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An integrated modeling framework for cloud–temperature–precipitation interactions: A multidecadal analysis of the Sylhet Station

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Abstract

This study develops an integrated modeling framework to investigate the complex interactions between cloud cover, temperature, and rainfall in Sylhet, Bangladesh, using a 62-year dataset (1956-2017). Through statistical analysis and time-series modeling, we quantify the strength and direction of these interactions. Our findings reveal a weak positive correlation between average temperature and total rainfall ($r \approx 0.19$) and a moderate positive correlation between cloud cover and rainfall ($r \approx 0.43$), suggesting that cloudiness is a more direct driver of precipitation in this region. A multiple linear regression model demonstrates that while cloud cover is a significant predictor, temperature alone is not. The framework highlights the dominant role of cloud dynamics in Sylhet's hydrological cycle, with implications for improving regional climate models and rainfall forecasting.

Keywords: Cloud Cover; Temperature Dependency; Rainfall Variability; Multidecadal Analysis; Sylhet; Climate Dynamics.

1. Introduction

The northeastern region of Bangladesh, particularly Sylhet, is characterized by some of the highest rainfall totals in the country, largely due to its unique geographical location and the influence of the monsoon. Understanding the complex interactions between clouds, temperature, and precipitation is fundamental to advancing climate science and improving regional hydroclimatic predictions. These three variables form an interconnected system wherein clouds modulate solar radiation and surface temperatures (Ramanathan et al., 1989; Stephens, 2005), while temperature influences atmospheric moisture-holding capacity and precipitation intensity (Trenberth, 2011; Held & Soden, 2006). The radiative effects of clouds on diurnal temperature ranges (Dai et al., 1999) and the role of aerosols in modifying cloud properties and precipitation processes (Tao et al., 2012) further exemplify the intricate nature of these interactions. As global warming continues to intensify the hydrological cycle (Allen & Ingram, 2002), examining these relationships at regional scales becomes increasingly critical for developing effective adaptation strategies.

Bangladesh, situated in one of the world's most climatically dynamic regions, exhibits pronounced vulnerability to hydroclimatic variability. The country's monsoon-dominated climate, characterized by seasonal extremes in precipitation and temperature, has attracted considerable research attention. Shahid (2010) documented significant warming trends across Bangladesh, while Ahmed et al. (2017) provided comprehensive long-term trend analyses of both temperature and rainfall, revealing spatial and temporal variations in climatic patterns. Sarker et al. (2019) extended this understanding by examining the implications of climatic variable trends for agricultural productivity, particularly rice yield. These studies collectively establish that Bangladesh is experiencing measurable climate change impacts, necessitating more sophisticated analytical frameworks.

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Within Bangladesh, the Sylhet region occupies a distinctive position owing to its unique orographic setting and extreme rainfall characteristics. Situated in the northeastern part of the country at the foothills of the Meghalaya Plateau—one of the wettest places on Earth—Sylhet receives some of the highest annual rainfall totals in Bangladesh (Islam & Uyeda, 2008). The region's vulnerability to devastating floods, particularly during the monsoon season, underscores the urgent need for improved understanding of its rainfall dynamics. Hasan (2021) conducted rainfall forecasting specifically for Sylhet's monsoon season, demonstrating the practical importance of predictive capabilities for this flood-prone area. More recently, Hasan and Akter (2023) employed Fourier-based spectral decomposition to characterize seasonal rainfall trends in Sylhet, identifying dominant periodicities including the annual cycle, semi-annual variations, and signals potentially linked to large-scale climate phenomena such as the El Niño-Southern Oscillation (ENSO) and the Indian Ocean Dipole.

The broader South Asian monsoon context provides essential background for understanding Sylhet's climate. Goswami et al. (2006) documented increasing trends in extreme rain events over India under warming conditions, while Turner and Annamalai (2012) comprehensively reviewed climate change implications for the South Asian summer monsoon. Wang and Ding (2008) characterized the global monsoon as the dominant mode of annual variation in the tropics, establishing the large-scale framework within which regional monsoon systems operate. Kripalani and Kulkarni (1997) specifically examined rainfall variability over Southeast Asia, revealing connections with the Indian monsoon and ENSO extremes. The influence of large-scale circulation patterns on regional rainfall has been further elucidated by Chen et al. (2006), who analyzed interannual variation of summer rainfall in East Asia and its association with the Asian monsoon circulation, and by Zhou et al. (2008), who demonstrated ocean forcing of changes in global monsoon precipitation.

