Preliminary assessment on climatological conditions in Royal Belum-Temenggor Rainforest Complex, Malaysia using MERRA-2 reanalysis datasets

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Abstract. Royal Belum-Temenggor Rainforest Complex (RBTRC) is renowned as one of the world's oldest tropical rainforests and biodiversity hotspots. Its extensive forest coverage serves as a crucial carbon sink that stock more than 185 Mg ha^{-1} carbon, thereby playing a crucial role in regulating Earth's temperature. Despite its significance as a major carbon sink and biodiversity ecosystem, studies on RBTRC have been limited primarily to biological and ecological studies. Baseline climate studies for this region are non-existent to-date. Baseline climate assessment is crucial for assessments of future climate change impact in this region. This study fills this critical research gap by investigating the climatological trends of annual-averaged temperature, surface pressure, specific humidity, wind speed and rainfall in RBTRC from 1991 to 2020 using the Modern-Era Retrospective Analysis for Research and Applications, version 2 (MERRA-2) reanalysis dataset. All atmospheric variables exhibit a normal distribution, and increasing trends are observed for all variables except for windspeed. Pearson's correlations indicate positive correlation between pressure and temperature (0.5), specific humidity and rainfall (0.45), and negative correlation in pressure and rainfall (-0.59), specific humidity and windspeed (-0.55), and temperature and windspeed (-0.42). This complements the fundamental physical laws, indicating the reliability of the MERRA-2 reanalysis datasets for further climatological evaluation.

1 Introduction

The RBTRC in Perak, Malaysia is one of the oldest rainforests in the world and plays a vital role in various ecological and climatic functions. The biologically diverse RBTRC is home to several indigenous communities, plays a pivotal role in maintaining the carbon and

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hydrological functions necessary for the regulation of the local and regional climate. The hydrological cycle such as the process of evapotranspiration in the rainforest contributes to cloud formation, which influences rainfall patterns locally and over distant regions [1-3]. Moreover, cloud formation process releases latent heat energy, which influences atmospheric wind circulation, thus moderates the moisture content in the atmosphere. Additionally, the cloud cover reflects incoming solar radiation, moderating sensible heat energy and surface temperatures, further influencing the local and regional climate [4]. Rainforests also regulate temperatures via its role as a carbon sink [5]. Carbon dioxide, being a greenhouse gas, contributes to warming, and the rainforest's capacity to sequester carbon through photosynthesis helps mitigate temperature rise. Royal Belum State Park, one of the forest reserves in the RBTRC, is estimated to have a carbon stock of 185 Mg ha^{-1} [6], further reinforcing its significant role in temperature regulation.

Deforestation and land use changes pose threats to rainforests [7], altering evapotranspiration, energy partitioning, rainfall patterns and temperatures [8]. However, emerging evidence from the Amazon basin suggests that large-scale changes in atmospheric convergence have counteracting effects to deforestation, resulting in increased rainfall in the region in recent decades [9]. Climate variability also influences the carbon fluxes and stocks of rainforests [10]. This highlights the complexity of forest-atmosphere interactions, warranting further studies to ascertain the potential impacts of changing climate patterns, both locally and regionally. Comprehensive and long-term meteorological records are essential for understanding past and current climate and for constructing a baseline climatology as a reference for comprehending climate changes and anticipating future climate patterns. While the Amazon and Congo basins have received considerable attention regarding forest-atmosphere interactions, such studies are lacking in the RBTRC. The scarcity of long-term meteorological records and meteorological stations in the RBTRC remains a persistent challenge in climate science, hindering the establishment of a climatological baseline for the region. However, reanalyses and satellite data products have emerged as useful alternatives for data-scarce region. Therefore, this study aims to analyse the long-term climatological conditions such as the pressure, temperature, humidity, wind speed and rainfall in the RBTRC using reanalysis datasets, specifically the Modern-Era Retrospective Analysis for Research and Applications, version 2 (MERRA-2) [11-12], to assess their reliability for further climatological evaluation.

2 Methodology

2.1 Study Area

The RBTRC is a vast dipterocarp rainforest region that encompasses an area of 290,000 hectares, situated in Perak, Malaysia (5°32′58.91″N 101°20′52.4″E; Fig. 1). The RBTRC comprises several forest reserves, including the Royal Belum State Park, Banding Forest Reserve, Gerik Forest Reserve, and Temenggor Forest Reserve, with only the Royal Belum State Park being fully protected since 2007 [13]. Connecting these forest reserves is the Temenggor Lake, a man-made lake spanning 15,200 hectares and a depth of up to 60.96 metres, utilised for hydroelectricity generation.

