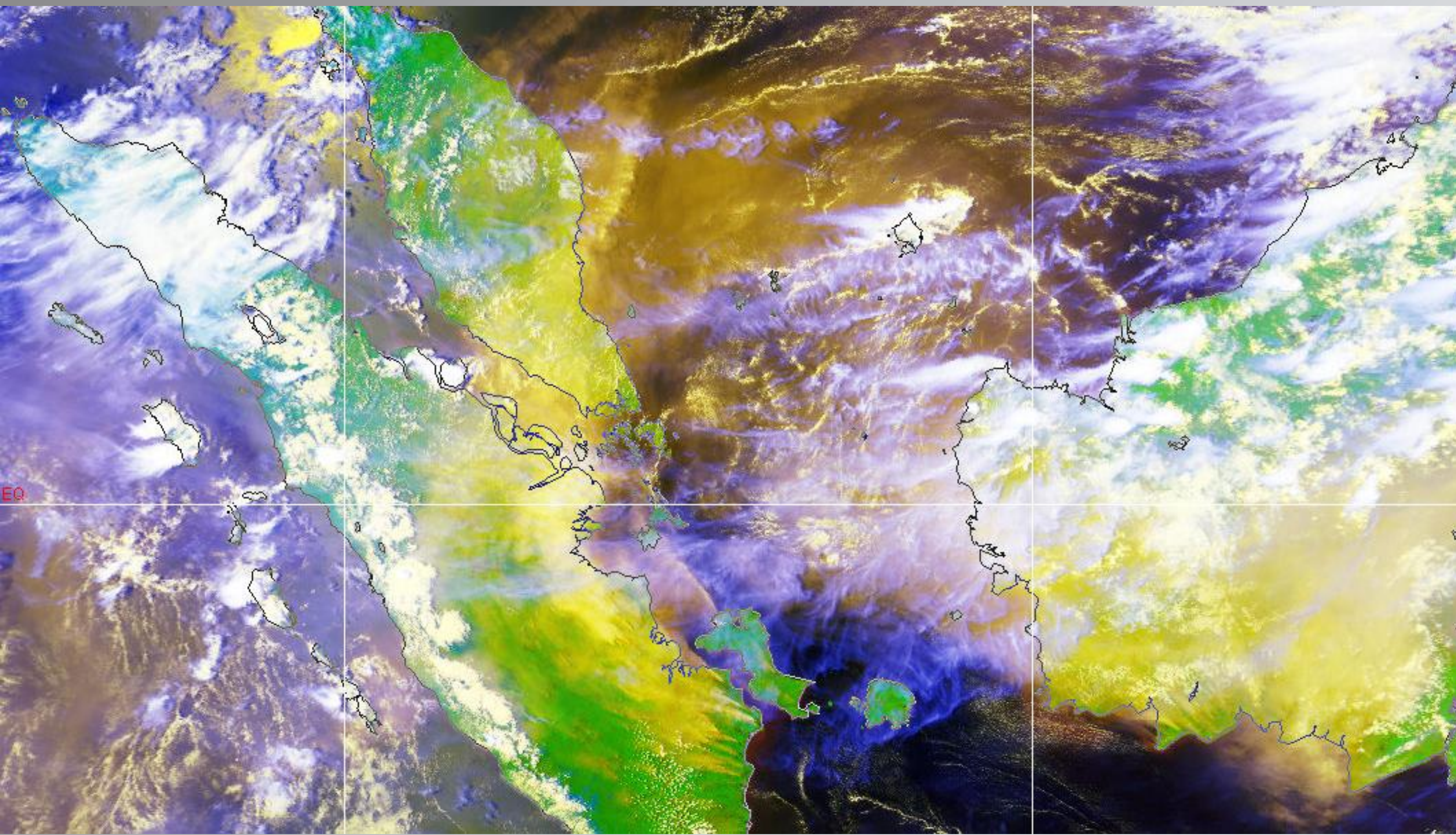
ANNUAL CLIMATE ASSESSMENT 2015

SINGAPORE



METEOROLOGICAL SERVICE SINGAPORE
Centre for Climate Research Singapore

Introduction

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

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

Key Points for 2015

- 2015 was the joint warmest and 2nd driest year on record for Singapore.
- During the latter half of 2015, Singapore's climate was substantially influenced by El Niño.
- 2015 set new monthly records for the warmest July and December; and tied the records for warmest October and November.
- There has been a warming trend over Singapore over a number of decades. The average rise is 0.25ºC per decade from 1948 to 2015. This is higher than the global warming rate of 0.12ºC over a similar period (1951 to 2012).
- Singapore was affected by one of the worst transboundary smoke haze episodes in recent history, lasting about three months.

Shrouded by thick smoke haze, the Singapore skyline is barely visible on 22 Sep 2015.
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Front cover: Satellite image on 24 September 2015 showing thick smoke haze (depicted in shades of yellow) from Sumatra and Kalimantan spreading to Singapore and the surrounding region during the prolonged transboundary haze event in 2015 (see page 12 for details).
(Satellite image processed by Meteorological Service Singapore from the polar orbiting satellite NOAA19, operated by the US National Oceanic and Atmospheric Administration.)

Singapore Climate in 2015

One of the strongest El Niño events on record occurred in 2015, resulting in below average rainfall over the Maritime Continent[1]. This worsened the forest fire situation during the traditional dry season, leading to one of the most severe occurrences of transboundary smoke haze episodes in recent history over Singapore and the surrounding region.

As expected from the long term climate trends, the year 2015 was warmer than the historical normal. Statistical analysis of historical records show Singapore to be warmer during El Niño events and this further increased the temperature in 2015. The monthly mean temperatures were above normal for all months except February 2015 and the annual mean temperature placed 2015 as the joint warmest on record, together with 1997 and 1998. Also associated with the El Niño, 2015 was the second driest year on record, behind 1997. The monthly rainfall totals were below average for most months. While there was no distinct dry spell in 2015, there were two periods in February and June in which the average rainfall over our 28 rainfall stations with long term records were below 1.0mm for 11 (7 February to 17 February) and 13 (18 June to 30 June) consecutive days respectively.

As the El Niño became established around mid-2015, Singapore began to experience temperatures much warmer than the climatological averages and several records for highest mean monthly temperatures were either equalled or broken in the second half of the year. 2015 set the record for the warmest July, October (joint), November (joint) and December with monthly mean temperatures of 29.1ºC, 28.7ºC, 28.0ºC and 27.7ºC respectively. The previous records for the warmest July and December were 28.8ºC (in 1997) and 27.3ºC (in 1997) respectively.

