PERFORMANCE VALIDATION OF NASA-POWER DATA FOR DROUGHT MONITORING IN THE KELANTAN RIVER BASIN, MALAYSIA

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by

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LIST OF SYMBOL

°C	Degree celcius
mm	Millimitres
n	samples
Xi	NASA-POWER-dependent rainfall data
X^{-}	the mean of the NASA-POWER datasets
Yi	station data
Y^{-}	the mean for the station-dependent data
μ	the mean of the rainfall datasets
σ	the standard deviation.
Dd	Drought duration
ts	is the start of the drought
te	is the end of the drought
Ds	Drought severity
j	the month
Index J	the value of the SPI in j month
Di	Drought intensity
Dp	Drought peak
xj and xk	annual for the years k and j
n	the value
N	the number of slopes valued sorted from the minimum to maximum
R	the value of the response rate in percentage
M	the number of drought episodes in SPI <0
D value	the difference between the drought index and atmospheric indices

LIST OF ABBREVIATIONS

IPCC	Intergovernmental Panel on Climate Change
EM-DAT	The Emergency Event Database
SPP	Satellite Precipitation Product
NASA-POWER	National Aeronautics and Space Administration's Prediction Worldwide Energy Resources
SPI	Standardised Precipitation Index
SSI	Standardised Streamflow Index
SPEI	Standardised Precipitation Evaporation Index
KRB	Kelantan River Basin
ENSO	El Nino Southern Oscillation
IOD	Indian Ocean Dipole
MJO	Madden Julian Oscillation
SEDI	Standardised Evaporation Deficit Index
PDO	Pacific Decadal Oscillation
MEI	Multivariate El-Nino Southern Oscillation
DMI	Dipole Mode Index
NEM	NorthEast Monsoon
SWM	SouthWest Monsoon
EDDI	Effective Drought Severity Index
MMD	Malaysian Meteorological Department
NOAA	National Oceanic and Atmospheric Administration
EOF	Empirical Orthogonal Function
SSTa	Sea Surface Temperature Anomalies
OLR	Outgoing Longwave Radiation
R	Pearson
RMSE	Root Mean Square Error
RB	Relative Bias

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PENGESAHAN PRESTASI DATA NASA-POWER BAGI PEMANTAUAN KEMARAU DI LEMBANGAN SUNGAI KELANTAN, MALAYSIA

ABSTRAK

National Aeronautics and Space Administration Predictions of Worldwide Energy Resources (NASA-POWER) menawarkan data meteorologi jangka panjang untuk menyokong sektor tenaga boleh diperbaharui dan pertanian. Walaupun NASA-POWER menyediakan data iklim sumber terbuka alternative, keberkesanannya untuk pemantauan kemarau di kawasan tropika masih tidak jelas dalam literatur. Oleh itu, kajian ini bertujuan untuk menilai keupayaan NASA-POWER dalam menganggarkan hujan dan kemarau dari 1985 hingga 2020 di Lembangan Sungai Kelantan (KRB), Malaysia. Untuk menganalisis corak kemarau yang berbeza, Indeks Hujan Standard (SPI) dan Indeks Aliran Sungai Standard (SSI) digunakan pada skala waktu 1, 3, 6, dan 12 bulan. Selain itu, ujian Mann-Kendall digunakan untuk mengukur trend, manakala cerun Sen digunakan untuk menilai perubahan dalam magnitud kemarau. Spearman's Rho digunakan untuk meneroka hubungan antara kemarau dan sirkulasi atmosfera utama seperti *El Niño-Southern Oscillation* (ENSO), *Indian Ocean Dipole* (IOD), dan *Madden-Julian Oscillation* (MJO). Hasil kajian menunjukkan bahawa NASA-POWER secara umumnya menunjukkan prestasi memuaskan dalam menganggarkan hujan dan suhu di seluruh skala waktu, terutamanya secara bulanan dan di kawasan pantai utara. Walau bagaimanapun, ia cenderung untuk merendahkan nilai suhu minimum dan maksimum, serta hujan. Kejadian kemarau telah dikenalpasti di KRB pada tahun 1989-1992, 1996-1998, dan 2013-2016. Kebanyakan stesen merekodkan sekurang-kurangnya enam kemarau yang teruk, dan 75% mengalami sepuluh kemarau ringan, dengan KRB atas lebih terdedah kepada kemarau yang kerap

dan teruk. SSI lebih responsif terhadap SPI semasa tempoh kering antara Januari dan Mei berbanding bulan hujan dari Ogos hingga November. ENSO dan IOD mempunyai pengaruh yang lebih kuat terhadap kemarau di KRB berbanding MJO. Penyelidikan ini boleh menjadi rujukan berharga untuk meningkatkan pemantauan kemarau dan pengurusan sumber air di kawasan tropika.

PERFORMANCE VALIDATION OF NASA-POWER DATA FOR DROUGHT MONITORING IN THE KELANTAN RIVER BASIN, MALAYSIA

ABSTRACT

The National Aeronautics and Space Administration Prediction of Worldwide Energy Resources (NASA-POWER) offers long-term meteorological data to support the renewable energy and agricultural sectors. While NASA-POWER provides an alternative open-source climate data, its effectiveness for drought monitoring in tropical regions is still unclear in the literature. Therefore, this study aims to evaluate the capability of NASA-POWER in estimating precipitation and droughts from 1985 to 2020 in the Kelantan River Basin (KRB), Malaysia. To analyse different drought patterns, the Standardized Precipitation Index (SPI) and Standardized Streamflow Index (SSI) were applied at 1-, 3-, 6-, and 12-month time scales. In addition, the Mann-Kendall test was utilized to measure trends, whereas the Sens slope was used to evaluate changes in drought magnitude. Spearman's rho was utilized to explore the relationship between droughts and major atmospheric circulations like El Niño-Southern Oscillation (ENSO), Indian Ocean Dipole (IOD), and Madden-Julian Oscillation (MJO). The findings indicate that NASA-POWER generally performed satisfactorily in estimating precipitation and temperature across all time scales, particularly on a monthly basis and in northern coastal areas. However, it tended to underestimate minimum and maximum temperatures, as well as precipitation. Drought events were identified in the KRB during 1989-1992, 1996-1998, and 2013-2016. Most stations recorded at least six severe droughts, and 75% experienced ten mild dry droughts, with the upper KRB being more susceptible to frequent and severe droughts. The SSI was more responsive to SPI during the dry period from January to

May than in the wetter months from August to November. ENSO and IOD had a stronger influence on droughts in the KRB compared to MJO. This research can serve as a valuable reference for improving drought monitoring and water resources management in tropical regions.