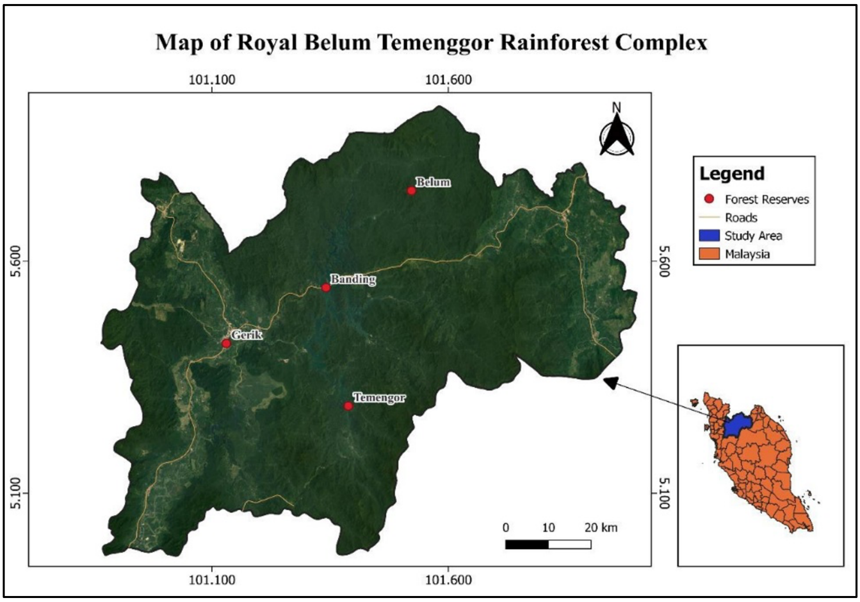

Fig. 1. Map of the study area: Royal Belum-Temenggor Rainforest Complex, Malaysia (digitised from Google Maps)

2.2 Data and methods

The MERRA-2 is a reanalysis product generated by the NASA Global Modelling and Assimilation Office (GMAO) using the Goddard Earth Observing System, version 5 (GEOS-5.12.4) atmospheric general circulation model [11-12]. MERRA-2 is a successor to the original MERRA reanalysis dataset, which ended in February 2016. MERRA-2 covers the period from 1980 to the present with horizontal resolution of 0.5° x 0.625°. The MERRA-2 is a well-established reanalysis dataset and was chosen for its expansive coverage with potentials to serve as a forcing dataset for hydroclimate applications [14]. The five key atmospheric variables evaluated in this study are annual averaged surface pressure (hPa), temperature (°C), specific humidity (g/kg), wind speed (m/s), and rainfall (mm), and spanned a period of 30 years, from 1991 to 2020. The distribution of each atmospheric variable was assessed using the Shapiro-Wilk normality test due to the sample size (years) being less than 50. The data was then presented in time-series format and trend analysis was conducted using ordinary least square regression. To explore the relationships between the atmospheric variables, Pearson's correlation analysis was performed, followed by multiple linear regression to predict rainfall with the remaining atmospheric variables serving as predictors.

3 Results and discussion

This study investigates the distribution patterns and temporal trends of the five annual-averaged atmospheric variables at the RBTRC between 1991 and 2020. Fig. 2(a-e) illustrates the normal distribution of all atmospheric variables, namely, pressure, temperature, specific humidity, windspeed and rainfall, with p-values greater than 0.05, affirming their adherence to normality. Fig. 2(f-j) depict the time-series plots of each variable throughout the study period. Surface pressure ranges from 96.33 to 96.52 hPa, temperature fluctuates between 23.8 and 24.7 °C, specific humidity varies from 16.72 to 17.76 g/kg, windspeed ranges from 1.17 to 1.36 m/s, and rainfall spans from 1587.3 to 3311.7 mm. Notably, all variables display an overall increasing trend throughout the study period, apart from windspeed, which exhibits a slight decreasing trend of -0.002.