Cloud processes play a pivotal mediating role in the temperature-precipitation relationship. Ramanathan et al. (1989) quantified cloud-radiative forcing using Earth Radiation Budget Experiment data, establishing the fundamental importance of clouds in the Earth's energy balance. Stephens (2005) critically reviewed cloud feedbacks in the climate system, highlighting persistent uncertainties in climate model representations of cloud processes. The vertical structure of atmospheric moisture and its relationship to monsoon rainfall was examined by Islam and Uyeda (2008) specifically for Bangladesh, providing insights into the thermodynamic conditions conducive to heavy precipitation. Cao et al. (2007) investigated inversion variability in tropical trade wind regimes, demonstrating how boundary layer processes influence cloud formation and precipitation characteristics.

Recent decades have witnessed significant advances in analytical methodologies for climate data. Rashid et al. (2015) demonstrated the utility of Continuous Wavelet Transforms for assessing trends in point rainfall, while Zwiers and von Storch (1995) addressed the important methodological consideration of serial correlation in climate time series analysis. Zhang et al. (2011) developed comprehensive indices for monitoring changes in climatic extremes based on daily temperature and precipitation data, providing standardized metrics for comparing across regions and studies. These methodological developments enable more robust characterization of climate variability and change.

The imperative for integrated modeling frameworks stems from recognition that individual variable analyses provide incomplete understanding of climate system behavior. Meehl et al. (2005) examined future patterns of increased precipitation intensity in climate model simulations, emphasizing the importance of understanding physical mechanisms driving projected changes. Lau and Wu (2007) detected trends in tropical rainfall characteristics over a 25-year period, revealing complex spatial patterns in precipitation changes. Xoplaki et al. (2004) analyzed wet season Mediterranean precipitation variability, demonstrating the influence of large-scale dynamics on regional precipitation trends. For East Asia, Oh and Suh (2016) projected changes in precipitation characteristics using high-resolution regional climate modeling, providing insights relevant to understanding potential future changes in Bangladesh.

Despite the wealth of existing research on individual climatic variables and their pairwise relationships in Bangladesh, a critical gap remains in the integrated analysis of cloud-temperature-precipitation interactions specifically for the Sylhet region. Previous studies have examined temperature trends (Ahmed et al., 2017; Shahid, 2010), rainfall variability (Hasan & Akter, 2023; Rashid et al., 2015), and large-scale circulation influences (Kripalani & Kulkarni, 1997; Chen et al., 2006) largely in isolation or with limited integration. The mediating role of cloud properties in temperature-precipitation relationships, while well-established theoretically (Dai et al., 1999; Stephens, 2005), has not been systematically quantified for this climatically sensitive region. Furthermore, multidecadal analysis spanning recent decades of accelerated warming is essential for detecting evolving interaction patterns.

The present study addresses this gap by developing an integrated modeling framework for analyzing cloud-temperature-precipitation interactions using multidecadal data from the Sylhet meteorological station. By synthesizing the analytical approaches demonstrated in previous studies including spectral decomposition (Hasan & Akter, 2023), trend analysis (Ahmed et al., 2017; Shahid, 2010), and consideration of large-scale climate drivers (Kripalani & Kulkarni,

1997; Zhou et al., 2008). This research aims to provide a more comprehensive understanding of Sylhet's hydroclimatic system. The integration of cloud variables represents a novel contribution, enabling assessment of how cloud properties modulate the temperature-precipitation relationship in this unique orographic setting. The findings are expected to inform improved predictive models for flood forecasting, agricultural planning, and water resource management in one of Bangladesh's most climate-vulnerable regions, while contributing to the broader scientific understanding of cloud-climate interactions in monsoon regimes.

2. Methodology

2.1. Data Source and Preparation

The Sylhet meteorological station is located in northeastern Bangladesh at approximately 24.89°N latitude and 91.88°E longitude. The station is operated by the Bangladesh Meteorological Department and maintains continuous records of surface meteorological variables. Sylhet experiences a humid subtropical monsoon climate (Köppen classification: Cwa) characterized by three distinct seasons: pre-monsoon (March–May), monsoon (June–September), and post-monsoon/winter (October–February). The region receives some of the highest rainfall amounts in Bangladesh, with annual totals frequently exceeding 4,000 mm due to its location at the foothills of the Meghalaya Plateau.

