Unveiling Nepal's Hydro-Climatic Diversity: A Comprehensive Study from East to West

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ABSTRACT

This study delves into the comprehensive analysis of temperature, precipitation, and wind patterns across four distinct blocks in Nepal, shedding light on regional climate variations. Examining a 30-year (1990 – 2020) dataset, temperature variations reveal the East: Block 1 consistently experiencing higher average temperatures. Findings align with existing research, emphasizing local geographical features influence on temperature gradients. The precipitation analysis indicates the Block 1 receives the highest rainfall, correlating with established monsoon patterns. Western regions (Block 3) transition to arid climates, influenced by its most area in rain shadow effect of the Himalayas. Regression analysis reveals a warming trend in all blocks, reinforcing global climate change impacts. Precipitation trends exhibit nuances, with the East and Centre (Block 2) experiencing increases, while the Block 4 shows a decreasing trend. Extreme precipitation values highlight spatial variability, crucial for climate adaptation strategies. The study extends to extreme wind analysis, showcasing distinct patterns in each block, providing insights into potential risks. Wind direction analysis reveals unique patterns, contributing to a holistic understanding of regional climate dynamics. These findings contribute to the scientific discourse on climate resilience, emphasizing the need for tailored strategies in diverse geographical contexts.

Keywords: Climate, Extreme precipitation, Temperature gradient and Temperature trend

1. Introduction

Nepal is a country located in the Himalayas, known for its beautiful landscape, diverse topography and rich natural resources (Wells, 1993). Its unique geographical location and rugged terrain contribute to significant variations in hydro-climatic conditions across the country (Bhattarai et al., 2019, 2022; Karki et al., 2017). Hydro-climatic variables encompass a wide range of climatic and hydrological factors that influence the water cycle, water availability, and distribution patterns (Immerzeel et al., 2020; Li et al., 2022). These variables include precipitation, temperature, evaporation, snow cover, stream-flow, and groundwater levels. Spatial and temporal changes in these variables intensity and frequency often leads to related extreme events (Agrawala et al., 2003; Chalise and Khanal, 2002; Karki et al., 2017).

Research into Nepal's hydro-climatic diversity emphasizes the importance of understanding both monsoon-driven precipitation and the contribution of snow and glacial meltwater, especially in high-altitude regions. Immerzeel et al. (2010) and Bhattarai et al. (2020b) highlight that glacial meltwater significantly contributes to river flows, particularly during the dry season, providing essential resources for agriculture and hydropower. However, rapid glacial retreat due to rising temperatures (Kattel et al., 2015) poses severe challenges to water availability, with significant implications for downstream communities dependent on glacial-fed rivers.

Nepal's extreme topographical variation also generates pronounced local climatic effects. Orographic lifting induces intense rainfall on windward slopes, leading to frequent landslides and floods, while leeward regions remain comparatively arid. Dahal and Hasegawa (2008) emphasize that Nepal's vulnerability to landslides, particularly in the mid-hill and mountain regions, is closely tied to intense monsoonal rainfall exacerbated by steep terrain. Climate models project that Nepal will experience increased precipitation variability, with more intense monsoons and prolonged dry spells, likely increasing the risks of both floods and droughts (Singh et al., 2016). This highlights the necessity of fine-scale hydro-climatic studies to anticipate these changes and mitigate their impacts. Akhtar et al. (2009) stress the importance of using high-resolution models to capture Nepal's complex terrain and microclimates, as global models often fail to represent these small-scale processes accurately.

With climate change altering precipitation patterns and water availability, effective water resource management is critical. Nepal's river systems, while offering immense potential for hydropower, are highly susceptible to seasonal

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and inter-annual variability in water flows. The frequent occurrence of floods and landslides poses significant risks to infrastructure and livelihoods (WECS, 2011). Addressing these challenges requires integrated approaches that account for the diverse hydro-climatic conditions across the country.

Understanding hydro-climatic variables is essential for effective water resource management, sustainable development, and disaster mitigation strategies in Nepal (Bhattarai et al., 2020a; Bhattarai and Regmi, 2016). The east-west and elevation gradients in Nepal create significant climate variations that have profound implications for agriculture, water resources, biodiversity, and human livelihoods (Malla, 2009; Öztürk et al., 2015). These variations present both challenges and opportunities for sustainable development and adaptation to climate change (Donohue and Biggs, 2015; Mahat et al., 2019). Studying these variations provides valuable insights into the complex interactions between topography, atmospheric dynamics, and climatic patterns. It allows researchers to investigate the drivers of climate variability, understand their impacts on natural and human systems, and develop strategies for climate resilience and adaptation.