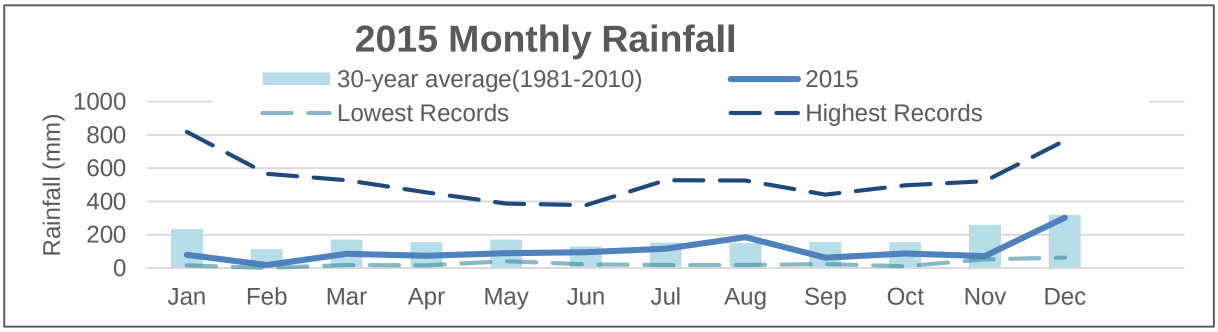


Figure 1a: Monthly rainfall in 2015 compared with the corresponding long-term average and lowest and highest values on record.

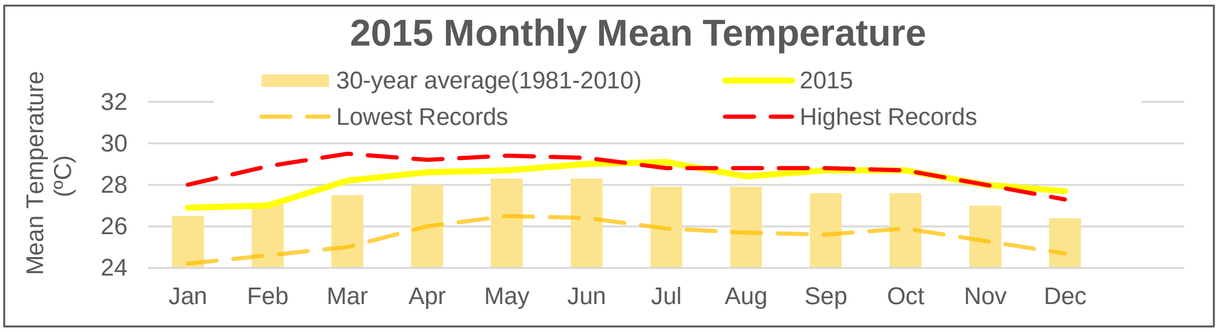


Figure1b: Monthly mean temperatures in 2015 compared with the corresponding long-term average and lowest and highest values on record.

[1] *The Maritime Continent is a term commonly used by meteorologists and oceanographers to describe the tropical region between the Indian and Pacific Oceans.*

The 2015-16 Strong El Niño Event

Around mid-2015, an El Niño event emerged as the eastern and central tropical Pacific Ocean warmed significantly. By that time, the trade-winds in the Pacific Ocean had weakened considerably and more rainfall appeared near the international dateline. Both these developments were supporting signs of a growing El Niño event. For Singapore, these effects would have a number of important implications, such as water resource management, contributing to enhanced risks of transboundary haze and dengue incidents.

The Evolution of El Niño Indicators in 2015

One of the indicators of an El Niño event is sea-surface temperature (SST) departures from normal in the Niño3.4 region situated in the central eastern Pacific (Figure 2). Another key indicator is the sea level pressure difference between Tahiti and Darwin shown in Figure 3. The reduction in this pressure difference is associated with large scale weather changes across our region. Both indicators provide evidence of a strong El Niño event in 2015.

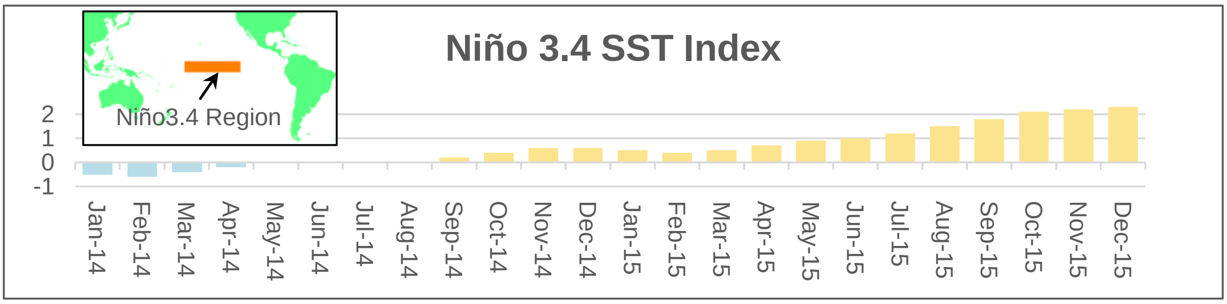


Figure 2: The Niño3.4 index, three-month running mean of SST anomalies in the Niño3.4 region bounded by 5°N to 5°S, from 170°W to 120°W. An El Niño event will result in warm anomaly while a La Niña event will cause cool anomaly. (Data source: ERSSTv4 from NOAA).

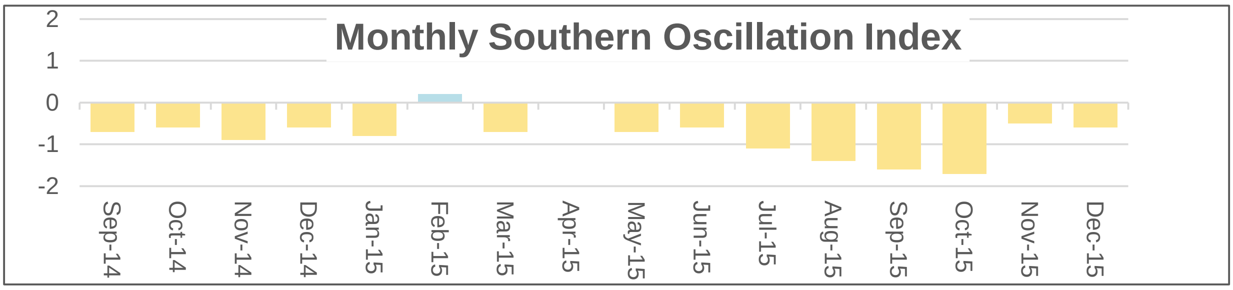


Figure 3: The Southern Oscillation Index (SOI) measures the difference in mean sea level pressure between Tahiti and Darwin. The more negative and downward trending the values are, the stronger the indication of atmospheric response from an El Niño event (Data source: NOAA).

Comparisons between the 1997-98 and 2015-16 El Niño events

By mid-2015, SST conditions in the tropical Pacific Ocean closely mirrored the strong 1997-98 El Niño event. The SST anomaly patterns in the season May-July 2015 resembled that of 1997's (Figure 4 a & b, next page) with temperature anomalies over the Niño3.4 region of the tropical Pacific averaging about 1.3°C. By the end of each year (Figure 4 c & d, next page), both events had matured. The circulation patterns and impact on rainfall also showed that the events were similar on the large scale. Figure 5 shows that the rainfall anomalies for both events across the Indo-Pacific region in the season June-September are similar. Both events caused severe drier-than-normal conditions over the Maritime Continent and exacerbated the transboundary haze conditions in the respective years.