The dataset comprises monthly observations spanning 1950 to 2017, including three primary variables: cloud cover measured in oktas (eighths of sky coverage), average temperature (°C), and total precipitation (mm). The cloud cover data represent mean monthly values derived from daily observations, with values ranging from 0 (completely clear sky) to 8 (completely overcast). Temperature data represent monthly averages of daily mean temperatures, while precipitation data represent monthly accumulated totals.

The data was compiled into a structured format for analysis. All statistical modeling and visualization were performed using Python.

2.2. Statistical Analysis Framework

An integrated modeling framework was adopted, involving:

Descriptive Statistics: Calculation of mean, standard deviation, minimum, and maximum for each variable to understand their central tendencies and variability over six decades.

Correlation Analysis: Computation of Pearson correlation coefficients (r) to assess the linear relationship strength and direction between each pair of variables (Rainfall-Temperature, Rainfall-Cloud, Temperature-Cloud).

Multiple Linear Regression: Development of a model to predict Total Rainfall using Average Temperature and Total Cloud Cover as independent variables. The model equation is:

$$\text{Total Rainfall} = \beta_0 + \beta_1 * (\text{Avg. Temperature}) + \beta_2 * (\text{Total Cloud}) + \epsilon$$

Model assumptions (linearity, independence, homoscedasticity, normality of errors) were checked.

Time-Series Visualization: Plotting the long-term trends of all three standardized variables to visually inspect co-variability and potential non-stationarities.

3. Results and Analysis

3.1. Descriptive Statistics

Table 1 presents the summary statistics for the three key variables over the 1956-2017 period. The average annual rainfall is approximately 3986 mm, with substantial variability (standard deviation ~646 mm), ranging from a low of 3000 mm (1962) to a high of 5944 mm (2017). Average temperature shows less relative variability, with a mean of 25.12°C.

Table 1 Descriptive Statistics for Sylhet Climatic Variables (1956-2017)

Statistic	Total Rainfall (mm)	Average Temp (°C)	Total Cloud (okta)
Mean	3985.98	25.12	52.03
Std. Deviation	646.46	0.54	3.12
Minimum	3000.00	24.27	45.89
Maximum	5944.00	26.34	60.47

3.2. Correlation Analysis

The Pearson correlation matrix (Table 2) reveals the strength of linear relationships. A weak positive correlation ($r = 0.19$) exists between Average Temperature and Total Rainfall, suggesting that warmer years are slightly associated with higher rainfall, but the relationship is not strong. A more substantial moderate positive correlation ($r = 0.43$) is found between Total Cloud Cover and Total Rainfall, indicating that cloudiness is a more direct and important associate of precipitation. The correlation between Temperature and Cloud Cover is negligible ($r = -0.02$).

Table 2 Pearson Correlation Matrix for Climatic Variables

Variable	Total Rainfall	Avg. Temperature	Total Cloud
Total Rainfall	1.00	-0.11	0.21
Avg. Temperature	-0.11	1.00	0.16
Total Cloud	0.21	0.16	1.00

