward trends at one rainfall station, with an average rate of about 1.1 days per decade. One station showed a downward trend but it is not statistically significant. The rest of the stations show generally upward but not statistically significant trends.

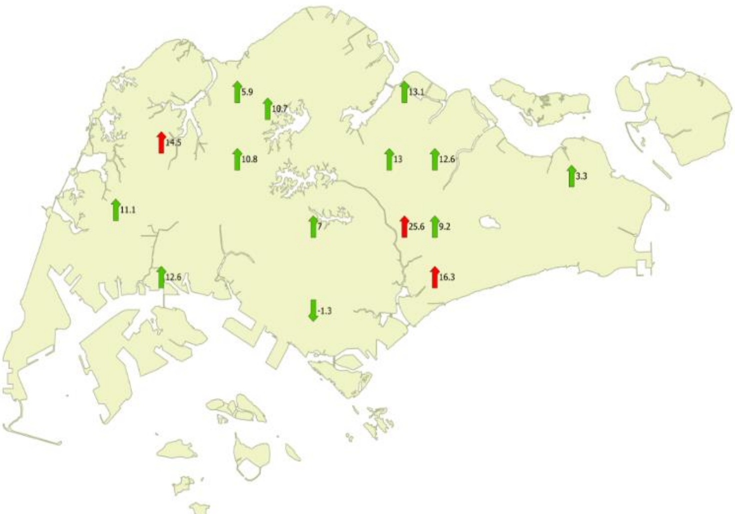


Figure 19: Map showing the past trends of annual rainfall total (mm/year) at individual stations. All stations indicate upward trends (up-arrow).*

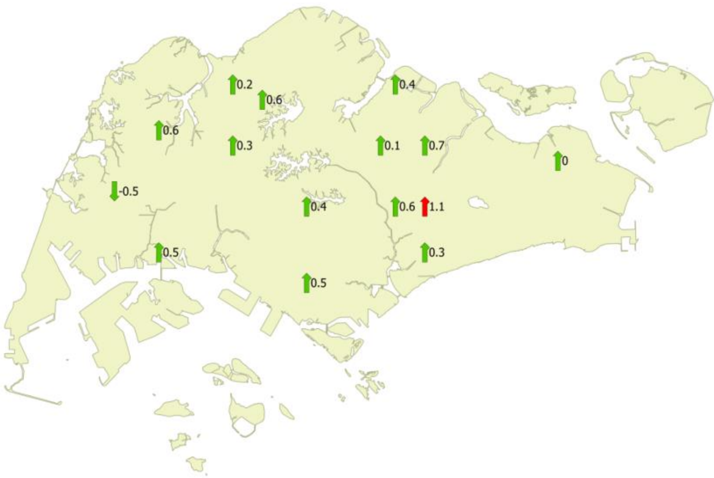


Figure 20: Map showing the past trends of number of days with hourly maximum rainfall totals exceeding 40 mm (heavy rain) at individual stations.*

**Upward and downward trends are depicted by up-arrow and down-arrow respectively. Red arrows represent statistically significant trends and green arrows are non-statistically significant changes. The numerical value next to each arrow indicates the rate of change per decade for the period 1980-2016.*

It is important to note that the trend analysis above is performed on a period from 1980 to 2016 where Singapore has experienced an increase in mean rainfall (Figure 21, next page). The on-going increase since the 1970s is unprecedented in the longest instrumental record available (rainfall measurement at MacRitchie reservoir). While the on-going mean rainfall increase coincided with the on-going global warming from 1970s, a longer term comparison of temperature alongside rainfall, heavily smoothed to remove high frequency climate variability (Figure 21, next page), suggests that the increase in mean rainfall might not be due to overall global temperature change. A similar plot using the difference between the temperature in the

Northern and Southern Hemisphere suggests that rainfall in Singapore, due to its position near the Equator, may be responding on multi-decadal timescale to the difference in rate of warming between the two hemispheres (Figure 22) rather than overall global warming.

