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Microclimatic Variation in Miri Region (NW Borneo): Inference from Rainfall and Temperature Trends, Isotopic Signature and Air Mass Movement

Fiona Bassy William, Prasanna Mohan Viswanathan* and Anshuman Mishra
Department of Applied Sciences, Faculty of Engineering and Science, Curtin University Malaysia
Miri – 98009, Sarawak, Malaysia
✉ prasanna@curtin.edu.my

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Abstract: Trend analysis is frequently utilised to identify the changes in meteorological and hydrologic time series data, such as rainfall and temperature. The variations in the intensity, rainfall pattern and temperature have gradually changed globally. Hence, in this study, an attempt was made to analyse the decadal rainfall and surface air temperature data to understand the microclimatic variations in the Miri coastal region of NW Borneo. A data series of records for daily total rainfall amount and daily surface temperature of 11 years from 2010 to 2021 was studied and analysed. In addition, representative rainwater and groundwater samples were collected and analysed for hydrochemical parameters and oxygen and hydrogen isotopes. A detailed literature review was carried out on rainfall patterns in Malaysia, which was used for the comparative study. Interpretation of results shows that the northeast monsoon (NEM) contributed a higher total rainfall rate with lower daily mean surface air temperature over the years compared to the southwest monsoon (SWM). The recorded data for rainfall amounts in SWM for the month of May, July, August and September were higher, particularly for the years 2010 and 2020. During NEM, a higher rainfall amount was recorded in the month of January for several years. February month has always been among the driest month in NEM, and September has been the wettest month throughout the year during SWM. The isotopic values of rainwater indicate a similar moisture source to the regional precipitation trend. Groundwater isotopes reveal the low water-rock ratio of retrograde exchange between water and primary silicate minerals in the aquifer. The moisture source of the precipitation was contributed from both oceanic and continent, affecting the rainfall intensity in this region. This study is a crucial outcome to determine the potential impacts of microclimatic variations on the rainfall patterns in the Miri coastal region.

Keywords: Precipitation; Moisture; Monsoon; Isotope; Water-rock ratio.

Introduction

Over the past few decades, global climate change has occurred intensely. A changing global climate is causing worldwide variations in temperature and rainfall intensity (Hanif et al., 2022). The leading cause of these changes is the rise in atmospheric quantities of greenhouse gases like carbon dioxide, which trap heat and cause global warming. The increasing global concern over changing temperatures and their impact on rainfall patterns is becoming crucial to climate change assessment. These evolving precipitation patterns are now recognised as important indicators of climate change (Palathoti et al., 2017). The most significant climatic factor influencing climate change's effects is rainfall. It is the primary determinant in the choice and

*Corresponding Author

adjustment of crop kinds across the tropics (Adhikari et al., 2015; Jonah et al., 2021). Variations in rainfall are associated with hydrological hazards such as drought and flooding (Duhan & Pandey, 2013). Microclimatic differences in coastal environments refer to the specific and distinctive meteorological conditions that occur within a comparatively limited geographic area near the shore. The complex interactions between the atmosphere, land, and ocean result in these changes, leading to specialised atmospheric conditions distinct from those in the nearby inland regions. Because of changes in the large-scale air circulation patterns and the physical properties of the ground surface, the impacts of climate change vary from place to place (Hansen et al., 2010). Micro-scale trend analyses have been employed in recent years to identify trends in meteorological datasets, such as the regularity of daily rainfall, through which the driving factors can be identified. Due to this, there is now more emphasis on studying these tendencies (Xu et al., 2018).

Many developed nations, including Japan, the United States, and countries in the European Union, have focussed heavily on climate change and air pollution (ref). In a comprehensive summary of the studies on anthropogenic climate change published in 2007, Roth (2007) emphasised that much of the work had been done in developed and mid-latitude regions (Swarno et al., 2017). Finding trends in hydroclimatic variables, including temperature, evapotranspiration, and rainfall, has traditionally been a significant focus of climate change research (Nalley et al., 2012). Understanding seasonal and regional variations requires assessing climate change through time using variables like rainfall, which varies on both a spatial and seasonal scale (Stocker et al., 2013). The Intergovernmental Panel on Climate Change (IPCC) working group looked into the variability in spatiotemporal rainfall trends from 1900 to 2005 throughout various parts of the world. Their findings showed a considerable rise in rainfall throughout Asia's central and northern areas (*AR4 Climate Change 2007: The Physical Science Basis — IPCC*, n.d.). Rainfall quantifies hydrological phenomena such as floods, droughts, and river discharge, which helps weather forecasters, hydrologists, and decision-makers by assessing seasonal and regional trends (Hanif et al., 2022). Each country has a different variation in weather conditions; for example, terrain, humidity, temperature, and wind, all have an impact on rainfall (Huang et al., 2015). Therefore, climate change predictions relating to elevated temperature incidences are becoming increasingly significant due to their effects on human populations and biodiversity (Fonseca et al., 2016). In a recent study, in Mozambique, it was discovered how climate change affects biomass and hydropower, with hydrological parameters influencing energy production owing to rainfall and temperature changes (Uamusse et al., 2017).

Utilising a few precise keywords, such as "Microclimate", "Coastal aquifer", "Rainfall", "Evaporation" and "Air mass movement", the bibliometric analysis has also been carried out using the Scopus database. The corresponding infographics are shown in Figure 1. VOSviewer 1.6.19 was used to operate the downloaded Scopus database for the "Co-occurrence analysis" study concerning "all keywords". In the co-concurrence analysis, 617 keywords met the threshold out of the 7467 examined index keywords with a minimum of five keywords. All these 617 items have been covered with 6 clusters to represent the network analysis of co-occurrence in terms of all keywords. Keywords related to "Microclimate" have a co-occurrence value of 510 and a link strength of 5508 occurred as the highest, with the term "Evaporation" coming in second with a value of 177 and a link strength of 2029. Between the years 1950 and 2023, documents from various sources, including conferences, journals, book chapters, etc., were collected from the Scopus database. The data show that 2021 and 2020 are the years with the highest number of publications, i.e., 58 and 54, respectively, which demonstrates that there has been plenty of room to work in this field of research. A detailed literature review on rainfall patterns worldwide and in the Malaysian region is shown in Table 1. Their key findings, objectives, study area, and methodology are documented in the table.