This study aim to analyze and compare hydro-climatic variables from east to west across the four divided blocks of Nepal (Fig. 1). By examining long-term climate data, including precipitation patterns, temperature fluctuations, and hydrological indicators, presented research aim to uncover regional trends, variations, and potential future changes across the studied blocks from east to west in Nepal. This comprehensive analysis will serve as a scientific foundation for evidence-based decision-making, resource allocation, and the formulation of effective climate adaptation strategies. The insights gained from studying the hydro-climatic variables at this scale will provide valuable information at the provincial level in Nepal, enabling policymakers and stakeholders to make informed choices and take proactive measures. By comprehending the unique difficulties and advantages connected with every province situated within their corresponding studied blocks, informed steps can be taken to tackle the consequences of climate change and foster practices that promote sustainable development. Ultimately, this research contributes to enhancing resilience and fostering a more climate-resilient future for Nepal.

2. Study area and climate

To examine long-term hydro-climatic data, Nepal has been divided into four distinct blocks: Block 1 (East), Block 2 (Centre), Block 3 (West), and Block 4 (Far-West). This division captures the significant east-west climatic gradient that exists across the country, driven by Nepal's complex topography and varying exposure to monsoonal winds. Studies have shown that eastern Nepal receives significantly more rainfall due to its proximity to the Bay of Bengal and the stronger influence of the monsoon, while the western regions experience comparatively lower precipitation due to the weakening of the monsoon and the rain-shadow effects of the Himalayas (Shrestha and Sheikh, 2008; Bookhagen and Burbank, 2010). Each block, therefore, represents unique topographical, climatic, and hydrological features. For example, Block 1 (East) is characterized by heavier monsoonal rainfall, while Blocks 3 and 4 (West and Far-West) exhibit drier conditions and greater seasonal variability (Karki et al., 2016a; Kansakar et al., 2004). This refined approach ensures a comprehensive representation of Nepal's diverse geographical features—spanning lowlands, mountainous areas, and the Himalayas—thus enhancing the accuracy and specificity of the analysis.

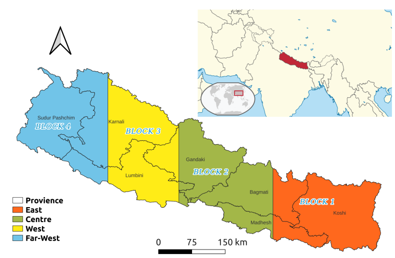

Figure 1. Map of Nepal, with different study blocks. The color bar represents the naming for different blocks.

Another crucial aspect of Nepal's climate variation is the altitudinal gradient from lower to higher elevations. The country's elevation ranges from just above sea level in the Terai region to the towering peaks exceeding 8,000 meters in the Himalayas. This vertical dimension plays a significant role in shaping climatic conditions and associated ecological patterns (Karki et al., 2016b). The U and V wind components (see Fig. 2) represent the east-west (zonal) and north-south (meridional) components of the wind, respectively (Lettau, 1950) and it provides valuable insights into the atmospheric circulation patterns and weather conditions. Seasonal variations in these components are influenced by the changing thermal conditions, monsoons, and other climatic factors.

During the winter months (DJF), Nepal encounters a dominance of westerly winds. The U components, representing the west-east flow, reveals a prevailing westerly direction. These winds brings cold and dry air from the western regions, contributing to the winter chill. The V-component, indicating the north-south flow, remains relatively week during this periods. During winter, the westerly winds exhibit a gradient from east to west. The eastern regions, shielded by the Himalayas, experience milder winter conditions, while the western regions (Northern parts of study blocks 3 and four), are more exposed to the influence of cold westerlies. This east-to-west gradient is reflected in both the U and V wind components. Wind patterns started to shift gradually from westerly to easterly during pre-monsoon season (MAM).