CHAPTER 1

INTRODUCTION

1.1 Research Background

According to the Intergovernmental Panel on Climate Change (IPCC), climate change refers to long-term changes in the climate, seen through shifts in average climate conditions that last for decades or longer (Brown et al., 2008). It is a global issue with serious effects on nature, poverty, health, sustainable development, and water supply. EM-DAT (2022) reported that in 2021, 432 natural disasters, including droughts and floods, were recorded worldwide, affecting over 101.8 million people, causing 10,492 deaths, and leading to losses of about USD 252.1 billion.

Drought is a slow-developing natural hazard caused by a long-term lack of rainfall (Mishra & Singh, 2010). Malaysia has experienced prolonged dry spells, especially during El Nino events in 1997-1998 and 2013-2014, especially in the southwestern regions (Sanusi et al., 2015). During these events, rice production losses amounted to nearly RM218 million (Al-Amin & Alam, 2015). Water levels in dams and catchment regions dropped significantly, resulting in the worst water shortage recorded in Klang Valley in 1998. Consequently, 3.2 million residents in Klang Valley faced water rationing for almost 150 days. Moreover, Astro Awani (2014) reported that Kelantan's farmers also suffered nearly RM90 million in losses during the 2013-2014 drought.

The main challenge in monitoring drought is gathering consistent, long-term, and high-quality data. Reliable long-term weather data is essential for effective observation and assessing climate risk, which helps to develop appropriate climate adaptation and mitigation strategies at regional and national levels (Duarte &

Sentelhas, 2020). However, rain gauge data is often limited, with some records covering relatively short periods and having gaps in the historical climate data (Mourtzinis et al., 2017; White et al., 2008). Remote sensing technology is increasingly used in global climate change studies, and satellite precipitation products (SPPs) greatly improve local and global precipitation estimations (He et al., 2017; Libertino et al., 2016). Recent advances in remote sensing have provided rainfall estimates at large areas and longer time periods compared to traditional methods.

Drought conditions have been identified using various drought indicators, which estimate a threshold for drought at different time intervals and classify its severity and location (McKee et al., 1993). For example, droughts have been studied using the Standardized Precipitation Index (SPI) and Standardized Streamflow Index (SSI) to understand their meteorological and hydrological aspects (Moccia et al., 2022). The SPI can be calculated at different time scales and only requires monthly rainfall data to be used. In contrast, the SSI is typically used to assess droughts in the water system (Shamshirband et al., 2020). While the SPI uses precipitation data, the SSI relies on monthly streamflow data. Researchers have examined how dry weathers affects hydrological drought by analyzing the SSI's response to the SPI in the Muda River and Johor River Basins (Luhaim et al., 2021; Tan et al., 2019). Local stakeholders in this region often reserve water in preparation for adapting drought during the dry season, which can result in hydrological dryness even when rainfall levels are normal. For Peninsular Malaysia, Fung et al. (2020) found that the SPI and SPEI exhibited similar responses to changes in dryness as the analysis period increased. However, the two indices behaved differently regarding the number of dry months, likely due to the effect of temperature on the SPEI.

1.2 Problem Statement

Inaccurate climate data can lead to poor water resource management and ineffective drought mitigation strategies, which are critical issues for the KRB, a region prone to drought and flooding. Despite the growing availability of global open-source climate datasets like NASA POWER, their accuracy in capturing local precipitation patterns in tropical regions such as the Kelantan River Basin (KRB) remains unclear. One key reason for selecting NASA POWER data is its accessibility as an open-source climate dataset, which provides long-term, high-resolution meteorological information. This makes it an invaluable resource for researchers and practitioners in various fields, including hydrology, agriculture, and renewable energy.

Droughts pose significant challenges to water resources, agriculture, and the livelihoods of local communities in Kelantan. For example, Kelantan experienced a severe drought in 2014, particularly during February and March, which caused an estimated 22 million in losses for over 8,000 paddy farmers (Tan et al., 2017). Additionally, dengue fever-related deaths that year tripled compared to 2013. Open-source climate data has the potential to serve as a valuable resource for monitoring droughts in basins that are ungauged or have limited gauging stations (Marzouk, 2021; Park et al., 2018 & White et al., 2008). However, there is a notable lack of comprehensive studies on drought occurrence, duration, and severity in the KRB, especially those utilizing open-source climate data such as NASA-POWER.

The hot and dry weather following the El Niño events of 1997/1998 and 2014 threatened water levels at several major dams in Malaysia (Shaadan et al., 2015). Tangang et al. (2007) emphasized the importance of understanding the effects of large-scale atmospheric circulations on local drought conditions to accurately project future drought pattern. In fact, the interplay between atmospheric circulations and drought phenomena remains inadequately explored, limiting the ability of stakeholders to formulate effective strategies for climate adaptation and mitigation.

1.3 Research Questions

Understanding the strengths and limitations of NASA POWER in capturing precipitation patterns and droughts events, as well as the influence of atmospheric circulation on these phenomena, are important for climate monitoring and planning in this region. Hence, this study aims to address the following questions:

1. How accurately does NASA POWER capture the spatial and temporal variability of precipitation in the KRB?
2. How effective is NASA POWER in identifying and quantifying drought events in the KRB?
3. What are the impacts of key atmospheric circulations on drought in the KRB?

1.4 Research Objectives

This study aims to analyze changes in drought in the KRB, Malaysia, for the past few decades using NASA POWER, drought indices and atmospheric circulations. There are three specific objectives to achieve the aim as follows:

1. To evaluate the capability of NASA POWER in capturing precipitation of the KRB from 1985 to 2020.
2. To assess the capability of NASA POWER in detecting droughts of the KRB from 1985 to 2020.
3. To analyse the impacts of atmospheric circulations on drought occurrences in the KRB from 1985 to 2020.

1.5 Scope of the study

This research used drought indices to examine droughts of the KRB in the north-eastern part of Peninsular Malaysia over the past 35 years, from 1985 to 2020. This research involved using climate data from NASA-POWER and local gauge stations. The GIS software, ArcGIS, along with Microsoft Excel were used for the analysis and creation of spatial distributions maps. Meteorological data was collected from the Malaysian Meteorological Department because it offers data on maximum and minimum temperatures, whereas the Department of Irrigation and Drainage does not provide temperature information.