The difference in temperatures between the Northern and Southern Hemisphere has increased due to the faster warming in the Northern Hemisphere. Thus, even though mean rainfall has increased together with the increase in global temperature since 1970s, such increase in mean rainfall might not continue in tandem with global warming. However, for frequency of extreme rainfall, future climate change and global warming is expected to lead to an increase in the frequency of extreme rainfall. (See section 4 of [Second National Climate Change Study – Report for Stakeholders]).

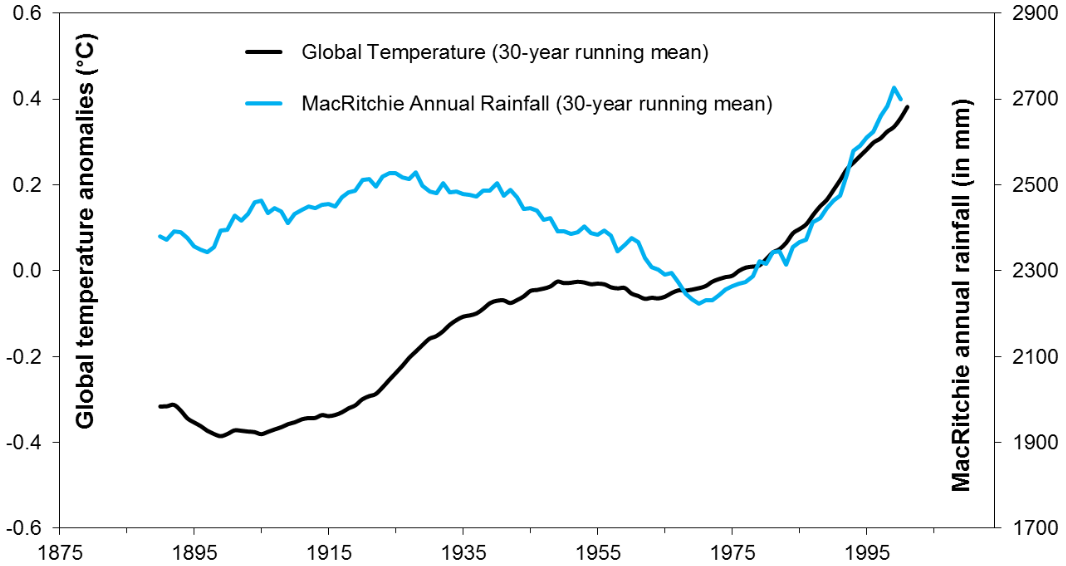


Figure 21: Time series of 30-year average of MacRitchie annual rainfall (in mm/year, right Y-axis) compared to the 30-year average of global mean temperature anomalies.