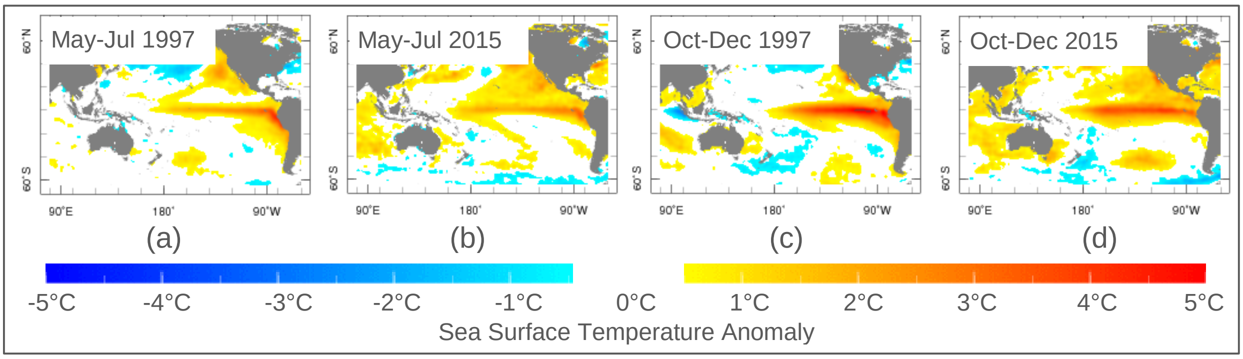


Figure 4: Seasonal sea-surface temperature anomaly for (a) May-Jul 1997 and (b) May-Jul 2015, and for (c) Oct-Dec 1997 and (d) Oct-Dec 2015
(Data source: NOAA NCEP[2] (OISST Version 2), image generated using IRI[3] Map Room).

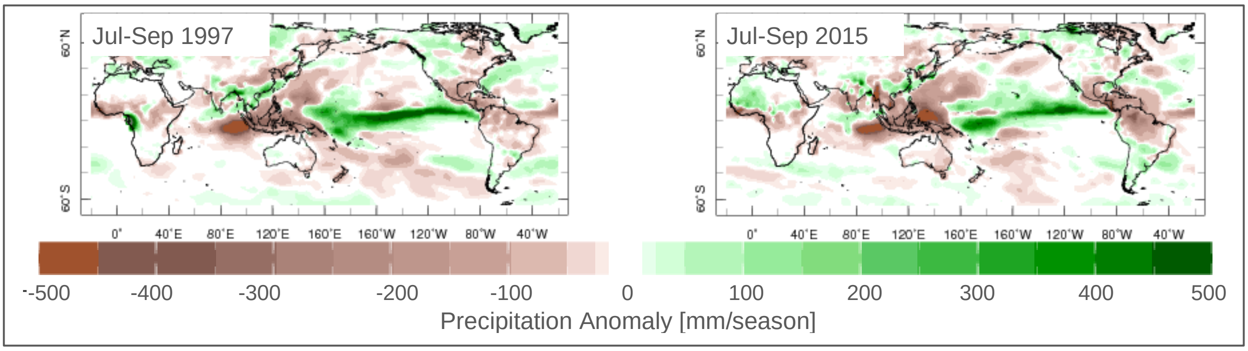


Figure 5: Jul-Sep 1997 and 2015 rainfall anomaly (brown/green shades) across the tropics (Data Source: NOAA NCEP[2] Climate Prediction Centre (CAMS_OPI), image generated using IRI[3] Map Room)

Impact on rainfall and temperature over Singapore

The reduced rainfall led to relatively warmer temperatures over land, as shown by the surface temperature anomaly for the season July-September 2015 (Figure 6). Locally, the effects on temperature (warmer) and rainfall (drier) were felt throughout 2015. However, the magnitudes of the effects varied from month-to-month and not all of them can be attributed to the El Niño alone. At the end of 2015, this El Niño event was continuing into its mature stage, but based on what happened in 2015, the event has already lived up to its reputation as being one of the strongest El Niño events in 60 years of recorded history.

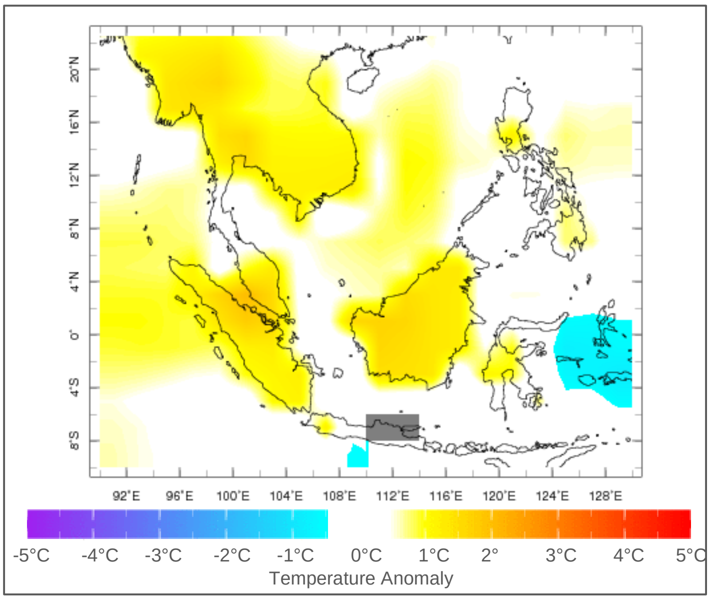


Figure 6: Surface temperature anomaly for Jul-Sep 2015 across Southeast Asia (Data Source: NOAA NCEP[2] Climate Prediction Centre, image generated using IRI[3] Map Room).