SPI and SSI were selected to evaluate the meteorological and hydrological droughts in the KRB over different time scales, including 1-, 3-, 6-, and 12-month periods. Atmospheric circulation refers to the large movement of air that distributes heat across the Earth's surface, along with ocean circulation. The ENSO, Indian Ocean Dipole (IOD), and Madden-Julian Oscillation (MJO), which are the major atmospheric circulations influencing Malaysia, were selected to assess their effects on drought in the KRB.

1.6 Significant of the study

This study provides useful insights in understanding drought events using the NASA POWER data in the KRB, making it as an important reference for assessing drought hazards in other regions with limited gauges. It helped fill data gaps and addressed issues related to the availability of weather data. Additionally, this study laid the groundwork for future forecasting studies, which are crucial for raising awareness and improving resilience to such events.

This work also contributes to understanding of how atmospheric circulations affect the KRB, the regional patterns of drought events. Although Peninsular Malaysia is a tropical region with high rainfall, humidity and abundant raw water resources, there have been increasing reports of water shortages in various states recently. Therefore, it is important for the development of future water resources management strategies in response to changing drought patterns. The purpose of using drought indices to examine the drought conditions in the KRB is to help experts effective monitor and manage water resources.

1.7 Conceptual and Operational Definitions

Performance evaluation refers to the process of assessing the accuracy, reliability and applicability of a dataset or model by comparing it with observations or data with higher standards. The operational performance evaluation of this study involves comparisons between NASA-POWER and observed data using commonly used statistical metrics such as root mean square error (RMSE) and correlation coefficient (R^2).

A drought occurs if the total amount of precipitation accumulates throughout a season or longer is insufficient to support human activities and environmental needs (Wilhite & Glantz, 1985). Iglesias et al. (2021) and Prajapati et al. (2021) said that droughts are local phenomena with varying features depending on the global climatic system in which they occur. Even while droughts aren't as physically severe as other natural catastrophes, they nonetheless have wide-ranging economic, environmental, and social effects on communities.

1.8 Summary

In summary, this chapter has provided a detailed explanation of the overall background of this research. The problem statement serves as the motivation to conduct further investigation in order to address the issues. Hence, clear research questions and objectives were established to carry out this research. The scope of the study has also been identified to ensure the research conducted is align with the objectives of this study.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter first explores the NASA POWER dataset and their capability in estimating precipitation in different parts of the world. Then, this chapter discusses the concept of drought, including their definitions, types, and the indicators used for assessment, as well as the drought cases in Southeast Asia, Malaysia and Kelantan, Lastly, the major atmospheric circulations that influence climate conditions in Malaysia were reviewed.

2.2 NASA POWER

The NASA Langley Research Center's Prediction Of Worldwide Energy Resources (NASA POWER) project provided daily data on various meteorological variables, including precipitation, maximum and minimum temperatures, throughout 1° spatial grid that encompassed an entire world (White et al., 2008). NASA POWER estimates precipitation using a combination of satellite observations, atmospheric models, and data assimilation techniques (NASA, 1981). Satellite data including passive microwave sensors and infrared sensors, which observe cloud formation, atmospheric moisture, and precipitation. The precipitation estimates are integrated into the Goddard Earth Observing System (GEOS) integration model (Stackhouse, 2021), which is a global weather reanalysis system. Then, NASA POWER uses data assimilation techniques to merge observational data with model outputs, providing estimates of meteorological variables like precipitation. These methods adjust the model outputs using real-world observations to improve the accuracy of precipitation estimates.

The reanalysis output is provided on a global 1°x1° grid and includes daily data. The GEOS model simulates precipitation over this grid based on atmospheric conditions, such as moisture, wind patterns, and cloud formation, ensuring a consistent dataset. The data is processed and interpolated to fill gaps in areas with sparse observational coverage, ensuring comprehensive global coverage of precipitation estimates.

2.2.1 Performance Assessment

Table 2.1 lists validation studies of various satellite precipitation products (SPPs) in Malaysia, which are generally available for users to download for free. Previous studies have validated the performance of NASA POWER in estimating precipitation compared to gauge observations (Al-Kilani et al., 2021; Duarte & Sentelhas, 2020). In a recent study by de Aguiar and Junior (2020), climate data from NASA POWER was compared with observational data from multiple stations in Brazil. The study found that NASA-POWER precipitation data exhibited a strong correlation (0.75-0.95) at most of the stations. Another study compared NASA POWER's precipitation estimates and SPI over various time periods with observed data from 13 stations in Jordan. The results showed significant correlations between NASA POWER and stations, with correlation coefficients ranging from 0.67 to 0.91, especially when annual precipitation surpassed 50 mm/year. The findings also revealed that SPI based on satellite estimations (SAT-SPI) performed well in identifying severe droughts and wet/dry situations, although it tended to overestimate drought severity (Al-Kilani et al., 2021). However, its capability to estimate SPI has been less explored in tropical regions and requires further investigation.

Table 2.1 Performance evaluation of satellite product in Malaysia.