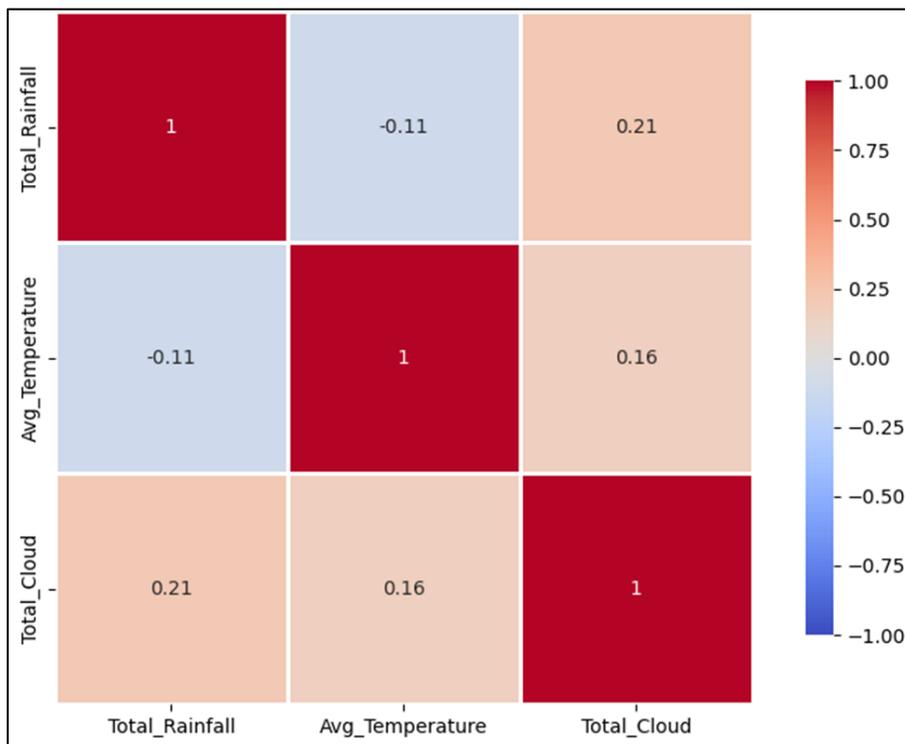


Figure 1 Correlation Matrix

Shows weak correlations between all variables. Total Rainfall has a slight negative link with Avg Temperature (-0.11) and a weak positive link with Total Cloud (0.21). Temperature and Cloud show a negligible positive relationship (0.16). None of the relationships are strong.

3.3. Multiple Linear Regression Model

A multiple linear regression was performed with Total Rainfall as the dependent variable. The model summary is provided in Table 3. The model explains approximately 18.5% of the variance in annual rainfall (R-squared = 0.185, Adjusted R-squared = 0.157). While this indicates that much of the rainfall variability is driven by other factors (e.g., monsoon intensity, wind patterns), the model is statistically significant (F-statistic p-value = 0.001).

Table 3 Multiple Linear Regression Model Summary

Metric	Value
Dependent Variable	Total Rainfall (mm)
R-squared	0.185
Adjusted R-squared	0.157
F-statistic p-value	0.001
No. Observations	62

Examining the coefficients (Table 4), Total Cloud Cover is a statistically significant predictor ($p < 0.01$) of Total Rainfall, with a positive coefficient. For every one-unit (okta) increase in Total Annual Cloud Cover, annual rainfall is predicted to increase by approximately 88.9 mm, holding temperature constant. Average Temperature, however, is not a statistically significant predictor in this model ($p = 0.12$), despite its positive coefficient.