[2] *NOAA NCEP: National Oceanic and Atmospheric Administration, National Centres for Environmental Prediction*
[3] *IRI: International Research Institute for Climate and Society*

Temperature

Figure 7: Annual mean temperature across Singapore in 2015

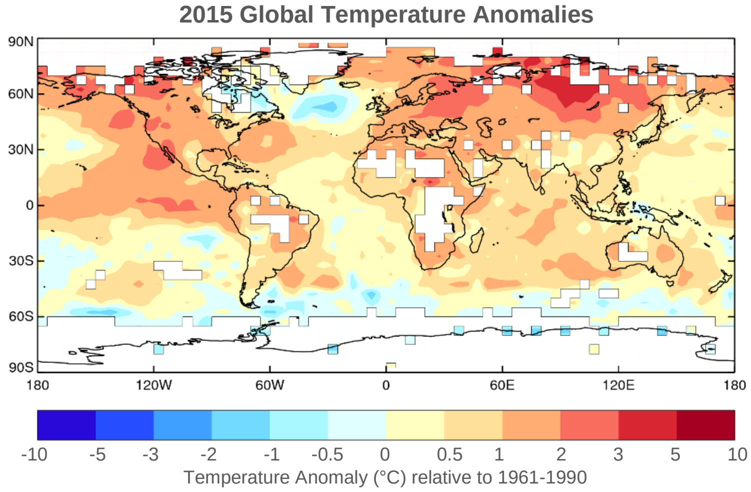
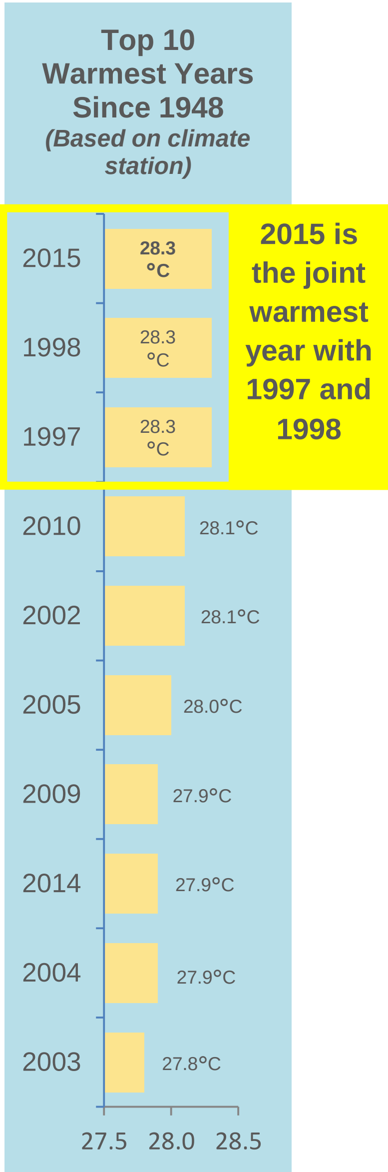


Figure 8: Global annual temperature anomalies in 2015 relative to 1961-1990 base period. (Source: Met Office Hadley Centre, data from the HadCRUT4 dataset produced by Met Office Hadley Centre, United Kingdom, and Climatic Research Unit, University of East Anglia, United Kingdom.



Under the influence of a strong El Niño, 2015 was an exceptionally warm year. According to the World Meteorological Organization (WMO), the global average surface temperature in 2015 was 0.76± 0.1ºC above the 1961-1990 average, which set it as the warmest year on record and broke the previous warmest year record in 2014 by a big margin of 0.19ºC. The next three warmest years are 2014(0.57 ± 0.09ºC), 2010(0.55 ± 0.09ºC) and 2005(0.54 ± 0.09ºC)[4]. Most parts of the world experienced above normal temperatures (see Figure 8 above) and many countries observed a record or near record warm year.

For Singapore, 2015 tied with 1997 and 1998 as the warmest years on record. Eight of the ten warmest years in Singapore have occurred in the 21st century and all have occurred since 1997. El Niño conditions prevailed in eight of the ten warmest years recorded in Singapore. In particular, the temperatures in the top three warmest years of 1997, 1998 and 2015 in Singapore were influenced by two of the strongest El Niño events on record.

[4] *The figures after "±" indicates the uncertainty associated with the global average surface temperatures.*

Past Temperature Trends

Analysis of the annual mean temperature from the climate station (refer to page 16 for more information on our climate station) shows that there was an average rise of 0.25ºC per decade from 1948 to 2015. The rate of increase in temperature is greater than the global temperature trend of +0.12°C[5] per decade from 1951 to 2012. Figure 9 shows the comparison of Singapore and global temperature anomalies over the years.

Although greenhouse warming has contributed to the rise in temperature over Singapore, it cannot account for all of the increase. Human activities can also influence the climate in ways that are not associated with the global warming resulting from increasing greenhouse gas concentrations in the atmosphere. A key example is land use change, such as urbanization, which can impact temperatures and this is likely to have played a significant role in Singapore.

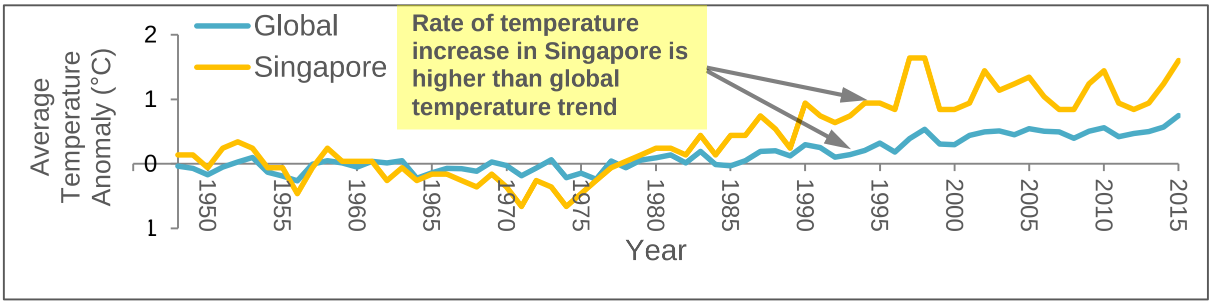


Figure 9: Global vs Singapore temperature anomalies (relative to 1961-1990 average) from 1948-2015.
Global temperatures are from the HadCRUT4 dataset produced by Met Office Hadley Centre, United Kingdom, and Climatic Research Unit, University of East Anglia, United Kingdom. Singapore temperature is from our climate station.

Accompanying the general warming trend, there have been changes in the frequency of extreme high and low temperatures across Singapore (Figures 10a and 10b). From 1972, Singapore has experienced an increase in the number of warm days and warm nights and a decrease in the number of cool nights. As with average temperatures, the frequency of warm days and nights, in particular, occur against a background of year-to-year climate variability, mostly associated with El Niño and La Niña events.

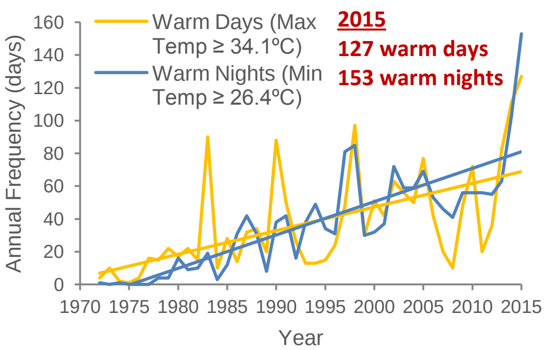


Figure 10a: Increasing frequency of warm days/nights in Singapore since 1972.*

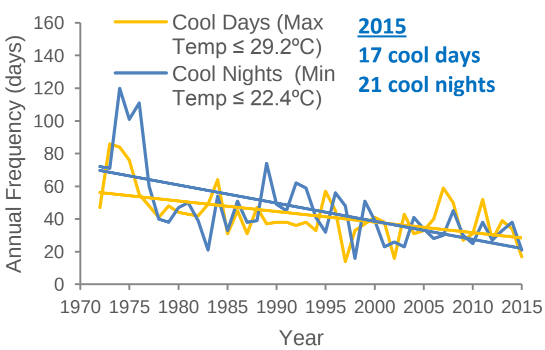


Figure 10b: Decreasing frequency of cool days/nights in Singapore since 1972.*

**Based on temperature records from Seletar, Tengah and the climate station.*
Thresholds for warm and cool days/nights (34.1/26.4 °C and 29.2/22.4 °C) are based on the 90th and 10th percentile value of the daily maximum/minimum temperatures recorded during the period from 1981 to 2010.