Overall, the complex interaction between the water, land, and atmosphere is what causes the microclimatic diversity in coastal regions. Knowing these variances is essential for urban development, tourism, and agriculture, as it enables preparation for and adaptation to the unique challenges of coastal living. Understanding the effects of climate change in a region requires first determining the average monthly rainfall and surface air temperature. Essential indications of microclimatic fluctuations in a region include the frequency, intensity, and number of rainy days as well as land surface temperatures. These aspects can assist in the understanding of how the local environment and human populations are being impacted by changing climate patterns over time. Few studies have been conducted in West Malaysia (Muhammad et al., 2020; Saimi et al., 2020; Wong et al., 2018), whilst significantly few

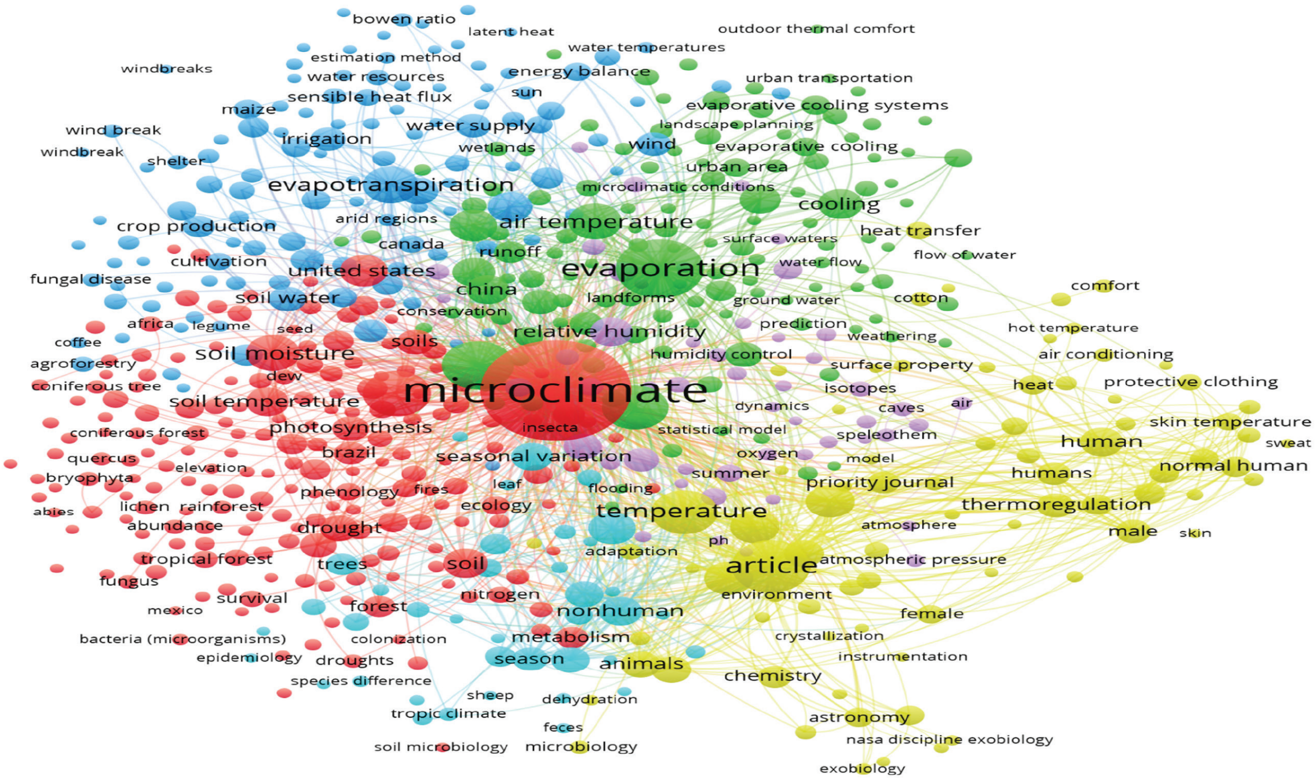

Figure 1: Co-occurrence analysis with respect to all keywords (Source: www.scopus.com, accessed on 12th June 2023).

studies have been done on the rainfall pattern in East Malaysia, where Miri City is located (Asmat et al., 2018, 2021).

In this current study, a decadal analysis of monthly rainfall and temperature pattern has been investigated to understand the microclimatic variations in the Miri region of NW Borneo. The study involves the collection of meteorological data from a weather station located in the study area (Miri). The collected data was used to identify significant trends in temperature and rainfall over the decade. Some of the factors considered in the analysis include temperature variability, frequency of extreme temperature events, seasonal and inter-annual variability in rainfall, and changes in rainfall intensity and frequency. In addition, oxygen and hydrogen isotopic signatures have been used to support the origin of precipitation and the moisture sources through the air mass movement transport model. The outcome of this study can also serve as a baseline for future research on climate change impacts in this region.

Study Location

The second-largest city in Sarawak, Miri City, is situated in the coastal region. The Sarawak coastline is 1035 km long, and around 80% of the state's residents reside close to the water. The South China Sea borders Miri's whole coastline. The study area is located within the boundaries of Miri City, specifically between latitudes N 04° 24′ 59″ to N 04° 26′ 45″ and longitudes E 113° 59′ 1.6″ to E 114° 00′ 13.1″ (Figure 2). The city has had a reputation as a hub for oil and gas development since Shell discovered oil on Canada Hill in 1910. This finding has stimulated economic development and given rise to a number of new businesses, construction projects, and agricultural activities, mostly oil palm plantations. The North-East (NE) and Southwest (SW) monsoons, which occur from October to March and April to September, respectively, impact the climate in the Miri region. The seasonal wind flow patterns determine the occurrence of these monsoons. The region's consistent temperature, high humidity, and abundant rainfall are favourable for the growth of tropical forests and diverse ecosystems. Steady temperatures characterise the tropical rainforest climate of Sarawak, copious amounts of rain and high humidity. The geological composition of the study area is characterised by sandstones, siltstones and mudstones, with a minor lamination of coal or immature organic matter as the main lithology.

Table 1: Literature review on rainfall patterns around the world and in the Malaysia region