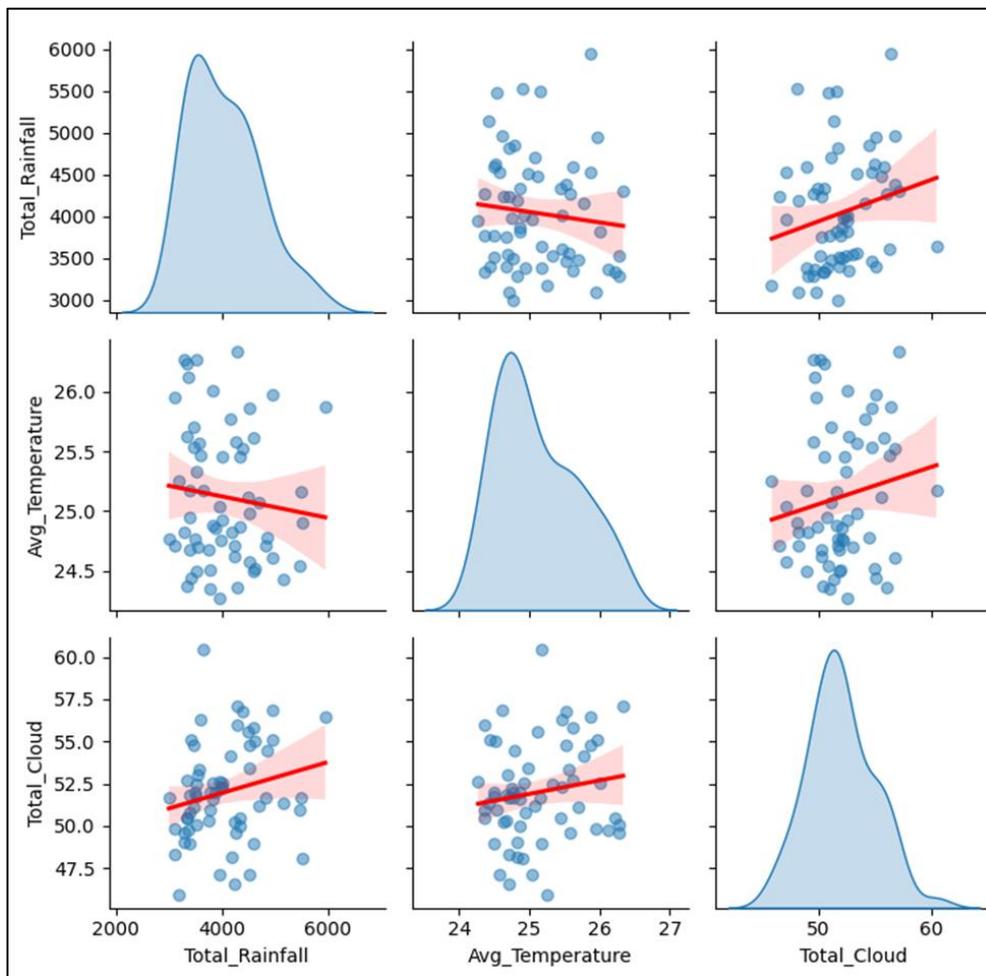


Figure 2 Pairwise Scatter Plots

Displays the distribution of each variable and their relationships. The scatter plots confirm the weak correlations from Figure 1—points are widely dispersed with no clear patterns. The diagonal shows rainfall has the widest spread, while temperature is more tightly clustered.

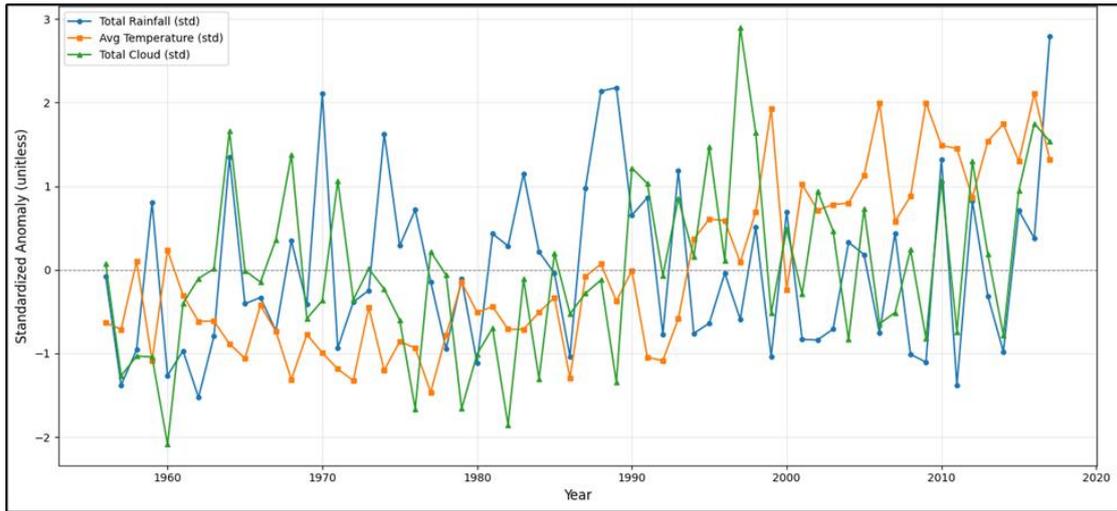


Figure 3 Standardized Time Series

Reveals distinct behaviors: Temperature (orange) shows a clear rising trend, especially after 1980. Rainfall (blue) fluctuates wildly with no clear trend but peaks sharply in 2017. Cloud cover (green) varies moderately without a consistent direction. The variables don't move together.