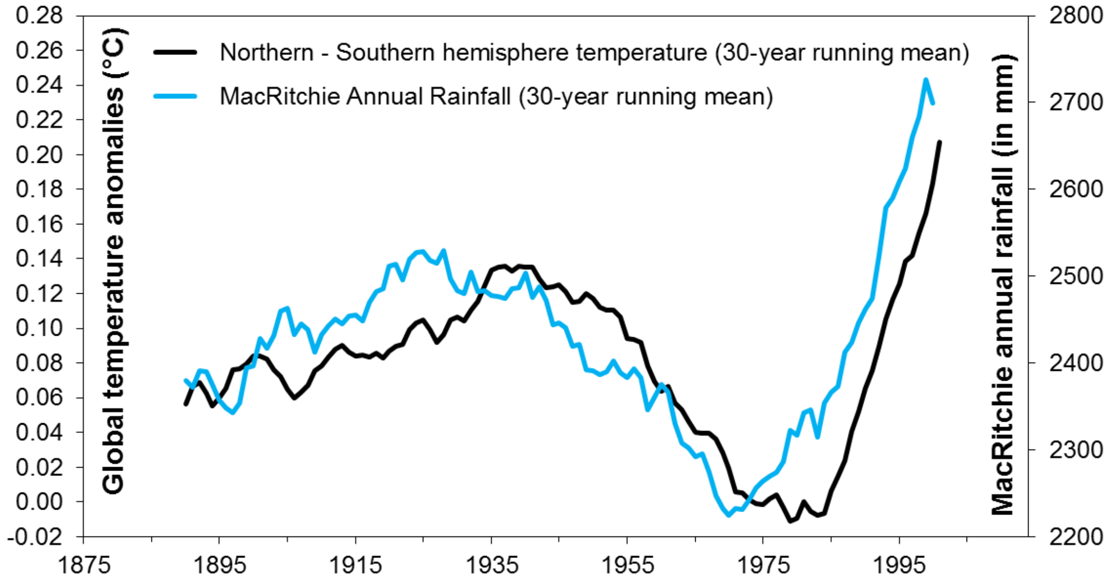


Figure 22: Time series of 30-year average MacRitchie annual rainfall (in mm/year, right Y-axis) compared to the mean temperature difference between the Northern and Southern Hemisphere.

Major uncertainties remain in attributing observed heavy rainfall trends to particular factors, either natural or anthropogenic.

Extremes in 2016

The coolest and wettest month in 2016 (based on our climate station) occurred towards the end of the year in November and December, and the warmest month in 2016 was April. These are consistent with our local climatology. The western parts of Singapore experienced significantly above normal rainfall (close to double the normal rainfall in some locations) in the months of June and July, with the highest monthly rainfall in 2016 (434.4mm) recorded over Jurong in July.

	Hottest Day (°C)	**Coldest Night (°C)**	**Wettest Day (mm)**	**Warmest Month (°C)**	**Coolest Month (°C)**	**Wettest Month (mm)**	**Strongest Wind Gust (km/h)**
All Available Stations*	**36.8** 30 Sep (Seletar)	**21.2** 26 Jul (Ang Mo Kio)	**217.0** 17 June (Tuas)	**30.0** Apr/May (Marina)	**26.8** Nov/Dec (P. Ubin)	**434.4** July (Jurong)	**114.8** 19 Oct (Semakau)
Climate Station (Changi)	**35.0** 10 Apr	**21.6** 3 Oct	**75.4** 3 Oct	**29.4** Apr	**27.4** Nov/Dec	**292.8** Dec	**65.2** 3 Aug
Climate Station Records	**36.0** 26 Mar 1998	**19.4** 30 & 31 Jan 1934	**512.4** 2 Dec 1978	**29.5** Mar 1998	**24.2** Jan 1934	**818.6** Jan 1893	**90.7** 29 Nov 2010

Table 1 – Extremes in 2016 across all available stations and the climate station (refer to the last page for more information on MSS' network of weather stations).

**The non-climate stations complement the measurements at the climate station, including providing indications of local conditions.*

Notable Weather Events in 2016

Record Warm Weather in 2016

2016 was Singapore's warmest year since local temperature records began in 1929. Temperatures were higher than usual for all months of the year and several temperature records were broken.

Figure 23: Singapore experienced more frequent hot weather in 2016.

January 2016, with a mean monthly temperature of 28.3°C, was the hottest January on record since 1929, surpassing the previous record of 28.0°C set in January 1998. The mean daily maximum temperature of 31.8°C and the mean daily minimum temperature of 26.0°C recorded during the month were 1.4°C and 2.1°C above their respective long-term means. Although it rained on most days of the month, the rain did not bring much relief from the sweltering heat, a contrast from the cooler weather typically experienced in January.

March 2016 was the second warmest March since 1929 after March 1998. The mean monthly temperature was 29.0°C, 1.5°C higher than March's long-term mean, and 0.5°C lower than the warmest March set in 1998. The second half of March 2016 experienced significantly warmer conditions with daily maximum temperatures exceeding 34.0°C on 13 days as compared to seven days in the first half of March 2016. March 2016 was also drier than usual with 96% below-normal rainfall for the month, setting a new record for the driest March since rainfall records began in 1869.

April 2016 was the warmest month of 2016. Notably it is a new record for the hottest April and the second hottest month since 1929. Daily maximum temperatures exceeded 34°C on all but two days (15 and 24 April 2016), and there were 16 days with daily maximum temperature of at least 35.0°C. Its mean monthly temperature of 29.4°C was 1.4°C higher than the mean monthly temperature for April.