Author(s)	*Year*	*Title*	*Research Objective(s)*	*Methodology*	*Key Findings*
Jonathan and Raju	2017	Analysis of rainfall pattern and temperature variations in three regions of the Sultanate of Oman	The study focussed on finding a significant relationship between rainfall and temperature, with varying impacts across the Muscat, Maseira, and Sur regions. The rainfall patterns showed apparent variations due to factors like topography, wind speed, relative humidity, and proximity to the sea, influencing precipitation rates differently in each region.	MECA and NCSI data from the Ministry has evaluated the relationship between temperature and precipitation while also evaluating the locals' experiences and the state of the climate. Using a line histogram chart, the relationship between variables, rainfall and temperature, and trend over time was determined.	• According to the analysis of the three regions, ambient temperature variations will impact the rainfall rate over the study period. In the Muscat region, the net amount of rainfall reduced less with temperature rise than in the Maseira and Sur regions. • The Muscat region experienced a negligible decrease in rainfall due to its topography, lack of mountain ranges, and presence of industrial zones.
Almazroui	2020	Rainfall trends and extremes in Saudi Arabia in Recent Decades	This study aimed to analyse extreme rainfall trends, identify homogeneous and heterogeneous trends, and aid in determining appropriate mitigation measures for water and agriculture sectors.	Identification of intensities and frequency of rainfall with the help of daily temporal rainfall distribution. Rainfall distribution models are used scientifically through annual maxima, threshold selection, and gamma distribution analysis. Robust assessments are obtained by analysing daily rainfall frequency over time.	• The studied period shows a decreasing tendency in Saudi Arabia's yearly and wet season rainfalls. • The central and southwestern region has had the most significant rate of annual (and wet-season) rainfall decline, which has accelerated to between 10 and 20 mm decade1, which is a worrying development for the nation's water supplies, agricultural output, and socioeconomic demands. • Several stations, though, in the eastern, northern, and southern regions exhibit slow (not statistically significant) growing patterns.
Praveen et al.	2020	Analysing trends and forecasting of rainfall changes in India using nonparametrical and machine learning approaches	The current study focused on identifying transition points, investigating fluctuation and trend evaluation, and forecast rainfall up to 2030; the study analyses fluctuation and pattern analysis of rainfall patterns throughout 34 meteorological sub-divisions.	To achieve the objectives, the study followed- Sen's innovative trend analysis, ERA-5 for analysing rainfall changes, ARMA, ARIMA, SARIMA for future forecasting, and Kriging interpolation method for spatial mapping used.	• The current study demonstrates that the sub-divisions of Western India had the most enormous total annual and seasonal variability in rainfall, whereas Eastern and North India had the lowest variability. • Rainfall reveals that a significant negative trend was found in the sub-divisions of North-East, South, and Eastern India, while a significant positive trend was found in the sub-divisions of Sub-Himalayan Bengal, Gangetic Bengal, Jammu & Kashmir, Konkan & Goa, Madhya Maharastra, and Marathwada.

Towfiqul Islam et al.	2020	Spatiotemporal trends in the frequency of daily rainfall in Bangladesh during 1975–2017	The study targeted to investigate the spatiotemporal pattern in the daily precipitation rate over Bangladesh's sub-climatic zones from 1975 to 2017. The study's findings were also expected to help address the problem of changes in the climate and meteorological disasters in the study areas.	The following research methodologies were adopted during the study-auto-correlation test, MK trend test, Spearman's rho test, Linear regression trend, Sen's slope estimator, Pettit's test, partial trend method and probability distribution function.	• The frequency of daily rainfall in the ranges of 5 mm, > 10 to 15 mm, > 25 to 30, and > 30 to 35 mm is shown by the results of partial trend analysis. • Showed a monotonic decrease trend over the past five decades in Bangladesh, whereas ranges of > 5 to 10 mm and > 15 to 20 mm showed a monotonic increase trend and > 20 to 25 mm and > 35 mm ranges showed no trend.
Jonah et al.	2021	Spatiotemporal variability of rainfall trends and influencing factors in Rwanda	The study aims to evaluate satellite rainfall data, examine the long-term variations in annual and seasonal rainfall patterns in Rwanda and investigate the relationship between ocean-atmospheric variables and rainfall in the region.	Statistical techniques like Pearson Correlation, Mann-Kendall (MK), Empirical Orthogonal Functions (EOF), and Sen's gradient estimator were utilised to evaluate the variability, trends, and teleconnections of rainfall. Results showed a bimodal rainfall pattern with a gradient from the south-west to the northwest.	• According to the results, the CHIRPS dataset, which may be used in place of in-situ rainfall data, effectively reflects the mean annual cycle and rainfall variability over Rwanda. Rwanda's yearly rainfall cycle was bimodal, with MAM and SOND being the two distinct seasons. • Rwanda's rainfall was distributed spatially with a southwest-to-northeast inclination. According to trend research, Rwanda's south-west yearly and seasonal rainfall decreased, whereas there was an increase in the northeast during SOND.
Kessabi et al.	2022	Annual, Seasonal, and Monthly Rainfall Trend Analysis through Non-Parametric Tests in the Sebou River Basin (SRB), Northern Morocco	This study focused on comparing yearly, seasonal, and monthly rainfall trends in Northern Morocco with those from earlier investigations.	Rainfall data were collected in the Sebou basin from ABHS, and quality checks and homogenisation were carried out. Theil-Sen Slope Estimator and the non-parametric Mann-Kendall test were employed globally to identify trends and their importance within hydrometeorological time series.	• Nearly all of the stations in the dataset showed a clear downward trend in yearly rainfall, which was mostly centred between Taza and Jabal Oudka. • Sen's slope varied from 9.7 to 58 millimetres per decade. On a seasonal scale, a slight upward trend was observed in the rainfall in the autumn and a downward trend in the rainfall in the summer. • However, most noticeably, we observed a downward trend in the rainfall in the winter and spring, which ranged between 7 mm and 47 mm/10 years in the winter months and 12 mm/10 years on average in the spring.

(*Contd.*)

Table 1: (*Cont.*)

Author(s)	*Year*	*Title*	*Research Objective(s)*	*Methodology*	*Key Findings*
			Malaysia		
Asmat et al.	2018	Identifying rainfall pattern in Sabah and Labuan, Malaysia	The study aimed to get the unimodal rainfall pattern and spatiotemporal distribution trend with the help of smoothing techniques of the Fourier series.	The study fits curves from the beginning to the end of the year using the Generalised Linear Model and sinusoidal components, using the Fourier series smoothing approach to discover rainfall patterns.	• According to the study's findings, two harmonics are suitable for predicting the average amount of rain that falls every rainy day at stations in Sabah. • The stations in Sabah experience a single mode of rainfall, with the combination of the second intermonsoon and northeast monsoon seasons influencing the wet periods and the combination of the northeast monsoon and first intermonsoon seasons affecting the dry periods.
Wong et al.	2018	Trend of daily rainfall and temperature in peninsular Malaysia based on a gridded data set	This study addressed the trend analysis of an everyday temperature and precipitation data set and investigated Peninsular Malaysia's rainfall and temperature fluctuations over space and time.	Using Shepard's angular distance weighting (ADW) method, a high-resolution hydrometeorological data set for Peninsular Malaysia evaluated rainfall and temperature variability. The Mann-Kendall non-parametric trend detection test was used to analyse the annual and monsoon rainfall data series, which span 32 years and are interpolated.	• Compared to SWM, NEM has a greater influence on the study region. Since most significant rainfall trends might not be discernible at coarse temporal resolutions, the mean temperature for the entire nation has been determined to be growing significantly (0.32°C/decade) at the 95% confidence level. • For the past 32 years, the country's average temperature has typically been increasing spatially. From 1975-1984 and 1994-2006, Peninsular Malaysia's west coast and Klang Valley experienced higher mean temperature increases (ranging from 0.95°C to 1.2°C).
Muhammad et al.	2020	Characteristics of Rainfall in Peninsular Malaysia	This study aims to examine the rainfall characteristics at gauging stations in Peninsular Malaysia, including Subang, Senai, and Kota Bharu and explores multi-day rainfall events and statistical dependence.	The research methodologies followed the following steps to achieve their objectives- Statistical analysis of rainfall data, the conditional probability of multi-day rainfall events, and statistical dependence of rainfall amounts.	• In comparison to Subang (the centre region) and Senai (the south), rainfall events in Kota Bharu (the east coast) are more intense, especially during the NE monsoon. It rains for longer periods, more frequently in Kota Bharu. • There are temporary and regional variations in the overall amount of rainfall observed across all sites. Since conditional probabilities rise with duration, wet and dry events are time-dependent at all locations.