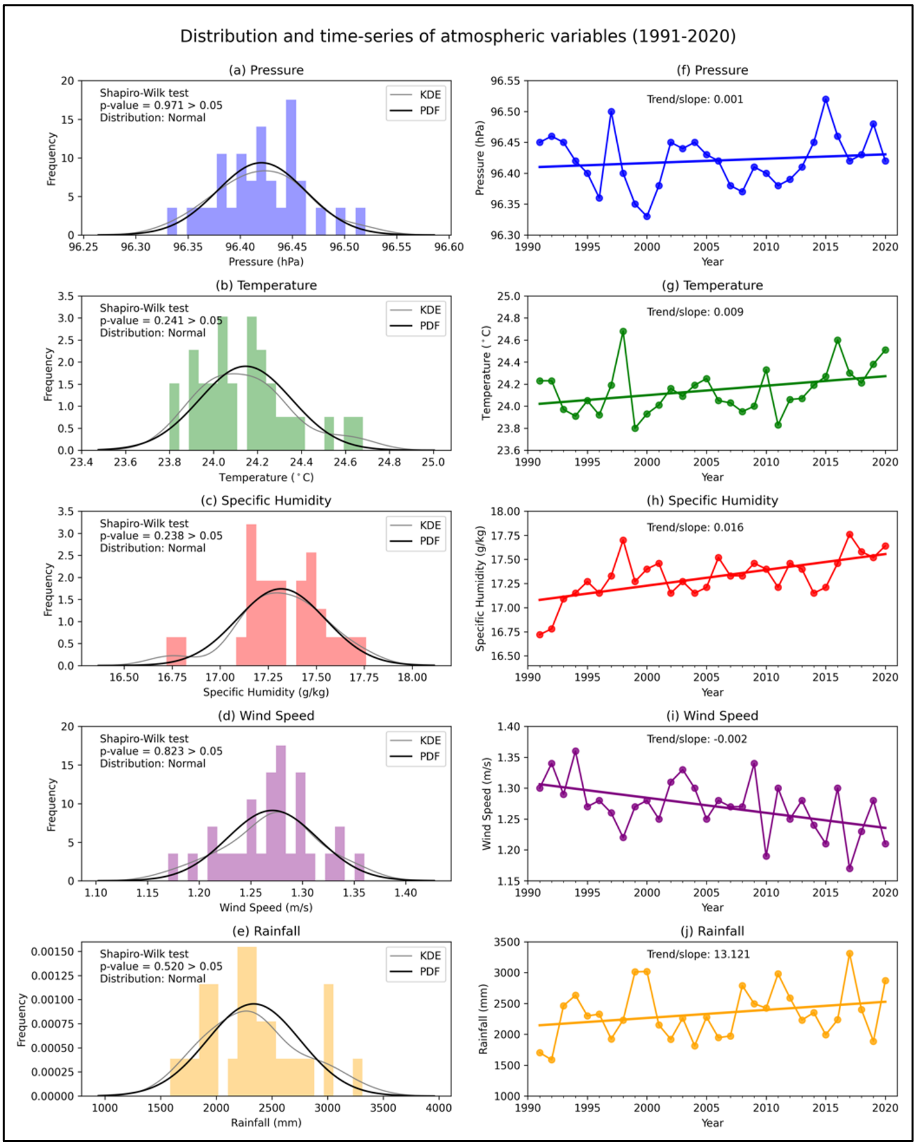

Fig. 2. Distribution plots (a-e) and time-series plots (f-j) for annual-averaged pressure, temperature, specific humidity, windspeed, and rainfall in RBTRC between 1991 and 2020.

The correlation heatmap in Fig. 3 illustrates the relationships between atmospheric variables. Atmospheric variables with statistically significant relationship include: i. rainfall-pressure (-0.59), ii. windspeed-specific humidity (-0.55), iii. temperature-pressure (0.5), iv.

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specific humidity-rainfall (0.45), and v. temperature-windspeed (-0.42). These relationships adhere to the fundamental physical laws that govern atmospheric dynamics and interactions. Higher surface pressure corresponds to clearer skies and increased solar radiation, leading to atmospheric warming as indicated in the positive correlation between temperature and pressure. Warmer temperature signifies a stable atmosphere which moderates the windspeed, as reflected in the negative correlation between temperature and windspeed. In the presence of low winds, the rate of evaporation increases, resulting in greater atmospheric moisture content, as reflected in the negative correlation between windspeed and specific humidity. In turn, higher specific humidity increases the availability of atmospheric moisture contributing to increased rainfall, as reflected in the positive correlation between specific humidity and rainfall. On rainy days, low surface pressure is commonly observed as reflected in the negative correlation between rainfall and pressure.