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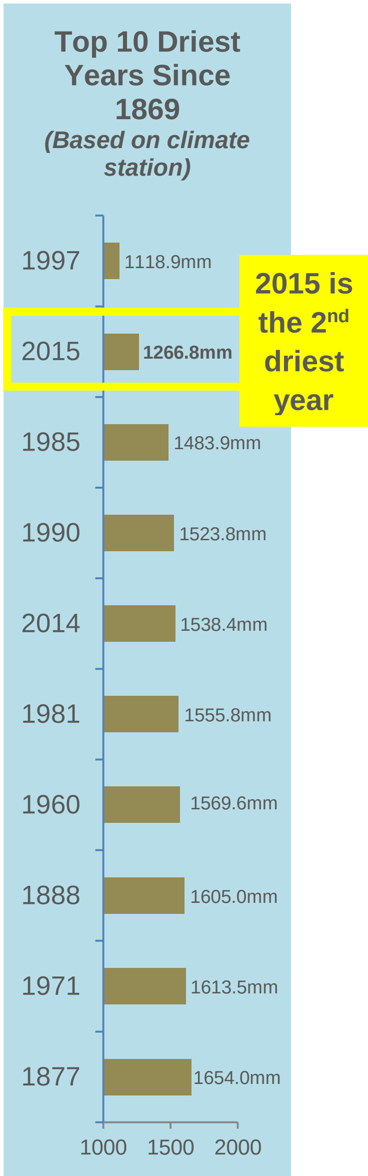
[5] *Source: Intergovernmental Panel on Climate Change, Fifth Assessment Report.*

Rainfall

Global average precipitation in 2015 was 22.5 mm below the 1961-1990 average of 1033 mm, according to NOAA (National Oceanic and Atmospheric Administration, USA). There was a mix of positive and negative precipitation anomalies globally, with the El Niño playing a big role in our region and most parts of Southeast Asia receiving below average rainfall.

Locally over Singapore, 2015 was the second driest year on record. Most parts of the island were below normal (Figure 11 below) compared to the 1981-2010 average[6], and the majority of the months recorded below average rainfall (Figure 12 next page).

Figure 11a: Annual total rainfall distribution across Singapore in 2015



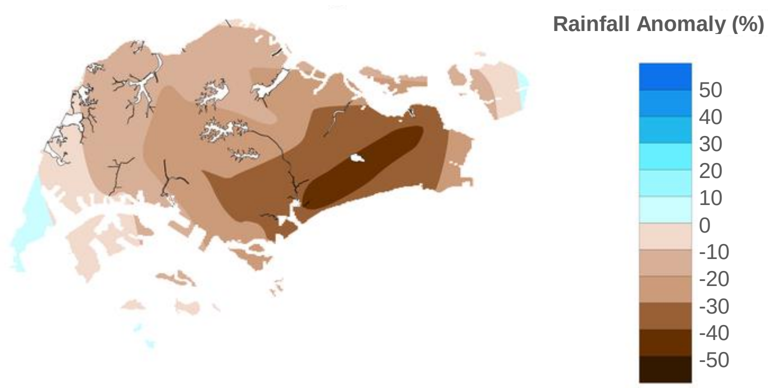


Figure 11b: Annual rainfall anomalies across Singapore (relative to 1981-2010 average) in 2015.
**Most parts of Singapore received below average rainfall for year 2015*

[6] *The use of 1981-2010 is in accordance to the latest WMO recommendation for climatological reference period. We also do not have sufficient rainfall stations with long term records before 1980 for plotting of rainfall anomaly map using 1961-1990 as the reference period, as done by NOAA.*

Monthly Rainfall Anomaly Maps 2015

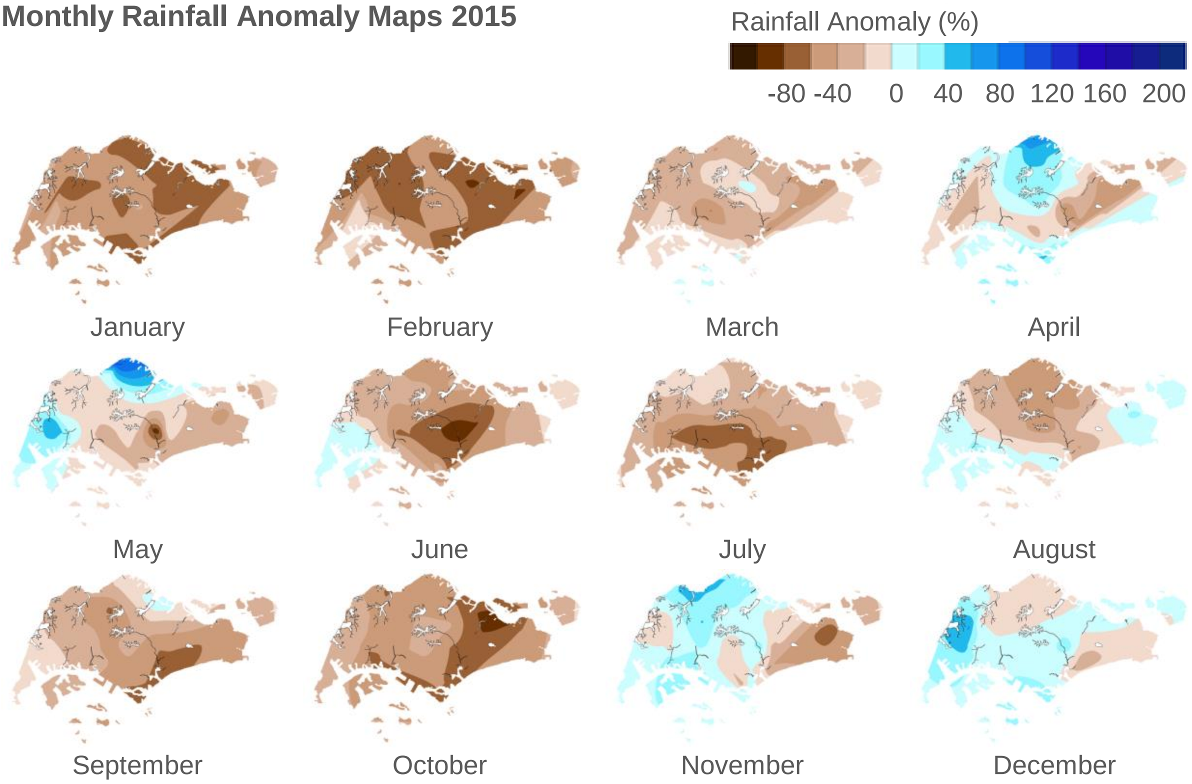


Figure 12: Monthly Rainfall Anomaly Maps in 2015

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 years, the average annual rainfall totals recorded at the 28 rainfall stations increased at a rate of 11.6mm per year (Figure 13). The spatial variation in the trends in annual rainfall totals since 1980 is depicted in Figure 14a (next page). Generally, there are consistent rainfall trends across Singapore since 1980, with 35 per cent of the rainfall stations showing a statistically significant upward trend in the annual rainfall total, ranging from +15.2mm to +19.2mm per year.