Saimi et al.	2020	Trend and Linearity Analysis of Meteorological Parameters in Peninsular Malaysia	The primary goal of this study was to look into the mean monthly patterns and predictability of meteorological variables in Peninsular Malaysia. The data from each station were then compared after that.	The linearity and seasonal patterns of meteorological variables have been examined using non-parametric statistical approaches. The analysis for both approaches is carried out and executed using R programming as a tool.	• Except August, Senai, Subang, and Kuantan did not show any trend in the MK trend test for precipitation. • However, the temperature increased monthly for the 47-year study period. Moreover, the Sen slope values show an upward tendency across all locations. • Except for December in Kuantan, all months pass the linearity test for precipitation and show linearity. Only Kuantan and Alor Setar displayed linearity for temperature throughout all months.
Asmat et al.	2021	Identifying rainfall patterns using Fourier series: A case of daily rainfall data in Sarawak, Malaysia	The current study targeted to analyse the rainfall pattern valuable for various sectors, including hydrology, water resource management, tourism, and agriculture. It also helped to predict and mitigate natural disasters like floods and droughts.	The estimated Fourier series parameter for estimating the average daily rainfall amount received was derived using the Generalised Linear Modelling approach, and performance was assessed using the deviation assessment.	• The analysis's findings demonstrated that three harmonics are essential for modelling the stations in Kuching, Sibu, and Miri, whereas only two harmonics are necessary to represent the station in Bintulu. • For the examined stations, the wettest months were January and December, while the driest months were June for the Sibu station, July for the Kuching station, April for the Bintulu station, and March for the Miri station.
Hanif et al.	2022	Evaluation of Long-Term Trends of Rainfall in Perak, Malaysia	The study focussed on examining seasonal and yearly rainfall patterns in Perak, Malaysia, affecting the regional hydrological cycle and water resources over 35 years.	To evaluate the effects of climate change on weather extremes, JCOMM and Marine Meteorology created 27 rainfall indices for spotting patterns in daily rainfall and temperature data. PCI, Autocorrelation, Spatial and several Trend analyses have been carried out.	• The South-west Monsoon (SWM) rainfall significantly decreased over the study period of 1980–2014, which was the study's most salient finding. • The research also revealed that most rainfall indexes are trending insignificantly downward. It was clear from the findings that the falling point extreme indices began to be noticed in 2005. On a regional scale, the rainfall represented a confluence of heavily populated areas in the northeastern and western regions.
Rahmat et al.	2022	Impacts of Climate Change on Rainfall Trends Under RCP Scenarios in Johor, Malaysia	The study investigated the impacts of climate variation on precipitation patterns through the General Circulation Model (GCM) with three representative concentration pathways (RCP).	The impacts of climate change on the trend of rainfall were carried out through SDSM-GCM simulation and Mann-Kendall test for trend analysis test.	The variations in the rainfall trend for the interval years 2030, 2050, and 2080 were thoroughly analysed using the Mann-Kendall analysis. In the interval years of 2030, 2050, and 2080, no discernible increasing or decrease trend was found for RCP 2.6 for any of the eight (8) rainfall locations. As a result, future rainfall trends will not be impacted by low greenhouse gas concentration levels.

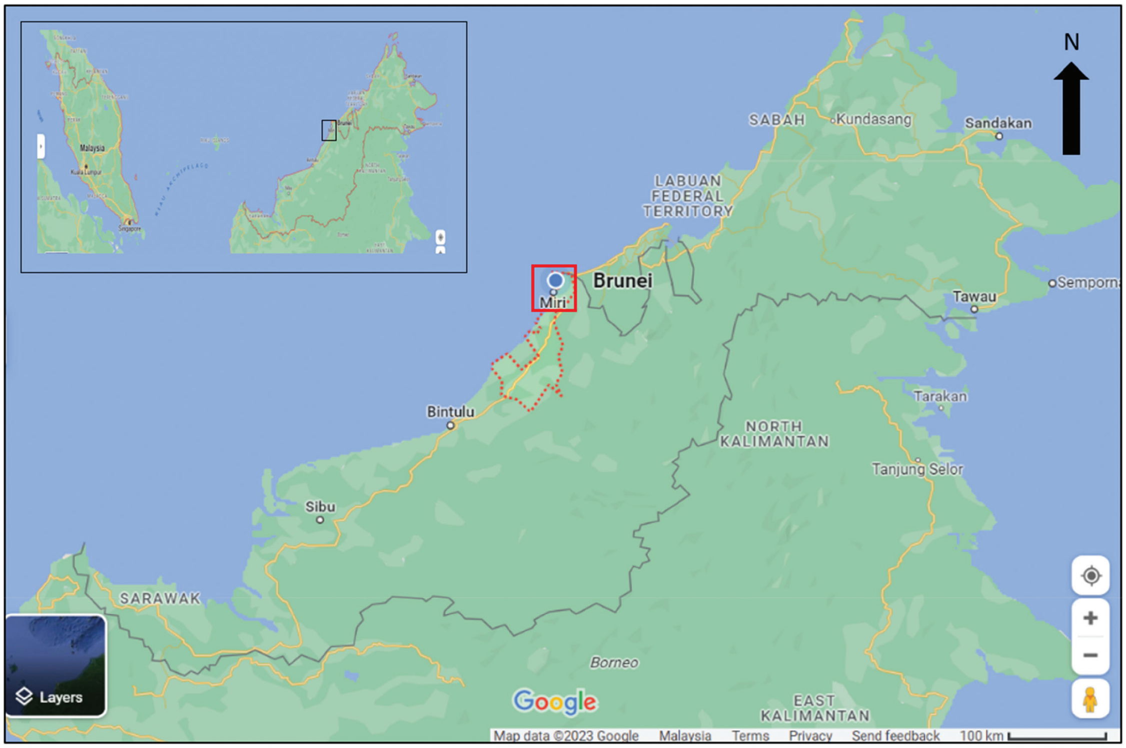

Figure 2: Location map of the study area (Miri).

Methodology

Records of daily mean surface air temperature and daily total rainfall amount (0800-0800MST) for 11 years from 2011 to 2021 were obtained from the Meteorological Department Malaysia (Sarawak Branch). Discussion on the average rainfall pattern and surface air temperature data were analysed by depicting the trend on the graph charts using MS Excel. A representative groundwater sample was collected from a bore well managed by Lembaga Air Kawasan Utara (LAKU), Miri. Upon collection, pH, electrical conductivity (EC), total dissolved solids (TDS), salinity, dissolved oxygen, and turbidity were measured *in situ*.