Warm and dry conditions similarly affected the surrounding region in the first four months of 2016. Water levels in the Linggiu Reservoir, which supplies water to Singapore, fell to low levels during the year.

Figure 24: Water levels at Linggiu Reservoir in Johor dropped during the hot and dry months in 2016.

All months in 2016 recorded mean monthly temperatures that were higher than the respective long-term mean monthly temperatures. Of note are February (4th warmest February), May (2nd warmest May after 1998), and December (2nd warmest December after December 2015).

Relatively Wet Southwest Monsoon Season

While 2016 was a record warm year for Singapore, there were some wetter than usual months during the Southwest Monsoon season. This coincided with the transition from the El Niño of 2015-16 to La Niña conditions which prevailed from mid-2016 and the influence of a strong Indian Ocean Dipole (IOD). The Southwest Monsoon season (June-October) is typically the drier period of the year in the southern region of Southeast Asia.

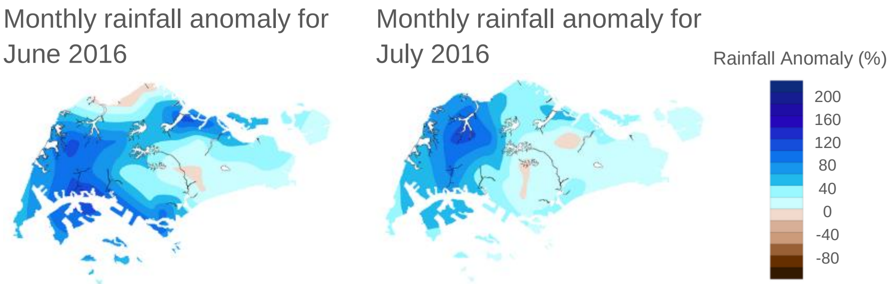


Figure 25: Rainfall anomaly map for June and July 2016.

Singapore experienced above normal rainfall in June and July 2016 (Figure 25). The thunderstorm activities on some days during these months were also more intense, particularly over the western parts of the island where the monthly rainfall was significantly above normal.

Overall the Southwest Monsoon in 2016 was relatively wet with above-normal rainfall recorded in many parts of the region (Figure 26).

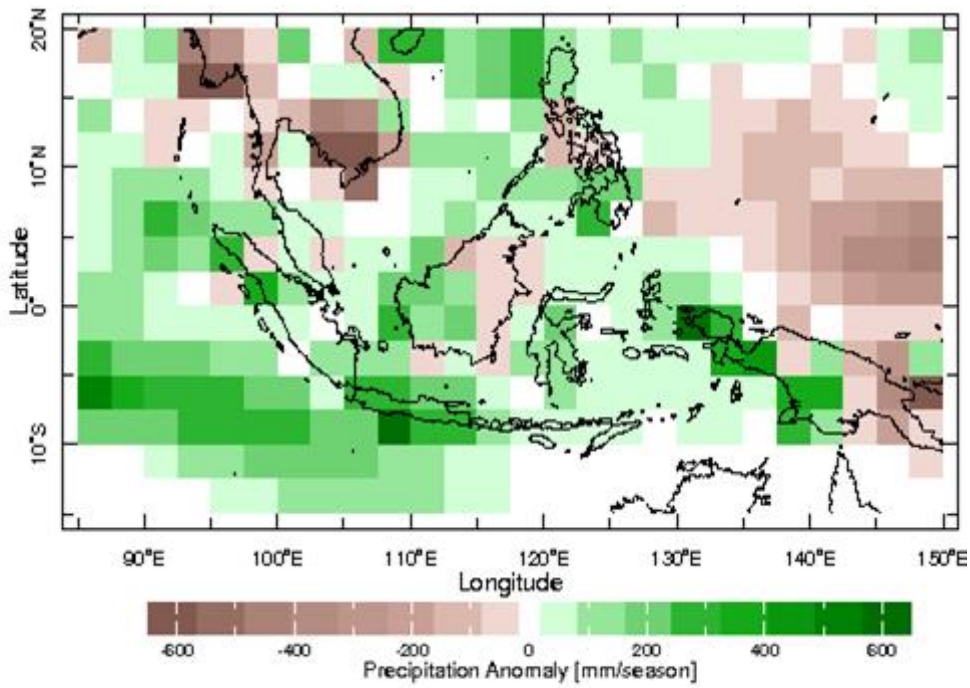


Figure 26: Rainfall anomalies during Jun – Aug 2016 show above-normal rainfall in many parts of region. Green shades on the map indicate areas with wetter than usual rainfall and brown areas indicate drier than usual rainfall.