No	References	Findings	Satellite Product
1.	Tan et al. (2015)	• 3B42V7 and APHRODITE showed the best performance, while GPCP-1DD exhibited the worst performance. • Precipitation was overestimated by 3B42RT (2%), 3B42V7 (4.7%), and PERSIANN-CDR (2.1%). • APHRODITE, CMORPH, and GPCP-1DD underestimated precipitation by 19.7%, 13.2%, and 2.8%, respectively. • SPPs performed better during the northeast monsoon than the southwest monsoon. • SPPs exhibited superior performance in eastern and southern Peninsular Malaysia, as well as northern East Malaysia, showing higher precipitation levels than in the western and drier regions of Peninsular Malaysia.	1. 3B42RT & 3B42V7 2. GPCP-1DD 3. PERSIANN-CDR 4. CMORPH 5. APHRODITE
2.	Hashim et al. (2016)	• The validation analysis indicated that the accuracy of monthly TMPA rainfall and MODIS evapotranspiration data improved significantly after the calibration process. • There is a strong correlation between satellite-derived runoff data, observed stream flow.	1. TMPA 2. MODIS
3.	Tan et al. (2017)	• TMPA-3B43 showed better performance during the wet season compared to the dry season. • The reliability of the TMPA-3B43 varies by regions, with superior performance in northern-eastern regions compared to central, southern, and hilly locations.	1. TRMM
4.	Tan et al. (2018)	• Daily rainfall estimates from various satellite precipitation products (SPPs) show a strong correlation, especially during the northeast monsoon season, when the highest values occur. • All SPPs, except for PERSIANN-CDR, successfully identify precipitation levels satisfactory.	1. IMERG 2. 3B42 and 3B42RT 3. PERSIANN-CDR
5.	Tan et al. (2018)	• IMERG_F performed better than IMERG_E and IMERG_L in simulating streamflow in the KRB using the SWAT model.	1. IMERG Early 2. IMERG Late 3. IMERG Final
6.	Soo et al. (2019)	• In a comparison of the Langat and Johor river basins, TRMM and CMORPH datasets performed better than PERSIANN. • All SPPs showed promising reliability in predicting heavy rainfall during the northeast monsoon, especially in the northern part of Peninsular Malaysia.	1. CMORPH 2. TRMM 3B42V7 3. PERSIANN
7.	Ayoub et al. (2020)	• GSMaP_RNL showed the highest monthly bias by underestimating rainfall amounts. • TMPA 3B42v7, PGFv3, CHIRPS25, and CHIRPS05 significantly overestimated rainfall measurements from the gauges.	1. CHIRPS 2. TMPA 3B42V7 3. PGFv3 4. GSMaP_RNL
8.	Chang et al. (2020)	• The simulated results align with observations, accurately reflecting the start, peak intensity, and decline of heavy rainfall at the right times. • There are differences in geographical distribution among the findings.	1. TRMM 2. CHIRPS 3. PERSIANN-CDR
9.	Bandira et al. (2022)	• The NASA POWER dataset performs well in measuring solar radiation, maximum, mean, and minimum temperatures in Georgetown Conurbation. • It is less accurate for relative humidity, mean wind speed, and rainfall.	NASA-POWER
10.	Sa'adi et al. (2022)	• The JRB generally showed larger CI values (≥ 0.60) compared to PCI due to broader categorization. • The rainiest 25% of NE monsoon days contributed to 67%–83% of the annual precipitation across all grid sites.	CHIRPS
11.	Tan et al. (2023)	• NASA POWER and ERA5-Land provided accurate measurements of rainfall and minimum temperatures in the KRB.	1. NASA-POWER 2. ERA5-Land

Tan et al. (2023) found that NASA POWER and ERA5-Land effectively represented climate trends in rainfall, maximum, and minimum temperatures in the KRB. However, both products often underestimate precipitation and maximum temperatures, while overestimating minimum temperature. They have a better correlation with gauges along the coast compared to central and mountainous areas. NASA POWER showed improved ability to identify rainy days versus dry days, based on POD, FAR, and CSI values. The PDF evaluation demonstrated that both products overestimate moderate rainfall (1–20 mm/day) but underestimate no/tiny (0–1 mm/day), heavy (20–50 mm/day), and severe (more than50 mm/day) rainfall. Both products exhibited good abilities in detecting precipitation during the 2014-2015 flooding event. However, both products intended to underestimate the actual amount of extreme rainfall.

In Mediterranean and Continental of Turkey, NASA POWER showed high correlations with most of the meteorological variables, except for the wind speed (Halimi et al., 2023). Additionally, Bandira et al. (2022) found there were no significant differences in the Area Under the Curve (AUC) values when comparing solar farm maps in Georgetown Conurbation generated using NASA POWER data with station data using GIS-based Multi-Criteria Decision-Making (MCDM) model.

2.3 Drought

2.3.1 Definition of Drought

Drought refers to inadequate precipitation over time in certain places. It is challenging to define drought that is generally applicable for everyone due to the different hydro-meteorological factors, socio-economic situations, and water usage capacities. To understand drought better, many researchers used operational definitions by differentiating the characteristics of drought in terms of frequency, severity, and duration within a specific return period (Mishra & Singh, 2010; Wilhite & Glantz, 1985).

Water demand has increased because of population growth and the expansion of agriculture, energy, and industry, which has led to water shortages in many parts of the world almost every year. Factors like climate change and water pollution have made these shortages worse. Typically, drought is defined in different ways based on what factors are being considered.

2.3.2 Drought Indices

The indications were combined into a single numeric value and utilised to generate drought indices presented numerically form. In particular, it incorporates the information from the indicators into a single number representing an instance of the drought event. It quantitatively evaluates droughts' severity, intensity, duration, and spatial distribution to study droughts over a specific period. Due to the limited information available and the brief time required to collect and consolidate all the data into indices, researchers and scientists had historically relied on a single indicator or index. Variables and indices have evolved over the past several decades to account for various temporal and spatial factors independently. The commonly used drought indices are Standardized Precipitation Index (SPI) and Standardized Streamflow Index (SSI). Table 2.2 lists several researchers from Malaysia and other countries who have utilized drought indices in their studies.

Table 2.2 Spatial-temporal drought studies in Malaysia and other countries

References	Title	Method	Study Area
Hamirdin & Nordin (1985)	The Use of Precipitation Indices as Indicators of Water Resource Sustainability: An Investigation of Developed States in Peninsular Malaysia	SPI	Peninsular Malaysia
K. Ibrahim et al. (2010)	The present study aims to assess the arid conditions in Peninsular Malaysia using bivariate copula analysis.	SPI	Peninsular Malaysia
Zin et al. (2013)	This study evaluated drought conditions and associated risks in Peninsular Malaysia using the Standardised Precipitation Index (SPI).	SPI	Peninsular Malaysia
Yusof et al. (2013)	The analysis presented in this study focuses on the characterisation of drought properties using bivariate copula analysis.	SPI	Peninsular Malaysia
Sanusi et al. (2015)	A Study on the Drought Features Utilising the First-Order Homogeneous Markov Chain Model with Monthly Rainfall Data in Peninsular Malaysia.	SPI	Peninsular Malaysia
Huang et al. (2016)	This study uses the Standardised Precipitation Index (SPI) and Effective Drought Index (EDI) methodologies to forecast drought in the Langat River Basin, Malaysia. The analysis is conducted within the context of the Representative Concentration Pathway 8.5 (RCP-8.5) climate change scenarios.	SPI & EDI	Langat River Basin
Tan et al. (2019)	This study focuses on the spatiotemporal analysis of hydro-meteorological drought occurrences within the Johor River Basin in Malaysia.	SPI & SSI	Johor River Basin
Fung et al. (2020)	This study aims to evaluate drought conditions in Peninsular Malaysia by examining temporal patterns, regional characteristics, and operational accuracy using the Standardised Precipitation Index (SPI) and the Standardised Precipitation Evapotranspiration Index (SPEI).	SPI & SPEI	Peninsular Malaysia
Noor et al. (2020)	This study focuses on monitoring drought indices, namely the Standardised Precipitation Index (SPI) and the Z Index Score, in Gua Musang, Kelantan.	SPI & ZI	Kelantan
Bong & Richard (2020)	They investigated drought and climate variability with the Sarawak River Basin's Standardised Precipitation Index (SPI).	SPI	Sarawak River Basin
Luhaim et al. (2021)	Variability of Drought Conditions and the Characteristics of Drought Events in the Muda River Basin of Malaysia from 1985 to 2019	SPI & SSI	Muda River Basin
He et al. (2021)	The study investigates the relationship between tropical drought variations and large-scale climate change in Peninsular Malaysia.	SPI, SPEI & PDSI	Peninsular Malaysia
Ng et al. (2022)	This study aims to assess the drought conditions in Peninsular Malaysia from 1989 to 2018 by using two widely used drought indices, namely the Standardised Precipitation Index (SPI) and the Effective Drought Severity Index (EDDI).	SPI & EDDI	Peninsular Malaysia
Chong et al. (2022)	The present study aims to investigate the spatiotemporal variability of droughts, explicitly focusing on standardised precipitation-indexed droughts. This research will be carried out using the wavelet transform method.	SPI & SPEI	Sabah & Sarawak