The DR2800 Portable spectrophotometer manual's recommended method was used to analyse the nutrients of 100 ml of filtered water samples. Each nutrient was tested using a different method, including nitrate (Method 8192), sulphate (Method 8051), phosphorus (Method 8048), ammonia (Method 8155) and silica. The DR2800 handbook recommended method 8043 for a 5-day BOD test was used. The laboratory's distilled water was used for all of the analysis's blank sample preparation. The DO meter was used to measure the initial and final readings of DO in the water samples being analysed for BOD.

Oxygen and hydrogen isotopes were analysed using continuous-flow isotope mass spectrometry (FINNIGAN DELTA^{PLUS} XP) and converted in per mil delta values (δ‰), and defined as (Craig, 1961; Coplen, 1994):

$$\delta(‰) = \left(\frac{R_{sample} - R_{std}}{R_{std}}\right)$$

A hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) transport model (online version) provided by the US National Atmospheric and Oceanic Administration (NOAA) Air Resources Laboratory (ARL) was used for the air mass back trajectory analysis.

Results

Rainfall Trend Analysis

Figure 3 shows the average total rainfall amount, which was represented for two seasons, namely NEM and SWM, for 11 years (2010–2021). The graph shows that eight years, particularly for NEM, have higher average rainfall than SWM. Furthermore, three years (2010, 2020 and 2021) of the SWM has a higher average rainfall than the NEM. It can be observed that some of the studied years have a significant contrast in their total rainfall amount between the two seasons (Figure 4). For example, in the years 2010, 2020 and 2021, the SW monsoon had a higher average rainfall amount than the NEM. While 2011, 2013, 2014 and 2019, the NEM recorded a higher average rainfall amount.

Figure 5 represents the monthly total average rainfall amount in the SWM. It was observed in 2019 that the rainfall for 5 months of the season was lower than others. In contrast, the total rainfall amount was significantly higher in September 2020. It is also observed that September for the years 2010, 2013, 2018 and 2020 have a higher total rainfall amount in comparison to other months. It was 14.5 mm, 12.2 mm, 11.2 mm and 14.7 mm respectively. Additionally, August 2019 and April 2021 have a lower total rainfall amount of 1.2 mm and 1.5 mm.

For the NEM, the rainfall amount varies on average for every month for the past 11 years. December 2013 had a particularly higher total rainfall of 24.8 mm (Figure 6). It can also be observed that January of the year 2011, 2014, 2015 and 2018 has the highest average total rainfall amount; this is 21.6 mm, 19.5 mm, 21.1 mm and 16.7 mm, respectively. The lowest recorded rainfall amount was recorded in the month of February for the years 2010, 2014, 2016, 2019 and 2020. It was 0.3 mm, 1.4 mm, 3.1 mm, 1.8 mm and 2.1 mm, respectively. A similar pattern can be observed in the month of January. The year 2010 to 2021 shows a very inconsistent total rainfall amount. There was a very low total rainfall amount in 2010 and a sharp increase in 2011, and it decreased again in 2012.

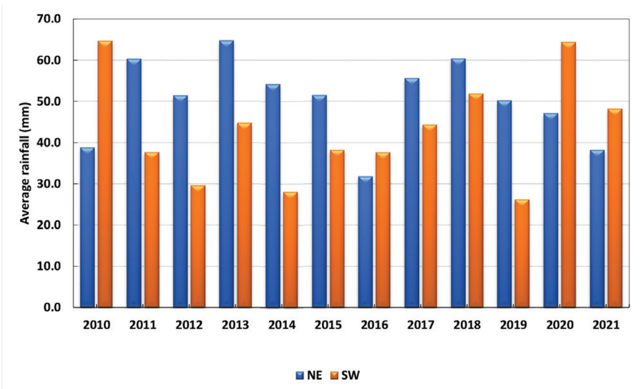

Figure 3: Trend of average rainfall amount for SW and NE monsoons for one decade (2010-2021).

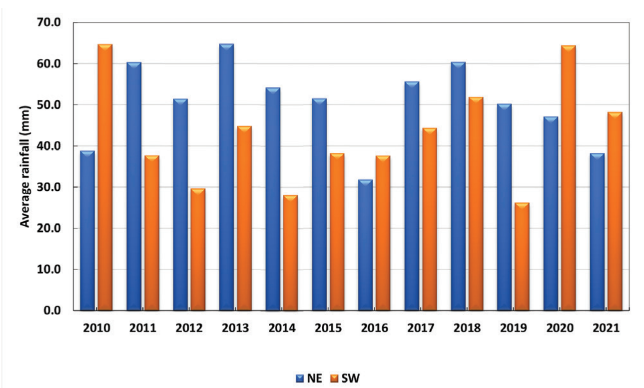

Figure 4: Trend of total average rainfall amount for SW and NE monsoons for one decade (2010-2021).

Temperature Trend Analysis

The daily mean surface air temperature record for 11 years from 2010 to 2021 was plotted in Figure 7 according to the two seasons (SWM and NEM). Generally, the daily mean surface air temperature was higher in the SWM. It was recorded as the highest in the year 2016, and the lowest in 2012 was 28.0°C and 27.1°C, respectively. As for the NEM, the highest surface air temperature was recorded in 2016 as well, which is 27.7°C, and the lowest was in the year of 2011 at 26.4°C.

An individual representation of each monsoon season temperature was plotted in Figures 8 and 9. The variation in the total rainfall amount for both seasons

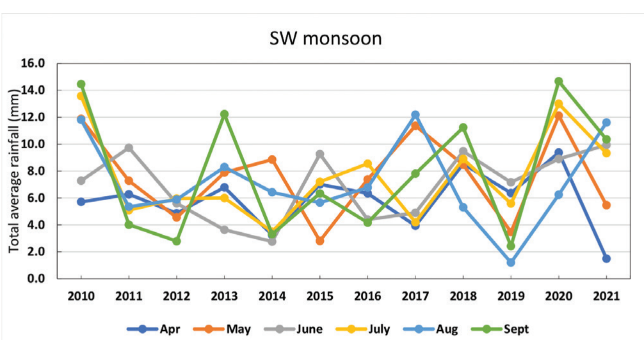

Figure 5: Trend of total average rainfall amount during SW monsoon.

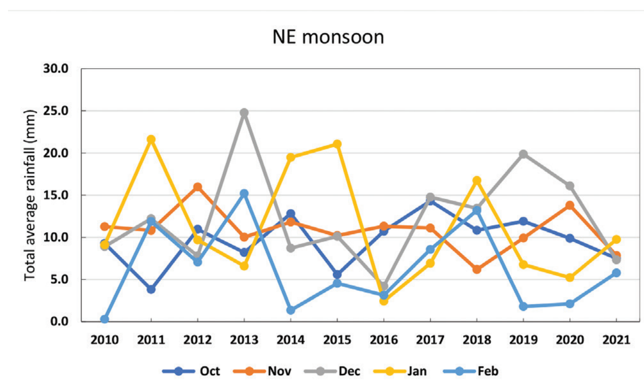

Figure 6: Trend of total average rainfall amount during NE monsoon.