Heavy Rain Event on 17 June 2016

Singapore experienced heavy rainfall on 17 June 2016, with several weather stations recording daily rainfall total of above 100mm. The heavy rainfall was due to a large scale wind convergence in the region coupled with strong solar heating of land areas, giving rise to the development of thunderstorms over Singapore and the surrounding vicinity. The thundery showers were heaviest over the western part of Singapore and led to flash floods in some places.

The daily rainfall total recorded on that day was 217.0mm in Tuas, which was the highest daily rainfall recorded in 2016. It was also the highest ever recorded daily rainfall total for June, exceeding the previous record of 144.6mm on 4 June 2011 over Pasir Ris.

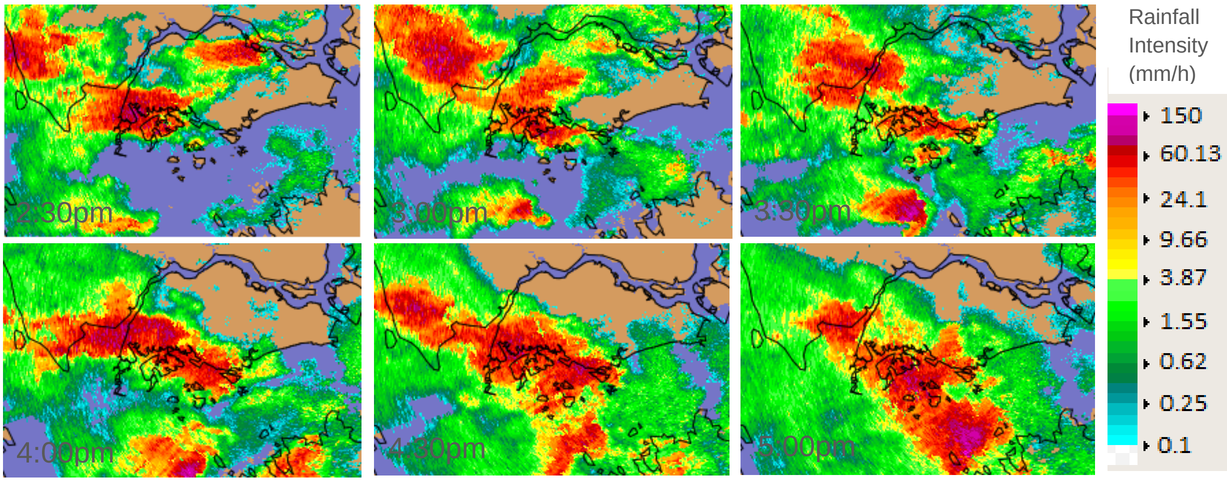


Figure 27: Rain areas from the weather radar showing spells of heavy thundery showers over the western parts of Singapore in the afternoon on 17 June 2016. The daily rainfall total recorded at Tuas on that day was the highest for 2016.

Figure 28: SCDF officers rescuing people from their vehicles stranded in the flood on 17 June 2016.

High Frequency of Sumatra Squalls

In the second half of 2016, La Nina conditions emerged alongside a strong Indian Ocean Dipole (IOD). A distinct development associated with the IOD during this period was persistent low pressure systems over the Indian Ocean southwest of Sumatra, bringing unseasonal westerly winds from the Indian Ocean towards the surrounding region including Singapore (Figure 29).