Table 2.3 Continue

References	Title	Method	Study Area
Isia et al. (2022)	The study analysed drought using two widely used indices: the Standardised Precipitation Evapotranspiration Index (SPEI) and the Standardised Precipitation Index (SPI).	SPI & SPEI	Sarawak River Basin
Spinoni et al. (2014)	The study aimed the frequency, duration, and intensity of global drought events between 1951 and 2010.	SPI	Worldwide
Haroon et al. (2016)	Based on MODIS data, the study focused on monitoring drought conditions and assessing the drought severity index (DSI) performance.	SPI & DSI	Pakistan
Wu et al. (2019)	An assessment of the CHIRPS precipitation dataset's performance and its efficacy in drought monitoring.	SPI	Yunan, China
Cunha et al. (2019)	This study examines the occurrence of extreme drought events in Brazil between the years 2011 and 2019.	VHI, SPI & IDI	Brazil
Barella-Ortiz & Quintana-Segui (2019)	The assessment of drought representation and spread in simulations conducted by regional climate models.	SPI, SSMI, SSI & SRI	Spain
Masroor et al. (2020)	Investigating climatic variability and its influence on the incidence of drought	SPI	India
Kyatengerwa et al. (2020)	The present study focuses on conducting a comprehensive drought study nationally in Uganda. The study primarily evaluated evapotranspiration shortages, using the Bouchet assumption as a theoretical framework.	SEDI & SPI	Uganda
Shamshirband et al. (2020)	This study aims to use models based on machine learning to predict the Standardised Streamflow Index (SSI) in the context of hydrological dryness.	SPI, SPEI & SSI	Navrood Basin
Salimi et al. (2021)	The monitoring of meteorological and hydrological drought is conducted using many drought indicators.	SPI, SPEI & SSI	East Azarbaijan
Bouaziz et al. (2021)	This study proposes a machine learning approach that utilises distant precipitation data and a standardised precipitation index to monitor and predict drought in desert areas.	SPI	Tunisia
Ma et al. (2022)	The study aims to investigate the dissemination dynamics and underlying causes of hydrological drought concerning meteorological drought, explicitly focusing on the seasonal timeframes.	SPI & SRI	Wei River Basin, China

2.3.3 Drought Characteristic

Drought characteristics are analysed statistically over time and across area to provide a clearer understanding of drought. Some studies employed run theory to assess drought characteristic such as duration, intensity, severity, and peak. Yevjevich (1969) suggested various methods to represent sequences of probabilistic variables, involving both stochastic and consistent elements. A drought period is indicated when the index value is below zero for an extended period. Other researchers also emphasised the importance of intensity, peak, and trends in drought characteristics (Mishra & Singh, 2010; Ayantobo et al., 2017). In prolonged droughts, the duration and cumulative severity may be more significant than peak intensity when assessing the impact on human and natural systems (Ge et al., 2016).

Based on Liu et al. (2021), drought intensity in eastern Sichuan eventually decreased (0.36-0.51), while in the western region, it increased to 0.54-1.05 in both intensity and frequency. In central mountainous and south-western Sichuan, there were between 24 and 47 recorded drought events. Additionally, the bivariate copula model was used to assess drought duration and severity by constructing a joint distribution. The findings showed that more recent drought events, especially those after January 2000, had longer return periods, indicating they were more severe or unusual (Espinosa et al., 2019). Figure 2.1 was an index value derived from the run theory that describes drought's defining features (Espinosa et al., 2019; Santos et al., 2011; Yevjevich, 1969).

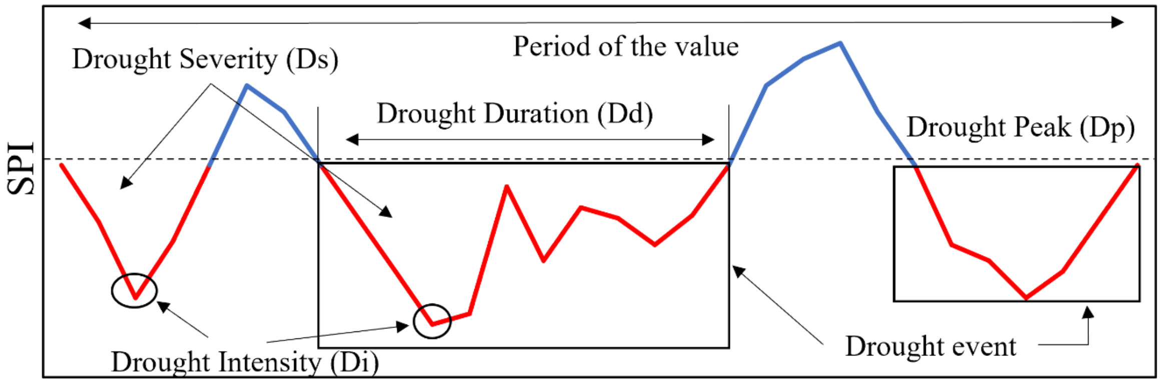

Figure 2.1 Scenario of run theory drought (Yevjevich, 1969)