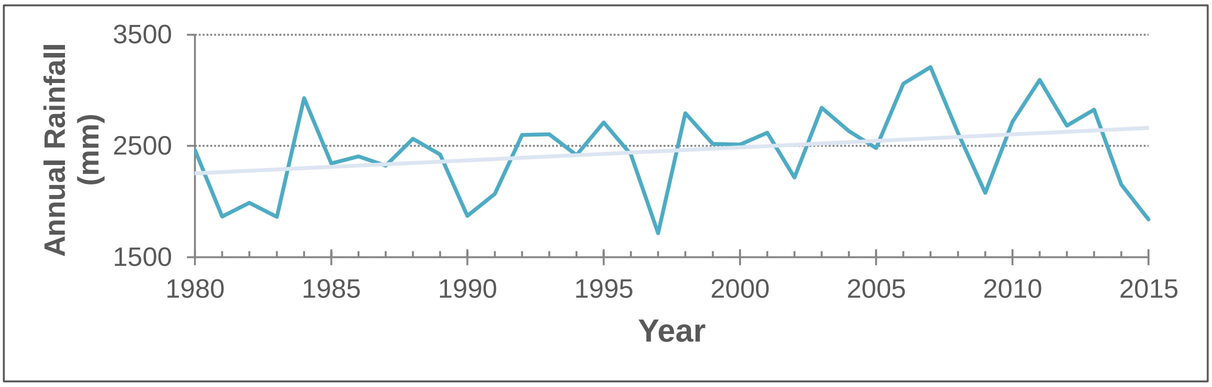


Figure 13: Time series of annual rainfall total in Singapore shows a statistically significant upward trend of 11.6mm per year, based on linear fit, on average from 1980 to 2015.

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 14b). There are statistically significant upward trends at six rainfall stations, with an average rate of about 0.9 days per decade. The rest of the stations show generally upward but not statistically significant trends.

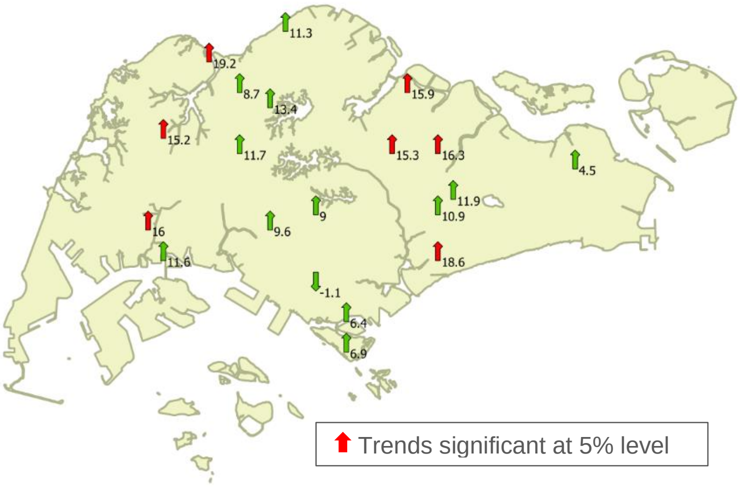


Figure 14a: Map showing the past trends of annual rainfall total (mm/year) at individual stations. All stations indicate upward trends (up-arrow).*

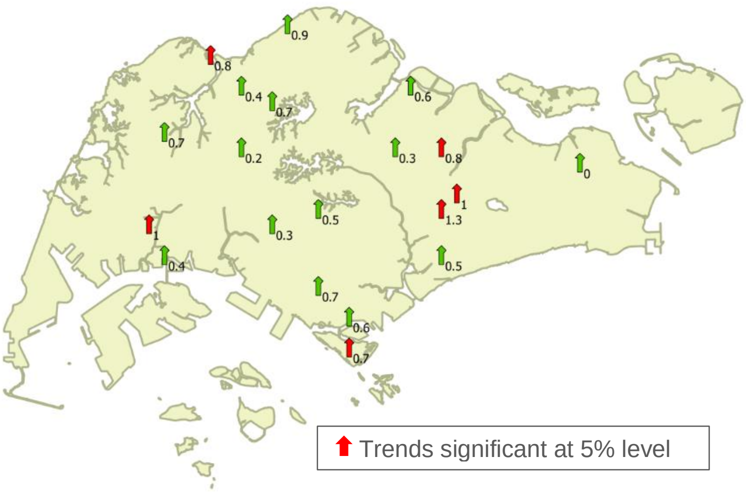


Figure 14b: Map showing the past trends of number of days with hourly maximum rainfall totals exceeding 40 mm (heavy rain) at individual stations.*

**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 1980-2015.*

There is considerable year-to-year variability in Singapore's rainfall. As was the case in 2015, the El Niño Southern Oscillation (ENSO) in particular plays an important role in this variability during the Southwest Monsoon season and the succeeding inter-monsoon season.
Major uncertainties remain in attributing observed heavy rainfall trends to particular factors, such as natural climate variability and anthropogenic influences. This is an area of ongoing research.

Notable Weather Events in 2015

Extremes in 2015

The wettest and coolest month in 2015 occurred in the Northeast Monsoon months of December and January respectively, in line with our local climatology. The warmest month in 2015 was July.

Table 1 – Extremes in 2015 across all available stations and the climate station (refer to page 16 for more information on our network of weather stations).