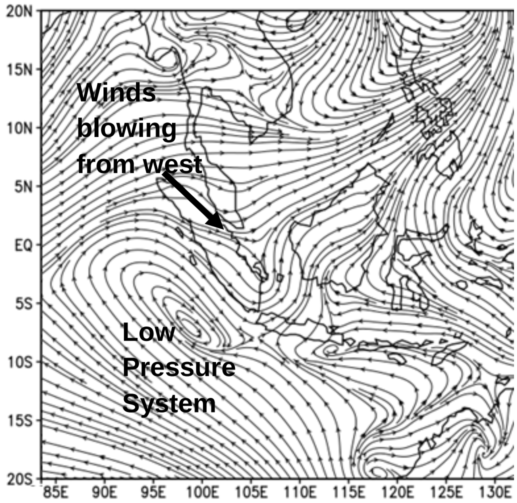


Figure 29: Average wind field (June – Oct 2016) showing winds blowing from the west and a low pressure system in the south-eastern Indian Ocean. (Source: Japan Meteorological Agency)

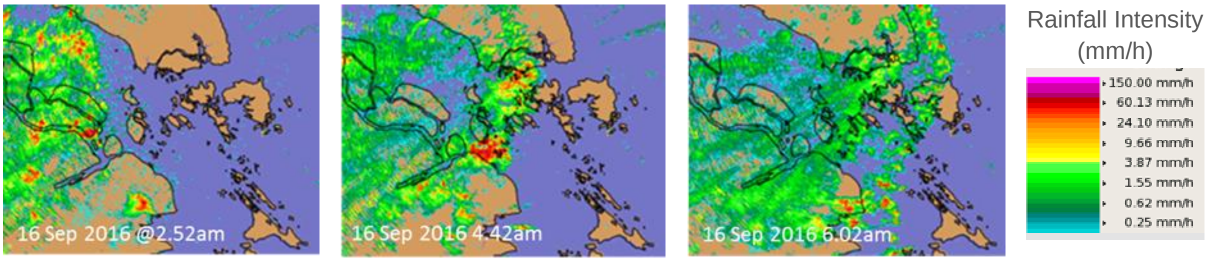


Figure 30: Sequence of weather radar images show a Sumatra squall moving eastward across the Strait of Malacca and affecting Singapore in the predawn and early morning on 16 September 2016

The unseasonal westerly winds in the surrounding region contributed to a high frequency of Sumatra squalls affecting Singapore in the second half of 2016. A Sumatra squall is an eastward moving line of thunderstorms that develop over Sumatra or the Strait of Malacca and usually brings moderate to heavy rainfall and gusty winds over Singapore. Notably, Sumatra squalls developed on seven consecutive days between 14 and 20 September 2016, under the influence of prevailing westerly winds and two typhoons present in the region. The Sumatra squall on 18 September 2016 brought winds gusting up to 77.4km/h in the early hours and predawn, uprooting several trees in the western and eastern parts of the island.

Figure 31: Workers clearing the trees felled by strong wind gusts from a Sumatra squall on 18 September 2016.
Source: The Straits Times © Singapore Press Holdings Limited. Permission required for reproduction

Sumatra squalls typically occur between April and November, and rarely during the Northeast Monsoon period between December and March when winds blow predominantly from the northeast. However, in December 2016, persistent westerly winds on some days led to the development of several Sumatra squalls that affected Singapore during the month.

Transboundary Smoke Haze Event in 2016

Compared to 2015 when prolonged dry weather (due to a strong El Nino) contributed to the worst smoke haze event in the region, the relatively wet Southwest Monsoon in 2016 helped to mitigate the occurrences of transboundary haze in the region.

In 2016, the only significant transboundary haze episode that affected Singapore occurred from 26 to 28 August. A sudden intensification of fire hotspot activities over Riau province in central Sumatra on the night of 25 August 2016 led to smoke haze being transported by strong westerly winds towards Singapore the following day. The hazy conditions persisted into 27 August 2016 and gradually improved later in the day due to a shift in the prevailing winds to blow from the southeast or southwest. The 24-hr Pollutant Standards Index (PSI) entered the Unhealthy range in the late afternoon of 26 August 2016 and reached a high of 143 at 8am on 27 August 2016, before gradually returning to normal levels in the late afternoon on 28 August 2016.