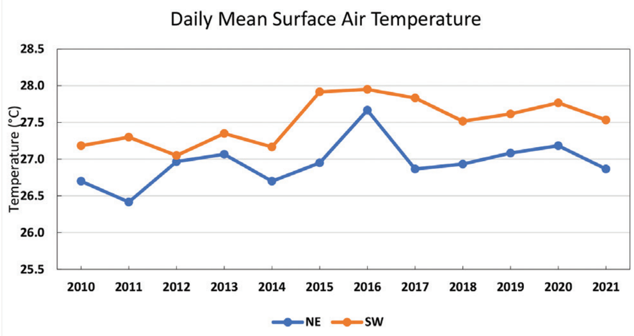

Figure 7: Trend of daily mean surface air temperature for 2010 to 2021.

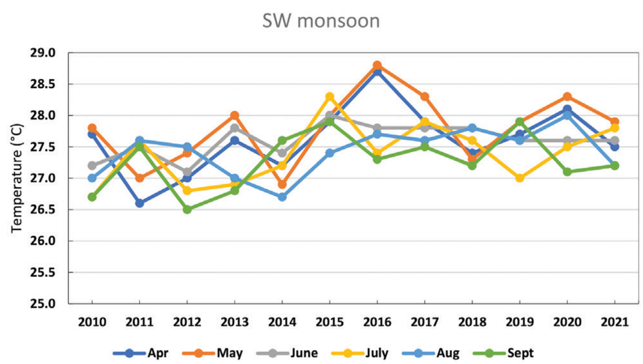

Figure 8: Trend of daily mean surface air temperature during SW monsoon.

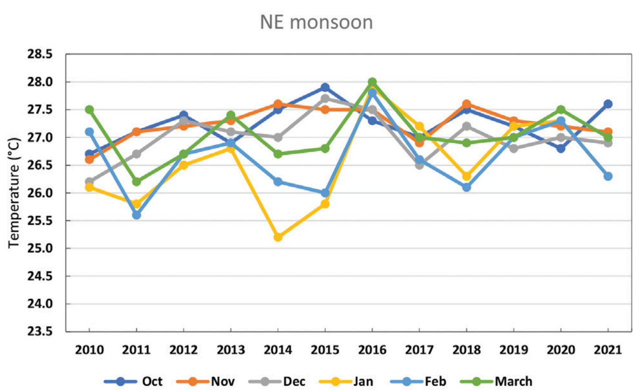

Figure 9: Trend of daily mean surface air temperature during NE monsoon.

was observed to be inconsistent with no intentional pattern. In SWM, April and May of 2016 and 2020 had slightly higher air temperature data recorded of 28.7°C and 28.1°C and 28.8°C and 28.3°C respectively. Other than that, September 2010, 2012 and 2013 have recorded the lower air temperature at 26.7°C, 26.5°C and 26.8°C, respectively. Overall, it is interesting to observe the increasing trend of temperature from 2010 to 2021.

During the NWM, obvious fluctuation was observed in January of 2014 as the lowest recorded surface air temperature was 25.2°C while the highest temperature recorded for the month of January was in 2016 at 27.9°C. Overall, it was observed that all the months in 2016 for this season have particularly consistently higher surface air temperatures compared to other studied years. In contrast to this data, the year 2011 has lower surface air temperature for the entire 6 months of the season. The highest temperature was recorded in the month of November and October, and the lowest was in February, which is 27.1°C and 25.6°C, respectively.

Discussion

Microclimatic Variation

The variation that was observed in the total average rainfall amount in each year of Miri was particularly attributed to the rapid development, which may influence the microclimate in the coastal region. Overall the air temperature shows an increasing trend from 2010 to 2021, whereas the rainfall data fluctuates with respect to each year. The analysis revealed that the SWM rainfall had the most significant trend. However, the NEM contributed significant rainfall amount in this region. These observations were comparable with Peninsular Malaysia and east Malaysia (Sabah) regions, where the NEM influences the wet periods (Asmat et al., 2018; Muhammad et al., 2020). During the SWM, September 2020 recorded a higher rainfall rate, where the temperature was lower (Figure 10). Similarly, 2017 had lesser rainfall with higher temperatures. This inverse relationship between rainfall and temperature supports the microclimatic variation in the study location. However, a proportional relationship was also observed between rainfall and temperature in some years during the SWM. During the NEM, December 2013 recorded a higher rainfall rate, but the temperature was considerably higher (Figure 11). But, a good inverse relationship was observed between rainfall and temperature in 2016. A study done by Asmat et al. (2021) on the rainfall pattern in Sarawak State indicated that the wettest months were January and December, which is also supported in the Miri region, particularly during NEM. However, they recorded that March was the driest month for the Miri station, but in this study, it was February. Overall, the temperature and rainfall data fluctuated throughout the years in the Miri region.

Hydrogeochemistry

The nature of the groundwater sample was alkaline with a pH value of 8.05 (Figure 12). Among nutrients,

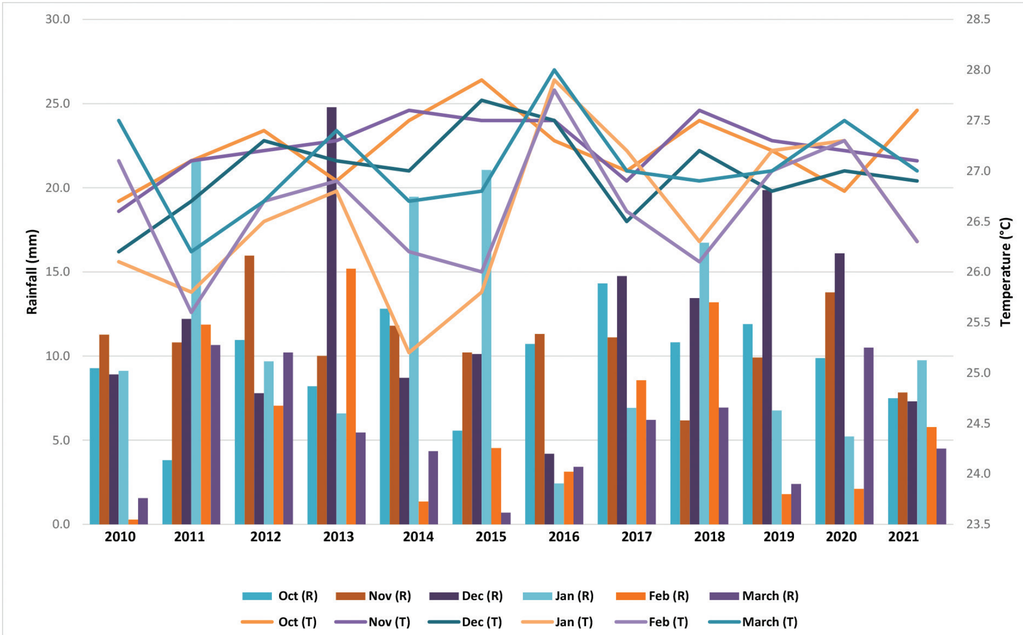

Figure 10: Correction between rainfall and temperature during SW monsoon.