	Hottest Day	Coldest Night	Wettest Day	Warmest Month	Coolest Month	Wettest Month	Strongest Wind Gust
All Available Stations	**36.4°C** 20 Apr (Seletar)	**21.6°C** 3 Aug & 28 Oct (Several)	**128.8mm** 28 Dec (Jurong Island)	**29.6°C** Jul (Tai Seng)	**26.3°C** Jan (Pulau Ubin)	**494.0mm** Dec (Jurong Island)	**131.8km/h** 25 Nov (Tengah)
Climate Station (Changi)	**34.4°C** 4 Mar & 18 Apr	**21.9°C** 28 Oct	**63.2mm** 12 Aug	**29.1°C** Jul	**26.9°C** Jan	**302.0mm** Dec	**59.4km/h** 4 Jul and 28 Oct
Climate Station Records	**36.0°C** 26 Mar 1998	**19.4°C** 30 & 31 Jan 1934	**512.4mm** 2 Dec 1978	**29.5°C** Mar 1998	**24.2°C** Jan 1934	**818.6mm** Jan 1893	**90.7km/h** 29 Nov 2010

Drier weather at the beginning of 2015

In 2015, the dry phase of the Northeast Monsoon season started earlier than usual around mid-January 2015 and lasted till end February 2015.
Unlike the first few months of 2014 when Singapore experienced a prolonged dry spell, the extended dry weather that prevailed in early 2015 did not meet the current criteria for a dry spell*. However, more than 70 per cent of the daily average rainfall (over our 28 stations with long-term records) recorded in January and February 2015 was below 1.0mm. The longest period of consecutive dry days with daily rainfall below 1.0mm was 11 days (7-17 February 2015).
In addition, the rainfall for January and February recorded at our climate station was 66 per cent and 82 per cent below the long-term average (reference period: 1981-2010) respectively.

Figure 15: Parched edge of Eco Lake at the Singapore Botanic Garden during the dry period in early 2015.
Source: The Straits Times © Singapore Press Holdings Limited. Permission Required for Reproduction

** A dry spell is defined as a period of at least 15 consecutive days with daily rainfall total of below 1.0mm, averaged over 28 rainfall stations.*

Prolonged Transboundary Haze

During the traditional dry Southwest Monsoon season in 2015, Singapore and many parts of the region were affected by transboundary smoke haze from uncontrolled land and forest fires in Sumatra and Kalimantan. The prolonged transboundary haze event, which occurred over a period of three months, was the worst in recent history. The last major haze event to affect the region was in 1997/1998. Both events occurred during a strong El Niño, which exacerbated the dry weather conditions in the region. In the 2015 event, the haze occasionally spread to as far as the southern parts of the Philippines, Thailand and Vietnam.

Singapore was affected by transboundary haze from late August to end October 2015 when the prevailing winds were blowing predominantly from the southwest or southeast, bringing in haze from fires in central/southern Sumatra and southern Kalimantan respectively.

In September and October 2015, we experienced a total of 10 haze episodes where the 24-hr Pollutant Standards Index (PSI) was in the Unhealthy range. The duration of these episodes ranged from 27 hours (16 – 17 October 2015) to 164 hours (27 September - 4 October 2015). On five occasions in late September and October 2015, the air quality entered the Very Unhealthy range. On 24 September 2015, as the haze situation worsened with a likelihood of the air quality crossing into hazardous levels the next day, the Ministry of Education and the Ministry of Health jointly decided to close all primary and secondary schools on 25 September 2015. The air quality breached the Hazardous range for several hours on 25 September 2015, peaking at 322 at 8am, the highest 24-hr PSI value recorded in 2015.

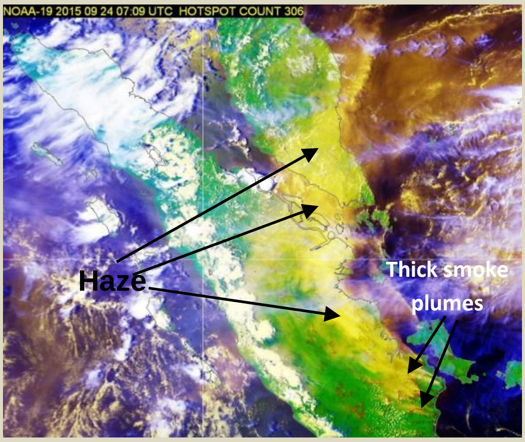


Figure 16: NOAA19 satellite image on 24 Sep 2015 showing smoke plumes emanating from fire spots in southern Sumatra, and the region shrouded by dense smoke haze.

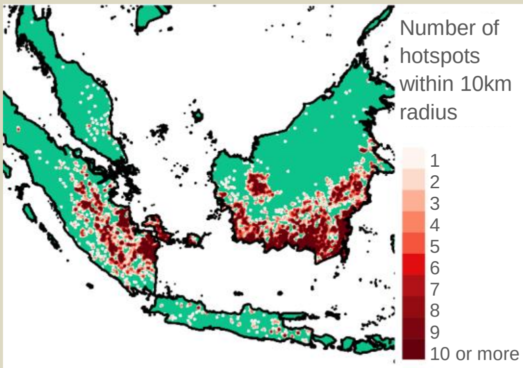


Figure 17: Heat map of fire hotspots detected by the NOAA18 satellite from Sep to Oct 2015, showing a high concentration of hotspots in southern parts of Sumatra and Kalimantan in Indonesia.

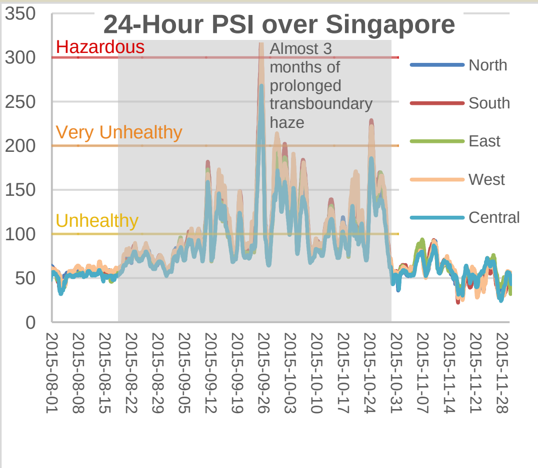


Figure 18: Time series of Singapore's 24-hour PSI in 2015. The 24-hr PSI was in the Unhealthy range or worse for most of Sep and Oct 2015.

Heavy Rain Spell

For three consecutive days on 10-12 December 2015, Singapore experienced intense localized thunderstorms in the afternoon, due to strong solar heating of land coupled with wind convergence. The heavy downpour led to flash floods in the Kallang and Boon Lay areas on the first two days. The highest daily rainfall total recorded at the rainfall stations for 10 and 11 December 2015 was 78.4mm and 80.6mm respectively. Rainfall of 63.4mm over 30 minutes was recorded at Toa Payoh on 11 December 2015. The thunderstorms were relatively less intense on 12 December 2015, with highest daily rainfall total of 64.2mm recorded.