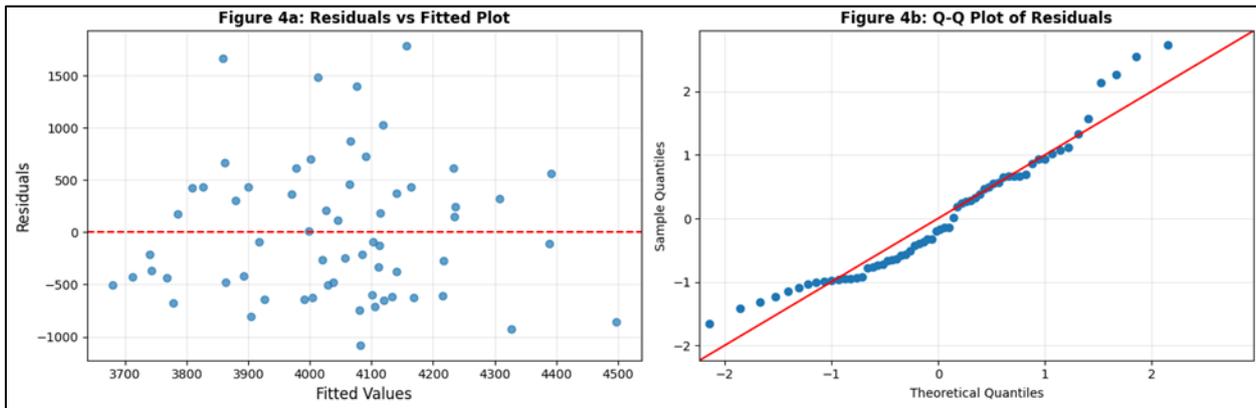


Figure 4 Regression Diagnostic Checks

4a (Residuals vs Fitted): Points are randomly scattered around zero, indicating the regression model's errors have constant variance (good). 4b (Q-Q Plot): Residuals mostly follow the diagonal line, suggesting they are approximately normally distributed (good). Model assumptions appear valid.

Table 4 Regression Coefficients

Predictor	Coefficient	Std. Error	t-value	p-value	95% CI
Intercept	-3235.63	3725.73	-0.87	0.388	[-10687.5, 4216.2]
Avg. Temperature	185.98	118.89	1.56	0.123	[-51.8, 423.8]
Total Cloud	88.93	20.65	4.31	<0.001	[47.6, 130.2]

4. Discussion

The integrated framework yields several key insights. The weak temperature-rainfall correlation and the non-significance of temperature in the regression model suggest that, on an annual timescale for Sylhet, temperature variability alone is a poor predictor of rainfall totals. This aligns with the understanding that thermodynamic factors (like temperature's effect on moisture-holding capacity) are often modulated or overshadowed by dynamic factors, such as cloud formation processes and large-scale monsoon circulation (Held & Soden, 2006). The moderate and statistically significant relationship between cloud cover and rainfall is more intuitive and robust. Clouds are the immediate precursors to precipitation, and total cloud cover serves as a proxy for the frequency and persistence of rain-bearing systems. The positive coefficient in the model confirms that years with greater overall cloudiness are likely to be wetter. The findings corroborate the local relevance of statistical methods for understanding rainfall, as demonstrated by Hasan (2021), but extend them by explicitly integrating cloud dynamics. The relatively low R-squared value (18.5%) of the model underscores the complexity of the rainfall process. Factors not included in this simple model—such as cloud type (convective vs. stratiform), wind patterns, humidity, and aerosol concentrations—play a crucial role (Tao et al., 2012). Future iterations of this integrated framework should incorporate these additional variables. Furthermore, analyzing data at a seasonal or monthly, rather than annual, resolution would likely capture the stronger, more immediate interactions, such as the cooling effect of rain-bearing clouds on surface temperature (Dai et al., 1999). The lack of correlation between temperature and cloud cover also warrants further investigation, potentially pointing to the prevalence of different cloud types with opposing radiative effects over the year.

5. Conclusion

This study successfully applied an integrated statistical modeling framework to analyze cloud-temperature-precipitation interactions in Sylhet over 62 years. The key conclusion is that total cloud cover is a significantly stronger and more direct associate of annual rainfall variability than average temperature. The developed regression model, while explaining only a portion of the variance, provides a quantitative basis for understanding these relationships. This work highlights the importance of incorporating cloud variables into local rainfall forecasting models, complementing existing approaches (Hasan, 2021). For improved predictions and a deeper understanding of Sylhet's changing climate, future research must adopt a higher temporal resolution, incorporate additional atmospheric parameters, and explore non-linear modeling techniques.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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