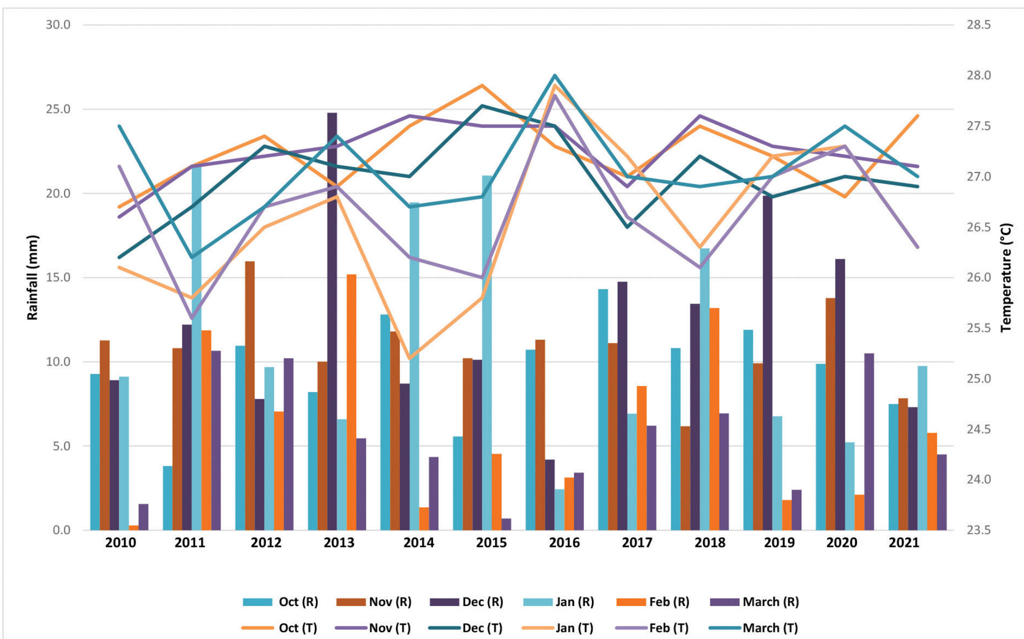

Figure 11: Correction between rainfall and temperature during NE monsoon.

silica was the highest concentration, which indicates the weathering and dissolution of silica-rich minerals in the study location. Miri predominately consists of sedimentary rocks, which include sandstone, siltstone and clay (Parvin Raj et al., 2023). The higher values of DO and BOD indicate the oxidation condition of water, which supports microbiological activity (Prasanna et al., 2012).

Isotopic Signatures

Isotope values of the groundwater sample and rainwater sample were plotted in the $\delta^{18}O$-$\delta^{2}H$ diagram (Figure 13). Limbang's atmospheric precipitation line was used as the local atmospheric water line (LMWL), which is close to Miri (Modon Valappil et al., 2022). The global precipitation line was also plotted in the diagram. It was observed that the rainwater sample fell on the

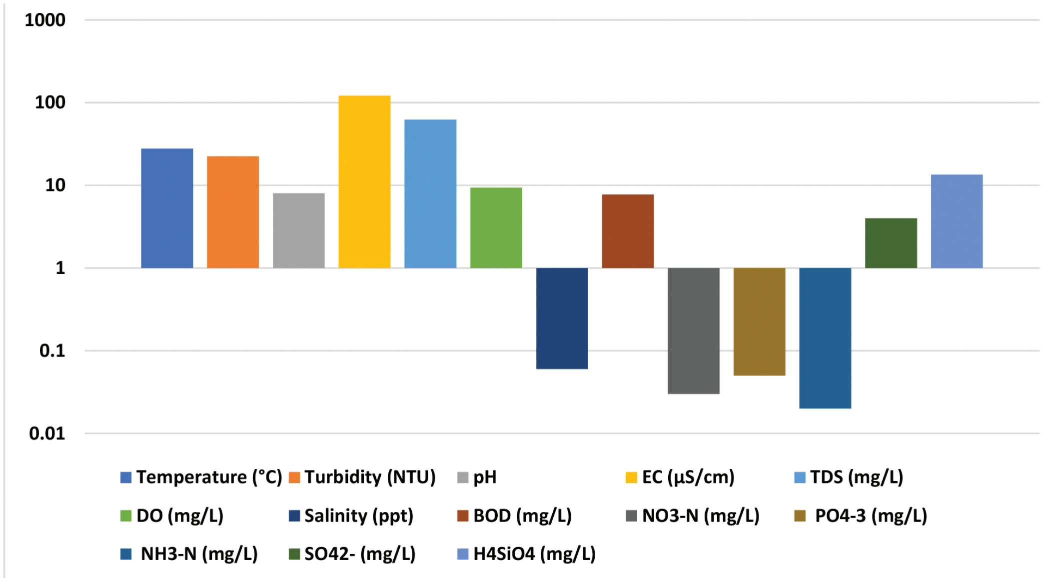

Figure 12: Hydrochemistry of groundwater sample.

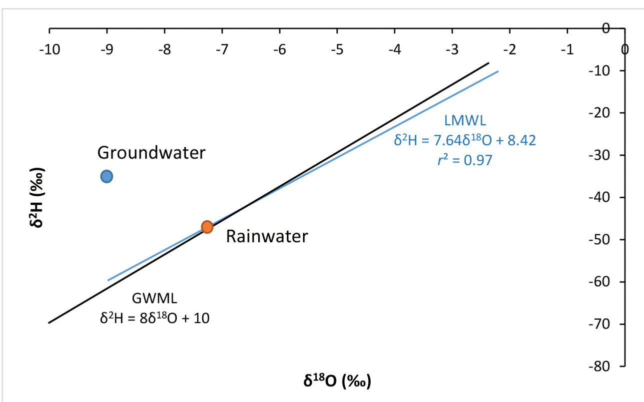

Figure 13: $\delta^{18}O$-δ^2H plot for rainwater and groundwater samples.

LMWL, which indicates a common moisture source in the two locations and the formation of rain in the equatorial tropical region (Dansgaard, 2012; Modon Valappil et al., 2022). The groundwater sample falls above the meteoric water line, indicating that increased fractionation between water and minerals results in δ^2H enriched and $\delta^{18}O$ depleted water during lower temperature environments (Clark and Fritz, 1997). The dominant exchange reactions are the retrograde exchange between water and primary silicate minerals and hydrated primary silicates. A very low water-rock ratio where the rock reservoir dominates in exchange reactions. At low temperatures, the hydration of silicate minerals becomes an important reaction affecting the isotopic evolution of water in crystalline rocks. Reactions such as the alteration of feldspar to clay result in significant uptake of water. Isotopic fractionation between the fluid and clay minerals partitions $\delta^{18}O$ into the mineral, resulting in a $\delta^{18}O$-depletion in the residual fluid. The reverse occurs for hydrogen, where δ^2H fractionates into the water. This imparts an enrichment in δ^2H in the residual fluid, leaving the clay mineral with depleted δ^2H.