Drought can be classified into four main categories of meteorological, hydrological, agricultural and socio-economic droughts. Spinoni et al. (2014) stated meteorological droughts occur when precipitation levels are abnormally low compared to historical averages for a specific region and time period. This results in reduced groundwater levels due to less penetration, runoff, persistent percolation, and replenishment (NDMC, 2016; Łabędzki & Bąk, 2015). Hydrological drought refers to the reduction of water in rivers, lakes, dams, or reservoirs, often persisting even after normal rainfall resumes (Van Loon, 2015). It leads to lower water levels in groundwater, wetlands, and rivers, indicating a severe water shortage throughout the hydrological cycle (Jahanshahi & Shahedi, 2018). Agricultural drought happens when low precipitation first affects soil moisture, which is crucial for plant growth. This leads to crop failure, especially when water supply during the key growth stages is insufficient (Ma et al., 2022). Agriculture drought impacts vary across different crop growth stages. For example, a lack of water during the early planting stage may have less impact on final crop yields if water needs at that stage are not critical (Wilhite & Glantz, 1985). Socioeconomic drought occurs when water supply fails to meet the demand, leading to economic impacts (Mishra & Singh, 2010). It happens when weather-related water shortages affect both people's needs and economic goods, causing widespread disruption in community (Guo et al., 2019).

2.4 Drought Cases

Droughts can lead to major social, economic, and environmental impacts, affecting different communities and locations. This section summarizes the drought studies that have been conducted in Southeast Asia, Malaysia and Kelantan.

2.4.1 Drought in Southeast Asia

Drought is a recurring climate phenomenon in Southeast Asia, significantly affecting agriculture, water resources, and livelihoods (Xavier et al., 2014). Thailand, Vietnam, Indonesia, and the Philippines frequently experience droughts due to irregular rainfall patterns influenced by El Niño and climate change. These droughts often result in reduced crop yields, water shortages, and economic disruptions, particularly in rural areas dependent on agriculture (Xavier et al., 2020; Amirudin wt al., 2020).

In recent years, Southeast Asian nations have made efforts to improve drought resilience through better water management, early warning systems, and the adoption of drought-resistant crops. The region's vulnerability to drought, combined with growing populations and increasing water demands, underscores the need for sustainable resource management and regional cooperation to mitigate the adverse effects of prolonged dry spells. Research on drought in Southeast Asia continues to highlight the importance of addressing climate variability and enhancing adaptive capacities in vulnerable communities.

2.4.2 Drought in Malaysia

The hydro-meteorological and drought studies conducted in Malaysia are listed in Table 2.3. This information can serve as guidance for researchers in assessing whether their work aligns with the documented drought events. Major drought events in Malaysia occurred during 1997-1998, 2014, 2018, 2021, and 2023. The Star (2023) reported that nearly 390 farmers in Kelantan were affected by drought events in 2022, causing 7000 hectares of failed paddy crop and resulted planting and harvesting in April 2023. A comparison of rainfall in June 2018 with the average monthly rainfall showed that 13 out of 41 monitored stations, especially in Kedah, Pulau Pinang, Perak, Selangor, Kelantan, and Terengganu, had rainfall deficits greater than 35% (Nasaruddin & Zaid et al., 2018). In Sarawak, Bong & Richard (2020) found that he El Niño event caused dry conditions in 1997-1998, and from 2006 to 2007, stations along the Sarawak River experienced their driest months compared to previous years, except in a few places.

Sanusi et al. (2015) observed that the north-western and central regions of Peninsular Malaysia experienced prolonged moderate droughts from 1970 to 2008. The severe drought in Malaysia during the El Niño year of 1997-1998 particularly affected urban areas such as Klang Valley, Selangor, and Negeri Sembilan, leading to critical water shortages and low dam levels. They also found that the increasing of frequency and severity of drought events impacted agricultural productivity. The findings emphasized the need for improved drought management strategies and the implementation of early warning systems to mitigate the adverse effects on agricultural yields and water resources in Malaysia.

Table 2.3 Drought studies in Malaysia.

No	References	Findings	Year
1.	Sanusi et al. (2015)	Several regions in Peninsular Malaysia, particularly in the northwestern and central areas, experienced prolonged moderate droughts from 1970 to 2008.	1970 - 2008
2.	Goh et al. (2016)	Klang Valley, Malaysia's most urbanized area, faced heavy rainfall, while Selangor and Negeri Sembilan suffered extreme droughts, leading to critical water shortages and low dam levels.	1998
3.	Tan et al. (2017)	In 2014, the KRB experienced severe droughts in February and March, resulting in over 8,000 paddy farmers incurring estimated losses of USD 22 million.	2014
4.	Nasaruddin & Zaid (2018)	A comparison of rainfall in June 2018 against the average monthly rainfall revealed that 13 out of 41 monitored stations, particularly in Kedah, Pulau Pinang, Perak, Selangor, Kelantan, and Terengganu, experienced rainfall deficits exceeding 35%.	Jun 2018
5.	Bong & Richard (2020)	The El Niño event contributed to the dry months in 1997-1998, and from 2006 to 2007, stations along the Sarawak River recorded their driest periods compared to earlier years, except in a few locations.	1997 - 2006
6.	Noor et al. (2020)	The 1998 El Niño event also affected areas from Perlis to Melaka, Negeri Sembilan, Selangor, and Kuala Lumpur, impacting around 3.2 million people for five months between April and September.	1998
7.	Abdullah (2021)	In Kelantan, the Bukit Kwong dam dried to critical levels of 12.20m during the hot North-East Monsoon.	2021
8.	The Star (2023)	In 2022, Kemubu Agriculture Development Authority (KADA) General Manager Mohd Faizul Mustafa reported that nearly 390 farmers were affected by a water shortage during a monsoon shift, leading to 7,000 hectares of failed paddy crops in Kelantan, impacting planting and harvest for April 2023.	2023
9.	Shaaban et al. (2011)	In the coming years, the Kelantan, Terengganu, Pahang, and Perak River basins are likely to have higher monthly streamflow during the rainy season, exceeding that of the Selangor and Klang rivers during dry periods.	1984-2050

2.4.3 Drought in Kelantan

Several studies have investigated hydro-meteorological changes and drought patterns in Kelantan, especially in the Kelantan River Basin (KRB) (see Table 2.4). In general, several significant droughts in the Kelantan 1997, 1998, 2002, 2003, 2005, 2006, 2007, 2009, 2010, 2015-2016, 2020, 2021 and 2023 (Tan et al., 2017; Abdullah, 2021). These studies highlight that changes in land use, such as deforestation for agriculture, have contributed to rising temperatures and shifting precipitation patterns in Kelantan (Tew et al., 2022). This connection emphasizes the need for sustainable land management and adaptive strategies to address the impacts of climate variability on water resources and agricultural productivity in Malaysia.