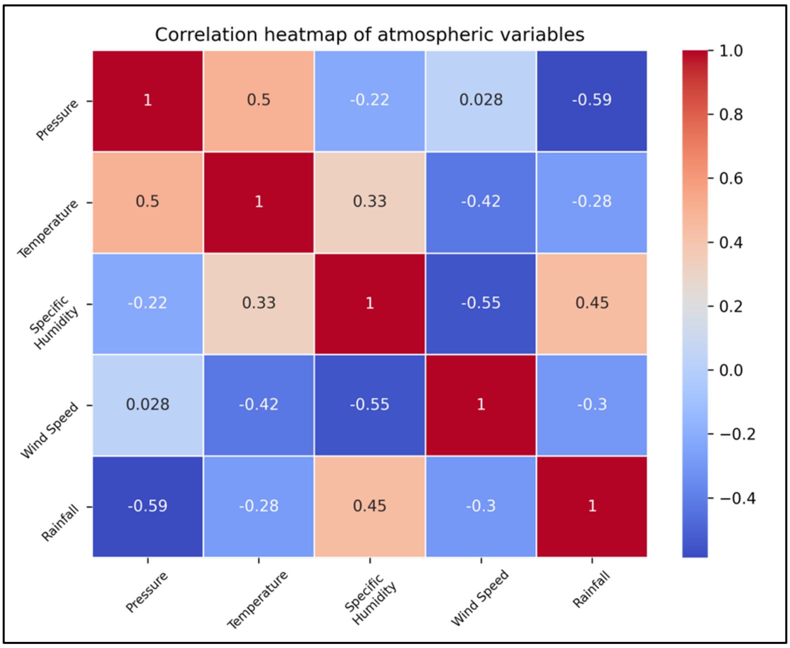

Fig. 3. Pearson's correlation heat map between pressure, temperature, specific humidity, windspeed and rainfall for RBTRC.

Building upon the observed correlations, a multiple linear regression model is developed to predict rainfall with the other atmospheric variables as predictors (Table 1). The resulting model is represented as

$$y = -3364.46x_1 - 640.86x_2 + 635.02x_3 - 2216.16x_4 + 334000 \qquad (1)$$

where y represents rainfall, while x_1, x_2, x_3, and x_4 denote pressure, temperature, specific humidity, and windspeed, respectively. The goodness-of-fit of the regression model is evaluated using the R-squared and adjusted R-squared values, which are 0.518 and 0.440, respectively. These values indicate the model's ability in predicting 51.8% of the variation in rainfall. The p-values associated with each predictor variable provide insights into their statistical significance in relation to rainfall. In this model, the p-values for pressure and specific humidity are closer to the significance level of 0.05, suggesting a potential statistically significant relationship that influences rainfall. However, the p-values for temperature and windspeed are greater than 0.1, suggesting weaker evidence of a significant relationship or the possibility of non-linear relationship. It is important to note that the absence of statistical significance does not necessarily imply the absence of a relationship, but rather suggests the need for further investigation and consideration of other factors. Nonetheless, the findings from this study highlights the correlation patterns that align with fundamental physical laws and underscore the reliability of the MERRA satellite datasets for further climatological evaluation.

Table 1. Multiple linear regression results

R-squared	0.518		**Adjusted R-squared**			0.440
	Coefficient	**Std. error**	**T**	**P-value**	**0.025**	**0.975**
Constant	334000	169000	1.976	0.059	-14200	682000
Pressure	-3364.47	1790.81	-1.879	0.072	-7052.71	323.78
Temperature	-640.86	392.46	-1.633	0.115	-1449.15	167.42
Specific humidity	635.02	331.70	1.914	0.067	-48.14	1318.17
Windspeed	-2216.16	1679.64	-1.319	0.199	-5675.44	1243.13

4 Conclusion

Five key atmospheric variables: pressure, temperature, specific humidity, windspeed, and rainfall obtained from the NASA MERRA-2 satellite datasets were explored for the RBTRC from 1991 to 2020. Normality test, trend analysis, correlation analysis and multiple linear regression were performed. The findings reveal that all atmospheric variables exhibit normal distribution and demonstrate an overall increasing trend from 1991 to 2020, except for windspeed which shows a slight decreasing trend. The observed relationships among the atmospheric variables conform to the fundamental physical laws that atmospheric dynamics, highlighting the validity of these relationships. The developed multiple linear regression model demonstrates the potential to predict annual average rainfall using pressure, temperature, specific humidity and windspeed as predictors. The model's goodness-of-fit was evaluated using R-squared and adjusted R-squared values, indicating its ability to explain 51.8% of the variation in rainfall. Statistical significance analysis reveals potential significant relationships between rainfall and both pressure and specific humidity. However, weaker evidence of significant relationships or the possibility of non-linear relationships is observed for temperature and windspeed. This emphasises the need for further investigation and consideration of additional factors to enhance the predictive capability of the model. Overall, the findings underscore the reliability of the MERRA-2 satellite datasets for climatological evaluation at the RBTRC. Future research endeavours should explore the inclusion of additional variables, examine longer timescales, investigate non-linear relationships, or conduct validation and comparative studies to develop more robust models and enhance our understanding of the complex interactions shaping the atmospheric conditions in the RBTRC.

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