Air Mass Movement

Miri region is geographically surrounded by oceans and land masses, which could contribute various moisture sources to the precipitation. Hence, in this study, air mass back trajectory analysis through the HYSPLIT transport model was used to determine the air mass circulation in the study location (Miri) during different seasons (Figure 14). September 2020 (SWM) and December 2013 (NEM) were selected as high rainfall periods from the archived GDAS1 database and modelled at three different heights (100, 500 and 1000 m above the ground level). It was noticed that the air mass reaching Miri from the south direction predominately has been derived from terrestrial sources originating from the Java sea during NEM. The rainout effects are strongest when moisture travels via landmasses (Modon Valappil et al., 2022). The moisture originates from the continental high-pressure centres with typically drier air masses (Aggarwal et al., 2002). During SWM, air mass movement travels through the South China Sea with typically wet air masses. Overall, it was observed

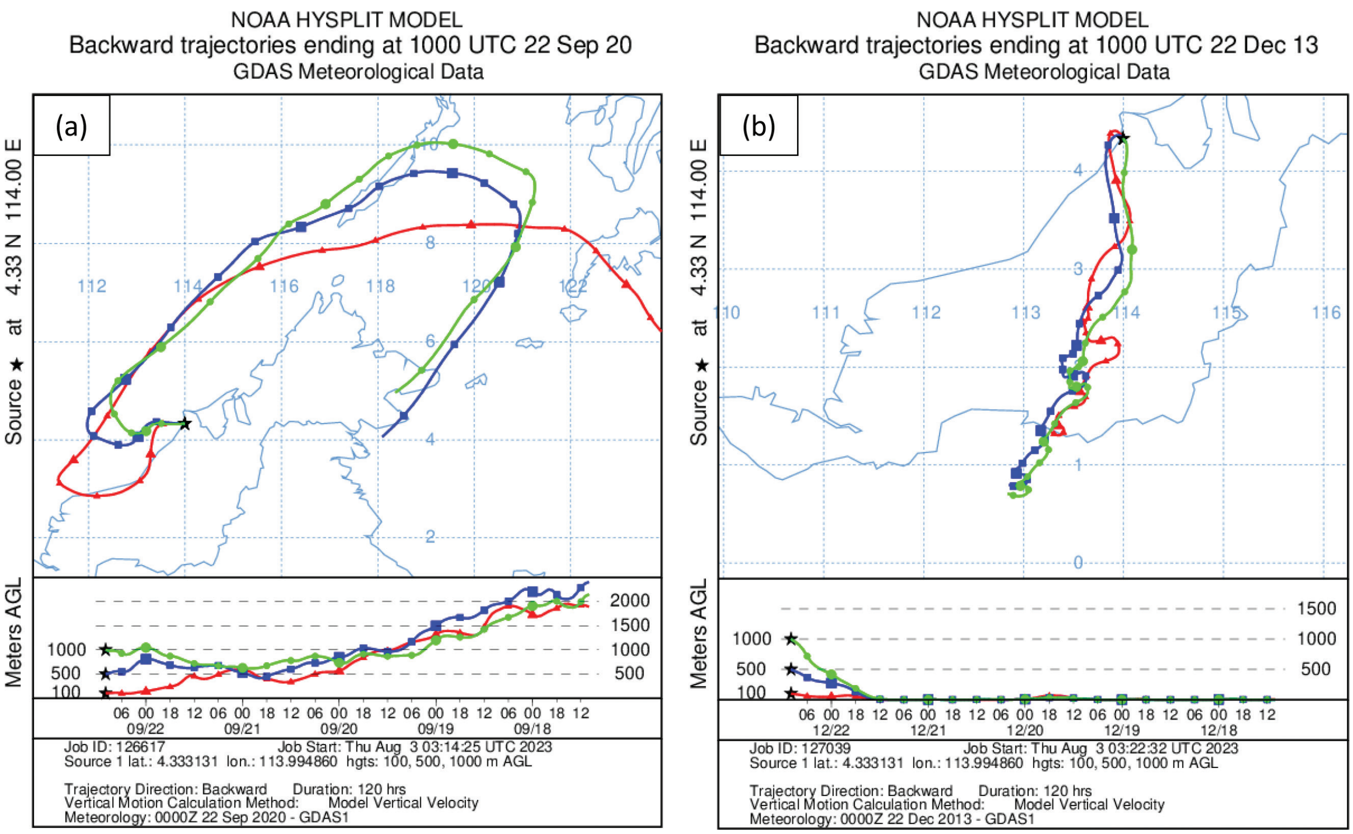

Figure 14: Air mass backward trajectories reaching Miri during (a) September 2021, (b) and December 2013.

that the moisture sources are from both oceanic and continental, affecting the rainfall rates in the study area.

Limitations of This Study

This study has used the decadal data (2010-2021) of rainfall and temperature to assess the microclimatic variation in the Miri region, which cannot understand the climatic pattern before 2010. We are also restricted to one data point due to the availability of meteorological stations in the Miri region. Similarly, one groundwater sample station is available in the study location, which limits the quantity of hydrogeochemical data. Lastly, the isotopic data for one precipitation sample has created the curiosity for more samples in future studies.

Conclusion

The research findings suggest that the annual average rainfall and surface air temperature have fluctuated over the past 11 years. The highest rainfall rate was recorded during NEM. However, a significant rainfall trend was observed during SWM. December 2013 contributed higher rainfall during the NEM, whereas September 2020 recorded higher rainfall during the SWM. A good inverse relationship between rainfall rate and temperature in certain years influences the microclimatic variations in the study location. A good correlation was observed for the wettest months between Peninsular Malaysia and East Malaysia. Hydrochemistry of groundwater indicated alkaline in nature with the dominance of silica content reflecting the weathering and dissolution of silica-rich minerals from the source rocks. Isotopic signatures of oxygen and hydrogen in the rainwater sample indicate the same moisture source of the regional meteoric water line in the study region. Groundwater isotopes indicate the increased fractionation between water and minerals results in δ^2H enriched, and δ^{18}O depleted water at lower temperature environments. The air mass backward trajectories indicated that moisture sources from both oceanic and continental affect the rainfall pattern in the study area. Overall, the effect of oceanic and terrestrial climate variations influences rainfall patterns in the coastal region of Miri. The outcome of this research could help in predicting future regional climatic changes, which supports sustainable land use planning and agricultural practices in Miri.

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