Table 2.4 Hydro-meteorological and drought related studies in Kelantan.

No	References	Findings	Study Area
1	Jha & Singh (2013)	The Spearman's rank test and standard homogeneity test on a 25-year dataset (1982-2006) found no significant patterns in the severe events of the Kelantan and Pahang rivers. The analysis showed no clear trend in the occurrence of severe events for these rivers.	Peninsular Malaysia
2	Tan et al. (2017)	The study found that monthly rainfall increases during the rainy season and decreases in the dry season, with significant increases in streamflow and surface runoff from November to January. However, there was a noticeable drop in monthly water output from June to October, ranging from 1.9% to 8.9% between 2015 and 2044..	Kelantan River Basin
3	Faizalhakim et al. (2017)	The study also indicated that climate change is significantly affecting land use, shown by the annual decrease in cloud cover alongside increases in precipitation, rainy days, temperature, global radiation, and atmospheric pressure. However, trends showed decreases in relative humidity, sunshine hours, and wind speed. These changes suggest that significant tree removal for land improvement is altering the local climate of the KRB.	Kelantan River Basin
4	Tan et al. (2020)	By 2100, under the RCP4.5 and RCP8.5 scenarios, rainfall is projected to rise or fall by 8.19% to 13.10% and temperatures may increase by up to 4.69°C. Streamflow is expected to decrease by 10.37% to 31.09% under RCP4.5 and 19.87% to 13.24% under RCP8.5, with reductions in January and February and increases in September. Droughts are expected to last longer than usual between 2081 and 2100 under RCP4.5.	Kelantan River Basin
5	Tew et al. (2022)	The trend analysis showed that the highest and lowest temperatures in KRB increased by about 0.01-0.03 °C and 0.01-0.05 °C each year. In areas like Pos Hau, Pos Bihai, Pos Gob, and Kuala Krai, annual rainfall rose by 17.5 to 29.74 mm..	Kelantan River Basin

Tan et al. (2020) developed the SouthEast Asia HydrO-meteorological Drought (SEA-HOT) framework to analyze changes in hydro-meteorological drought in the KRB. This framework integrates the Coordinated Regional Climate Downscaling Experiment - Southeast Asia (CORDEX-SEA) regional climate models with the Soil and Water Assessment Tool (SWAT) model. Projections indicate that by

2100, rainfall could vary between 8.19% and 13.10%, while temperatures may increase significantly under different climate scenarios. Streamflow reductions of up to 31.09% are expected, particularly in the northwest region of the basin.

2.5 Atmospheric Circulation

Atmospheric circulation refers to how air moves around the Earth, influenced by areas of high and low pressure at the surface. There are extreme pressure zones at around 30° N/S latitude near the poles, while low pressure is found at the equator between 50° and 60° N/S (Chen et al., 2018). In these regions, high pressure can form and cause warm air to rise. This creates a continuous low-pressure zone around the equator. The warm air then moves north towards the poles, where it cools and sinks, creating areas of high atmospheric pressure (Amirudin et al., 2020).

The difference in temperature and pressure drives the cold air to move back toward the equator, creating a simple global circulation model (NOAA, 2023). Drought predictions can be affected by changes in the atmosphere throughout the seasons (Park et al., 2018). For example, shifts in atmospheric circulation in Portugal can impact rainfall, leading to significant differences in drought patterns (Santos et al., 2011). Juneng and Tangang (2005) noted that atmospheric circulation is linked to rainfall changes that occur in a northeast direction from summer until the following spring.

2.5.1 El Niño -Southern Oscillation (ENSO)

The El Niño Southern Oscillation (ENSO) is a relationship between atmosphere and the tropical Pacific Ocean. It has a global impact by affecting the Walker Circulation and causing unusual interactions between air and sea. ENSO describes the link between warming in the eastern Pacific Ocean, known as El Niño (the warm phase), and cooling, called La Niña (the cold phase) (Juneng & Tangang, 2005). Figure 2.2 shows the conditions of El Niño and La Niña. This cycle reverses every two to seven years, leading to changes in ocean surface temperature and disrupting wind and precipitation patterns across the tropics (Heureux et al., 2023). These changes can have various global effects (Yue et al., 2021;Oertel et al., 2020; Huang et al., 2017).

ENSO influences the weather in Malaysia, with El Niño typically bringing drier conditions and La Niña leading to wetter weather. Nevertheless, the effects can vary depending on the intensity of each event. Several studies have shown that ENSO is a major factor affecting Malaysia's weather patterns (Kemarau & Eboy, 2021; Luhaim et al., 2021; Tangang et al., 2017). Tan et al. (2021) showed that ENSO has a stronger impact on hot weather than cold conditions, and the peak of ENSO often delays the temperature response in extreme cases. Malaysia has experienced prolonged droughts due to ENSO, causing severe water shortages and other issues. The worst drought in Malaysia occurred during the 1997/1998 El Niño event, which affected much of Southeast Asia (Ibrahim et al., 2016). Additionally, studies of the Muda River Basin show that ENSO has a greater influence on hydro-meteorological drought than other factors like the Indian Ocean Dipole (IOD) and the Madden-Julian Oscillation (MJO) (Luhaim et al., 2021), particularly during the second phase of the northeast monsoon, which is the driest season in the northwest part of Peninsular Malaysia (Deni et al., 2010).