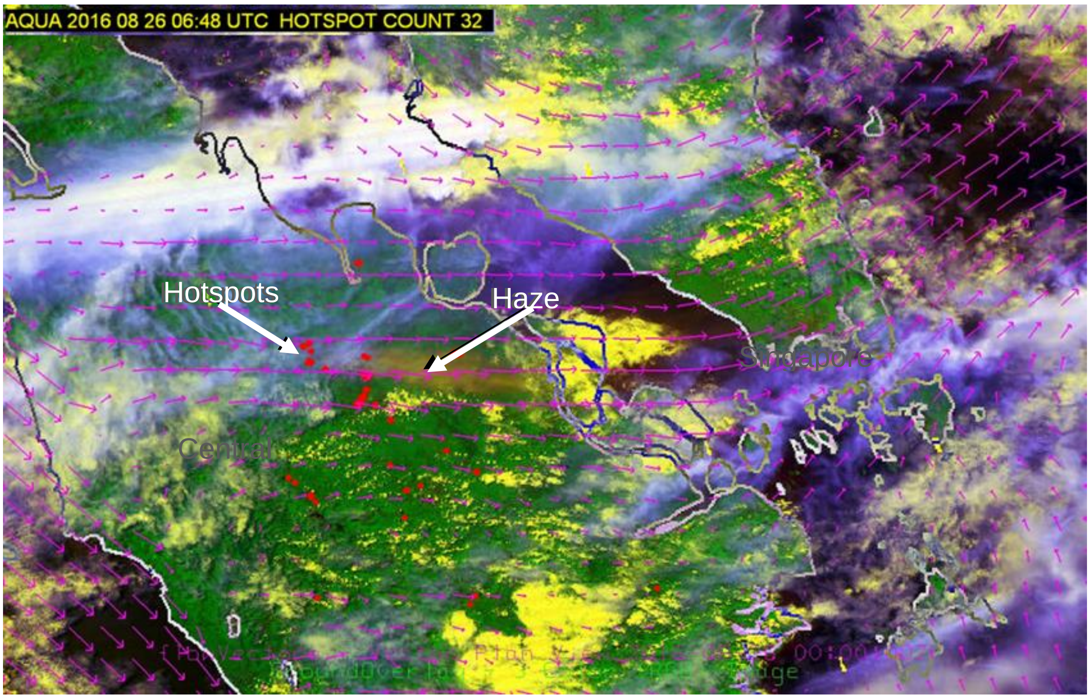


Figure 32: Satellite image at 2.48pm (0648UTC) on 26 August 2016 showing smoke plumes and smoke haze over central Sumatra being blown by prevailing westerly winds towards Singapore.

General Climate of Singapore

Singapore has a tropical climate which is warm and humid, with abundant annual rainfall of about 2,170mm. 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 ºC during the night, and maximum usually not rising above 31-33ºC 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)

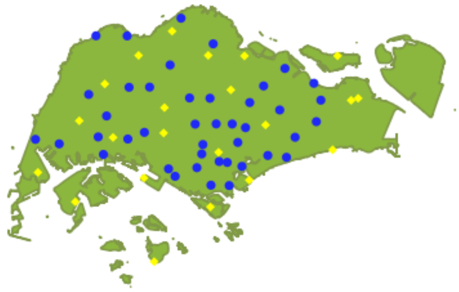
The transitions between the monsoon seasons occur gradually, generally over a period of two months. The winds during the inter-monsoon periods are usually light and tend to vary in direction. The three main rain-bearing weather systems that affect Singapore are the Northeast Monsoon surges, "Sumatra" 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 80km/h 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 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 quite significantly to the rainfall in these months. A typical rain spell generally lasts for a few days.

Network of Automatic Weather Stations as of Dec 2015



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

Manned Weather Stations

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).


The Changi Climate Station

MSS currently operates a network of five manned observation stations, one upper air observatory and 64 automatic weather stations. All the automatic weather stations measure rainfall and more than one-third 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 for rainfall and three for temperature.

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

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Figure 28: Thessa Huiying

Front cover: Map of annual temperature anomaly over Southeast Asia in 2016, the warmest year on record globally (Data sourced from GISS/NASA).