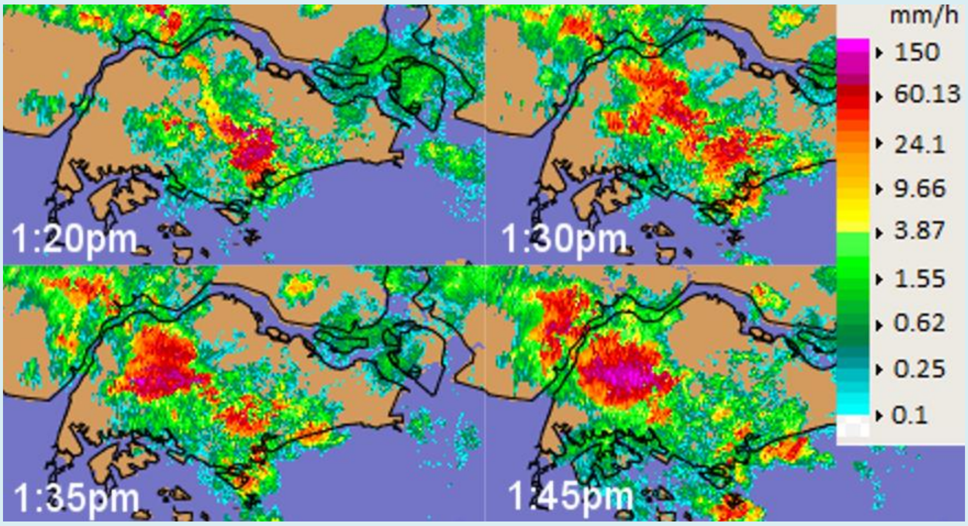


Figure 19: Sequence of rain radar images shows the very rapid development of thunderstorms over Singapore on 11 December 2015.

Figure 20: Heavy thunderstorms on 11 December 2015 felled some trees in the Macpherson area.
Source: Shin Min Daily News © Singapore Press Holdings Limited. Permission Required for Reproduction

Projections of Future Climate in Singapore

In April 2015, the Meteorological Service Singapore, working in collaboration with the UK Met Office Hadley Centre, released a new set of climate projections for Singapore. Reports detailing the outcomes of this Second National Climate Change Study can be found at http://ccrs.weather.gov.sg. The projections used two Representative Concentrations Pathways (RCPs) for the concentrations of greenhouse gases in the atmosphere. One pathway RCP4.5 is related to a scenario where emissions peak mid-century and then decline, whereas RCP8.5 is related to a scenario with very high greenhouse gas emissions that continue to increase throughout the 21st century.

The results from the projections indicated that mean temperatures over Singapore will continue to rise, together with more frequent occurrences of warm days and nights. For example, the number of warm days (>34.1ºC) during February to May is projected to increase from 25 days to over 100 days per year by 2070-2099. For rainfall, while the annual average rainfall is not expected to change significantly, the climatologically wetter periods (November to January) and drier periods (February and June to September) are projected to get wetter and drier respectively. There will also likely be more frequent and heavy extremes of rainfall.

The results are summarised in the figure below. The actual extent of the climate changes that will be experienced will depend strongly on the future emissions of greenhouse gases and associated mitigation actions taken by the global community.

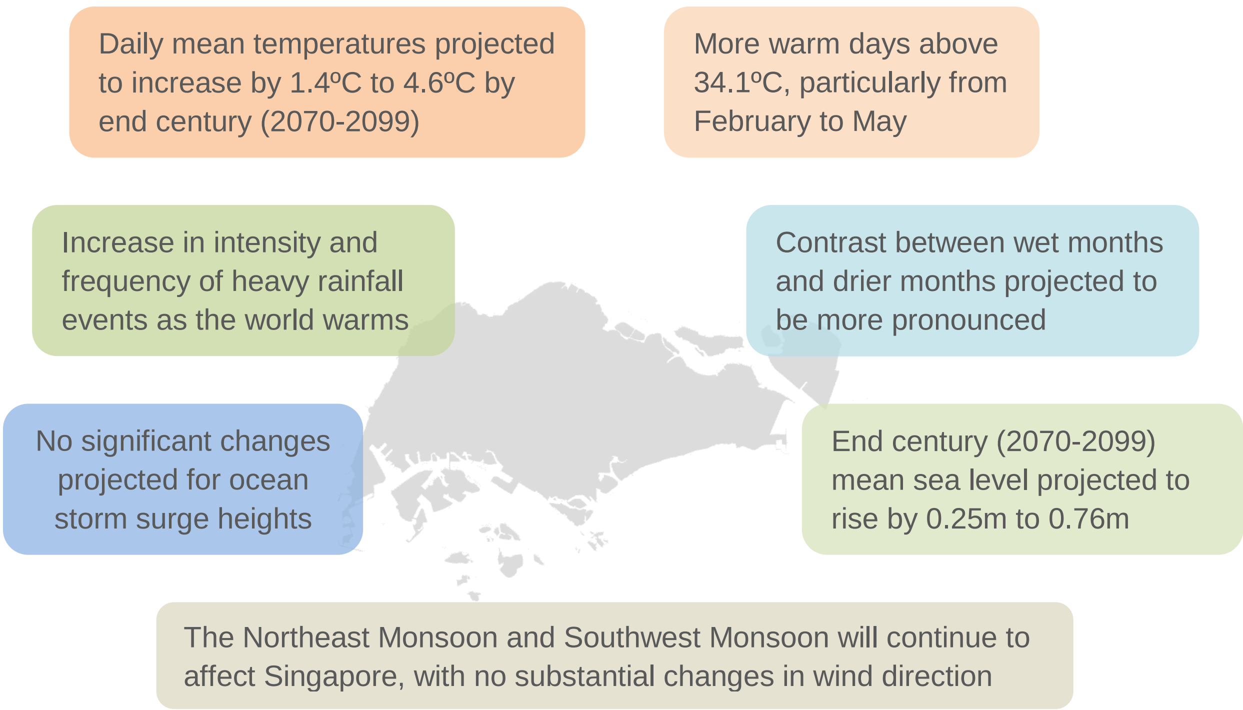


Figure 21: Climate changes that are projected for 2070-2099 relative to 1980-2009. These results are from climate models that employed two greenhouse gas Representative Concentration Pathways (RCPs), RCP4.5 and RCP8.5. The range of temperature and sea level rises shown correspond to these two RCPs. The precise values can only be regarded as indicative of what future conditions may be.

General Climate of Singapore

Singapore has a tropical climate which is warm and humid, with abundant annual rainfall of about 2400mm. 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 ^{o}C during the night, and maximum usually not rising above 31-33^{o}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*

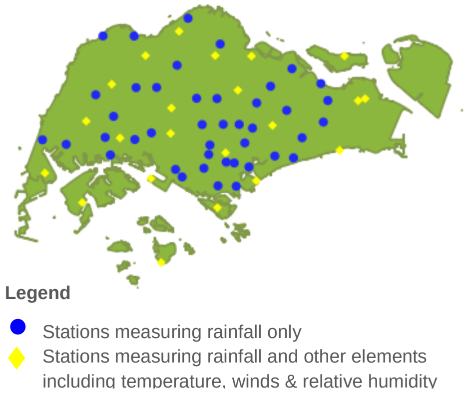
The transitions between the monsoon seasons occur gradually, generally over a period of two months. The winds during the inter-monsoon periods are usually light and tend to vary in direction. The three main rain-bearing weather systems that affect Singapore are the Northeast Monsoon surges, "Sumatra" 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



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).

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 for records since 1980.

Further Information

Meteorological Service Singapore : www.weather.gov.sg
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