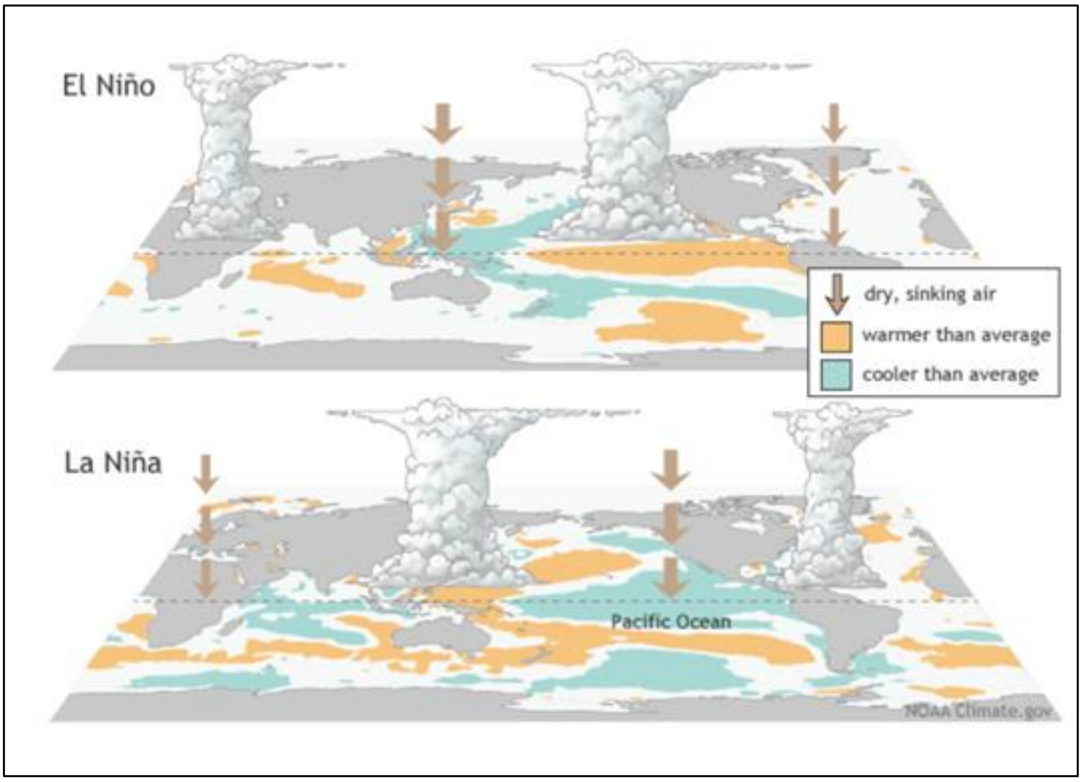

Figure 2.2 El Niño and La Niña (Johnson, 2020)

2.5.2 Indian Ocean Dipole (IOD)

The IOD is an ocean-atmosphere event that occurs over the central Indian Ocean, similar to the ENSO. It is believed that the IOD is linked to ENSO occurrences through a westward movement of the Walker Circulation and the Indonesian Through flow, which is the flow of warm tropical ocean water from the Pacific into the Indian Ocean (Bureau of Meteorology, 2023; Izumo et al., 2010). The IOD index reflects an unusual trend in sea surface temperature, with gradients observed in the western equatorial Indian Ocean from 50°E until 70°E and 10°S to 10°N, and in the south-eastern equatorial in Indian Ocean from 90°E to 110°E and 10°S to 0°N (Dong et al., 2019). When the IOD and ENSO are in phase, the effects of El Niño and La Niña events tend to be more severe across Australia (Potop et al., 2014). In contrast, when both phenomena are out of phase, the effects of El Niño and La Niña events can be weaker. Figure 2.3 represents the positive phase of IOD, which typically occurs between September and November, characterized by cooler sea surface temperature to the west of Indonesia and warmer temperatures in the western Indian Ocean (Hidayat et al., 2016; Behera et al., 2005).

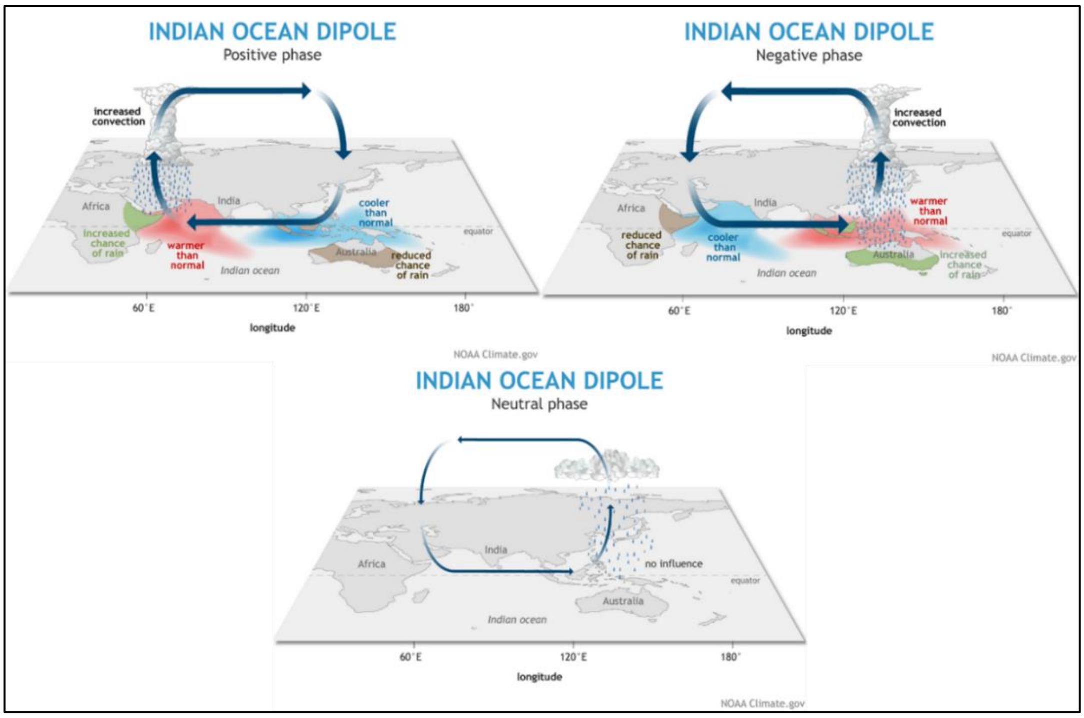

Figure 2.3 IOD in positive, negative and neutral phases (Meteorology, 2023)

The negative phase of the IOD is the opposite of the positive phase, while a neutral phase shows no distinct characteristics (Johnson, 2020). Previous research had shown that the presence of the IOD, resulting in natural oscillations in the Indian Ocean, is influenced by ENSO, significantly affecting the climate in Asia (Nagamuthu et al., 2022; Sahu et al., 2010). Moreover, when El Niño and IOD events occur together, their combined effects can be more profound than those of either phenomenon alone. The impact of isolated El Niño and IOD occurrences are comparable but generally less significant during June–July–August and September–October–November (Amirudin et al., 2020). Tangang et al. (2007) investigated how ENSO and IOD influence Malaysia's inter-annual temperature. Their findings show that while ENSO