The summer monsoon (JJAS) brings a remarkable reversal in the wind patterns across Nepal. The u component becomes predominantly westerly, ushering in moist air from the Bay of Bengal. However, the monsoon's impact is not uniform across the country. In the eastern regions (Block 1), the monsoon is vigorous, resulting in heavy rainfall. The v component strengthens, indicating a significant northward movement of the intertropical convergence zone (ITCZ). One notable feature in Nepal is the variability in monsoon patterns from east to west. The eastern regions, particularly Block 1, receive more intense and prolonged monsoon rains compared to the block 3 and 4. This variation is influenced by factors such as the proximity to the Bay of Bengal, topography, and the rain shadow effect caused by the Himalayas (Yadav, 2011).

As it can be see in the Fig. 2, after the monsoon retreats, the u component shifts back to easterly, marking the post-monsoon (ON) period. The eastern regions may experience lingering monsoon showers during early October. The v component weakens during this transition, and the weather becomes relatively drier.

3. Data and Methods

In this study, 30 years (1990 – 2020) ERA5 climate reanalysis data were retrieved using the Google Earth Engine platform with its API (Tamiminia et al., 2020). Google Earth Engine (GEE) is a cloud-based platform that enables users to access and analyze large-scale geospatial datasets, including satellite imagery, climate data, and more. It provides a powerful and efficient environment for processing, visualizing, and extracting valuable insights from Earth observation data (Amani et al., 2020).

Fig. 3 shows the data extraction procedure using GEE. The first step in retrieving the data was to define the region of interest using a shapefile. The shapefile was created over the area of interest using QGIS (Moyroud and Portet, 2018), and subsequently, the created shapefile was uploaded to Google Drive, obtaining its unique identifier. This identifier, referred to as the "shapefileId" in the code, and is used to access the shapefile data within the Earth Engine environment. Next, is to specify the desired variables for analysis. To ensure consistency in the units of the variables, data preprocessing was carried out. For example, surface pressure, initially provided in Pascals (Pa), was converted to hectopascals (hPa) by dividing the values by 100, aligning the data with commonly used pressure units. Subsequently, the gridded data covering the designated area of interest were spatially averaged using area-weighted methods described in Faisal and Gaffar (2012) and Klanfar et al. (2021). Finally, the processed data were exported as a CSV file to Google Drive using the Export.table.toDrive function. This function allows us to specify the collection of data, description, destination folder, and file format.

ERA5 is a comprehensive climate reanalysis dataset provided by the European Centre for Medium-Range Weather Forecasts (ECMWF) (Hersbach et al., 2020). It offers a wide range of climatic variables, including temperature, precipitation, wind components, evaporation, and more. Here, this research have focused on six key variables: mean 2 m air temperature, total precipitation, snowfall, evaporation, potential evaporation, and 10 m u and v wind components (Chattopadhyay et al., 2022).

The numerical weather prediction model used in ERA5 is based on physical equations that simulate the behavior of the atmosphere. It takes into account factors such as temperature, humidity, wind patterns, and pressure systems to generate continuous predictions of weather variables (Dee et al., 2011). By assimilating real-time observations, the model is regularly updated, improving its accuracy and reliability over time. The assimilated data sources used in ERA5 include surface observations from weather stations, satellite measurements of atmospheric parameters, and additional information from reanalysis models (Bell et al., 2021). Weather station data provide valuable ground-based measurements, while satellites provide a broader spatial coverage, capturing atmospheric conditions across large areas. Reanalysis models integrate the available data and apply sophisticated algorithms to produce a consistent and continuous representation of climate variables over time (Albergel et al., 2020; Bell et al., 2021; Dee et al., 2011).

In this study, the well-known Mann-Kendall test from the Python library (Hussain and Mahmud, 2019) was used to calculate the trend of climatic data in the study area. It is a non-parametric statistical test specifically designed to detect monotonic trends in a dataset. Existence of monotonic trend in the rainfall time series has been examined using the least square linear fit, and its significance is tested using the Student's t-distribution (Ahsanullah et al., 2014). In this analysis, the extreme precipitation values were determined by establishing threshold values using the 90th percentile. This threshold serves as a benchmark for isolating and analyzing extreme events within the datasets. Subsequently, the Mann-Kendall test was applied to the extreme precipitation data to compute the linear regression and determine the slope of the regression line. This slope provides valuable insights into whether there exists a statistically significant increasing or decreasing pattern in extreme precipitation over time.

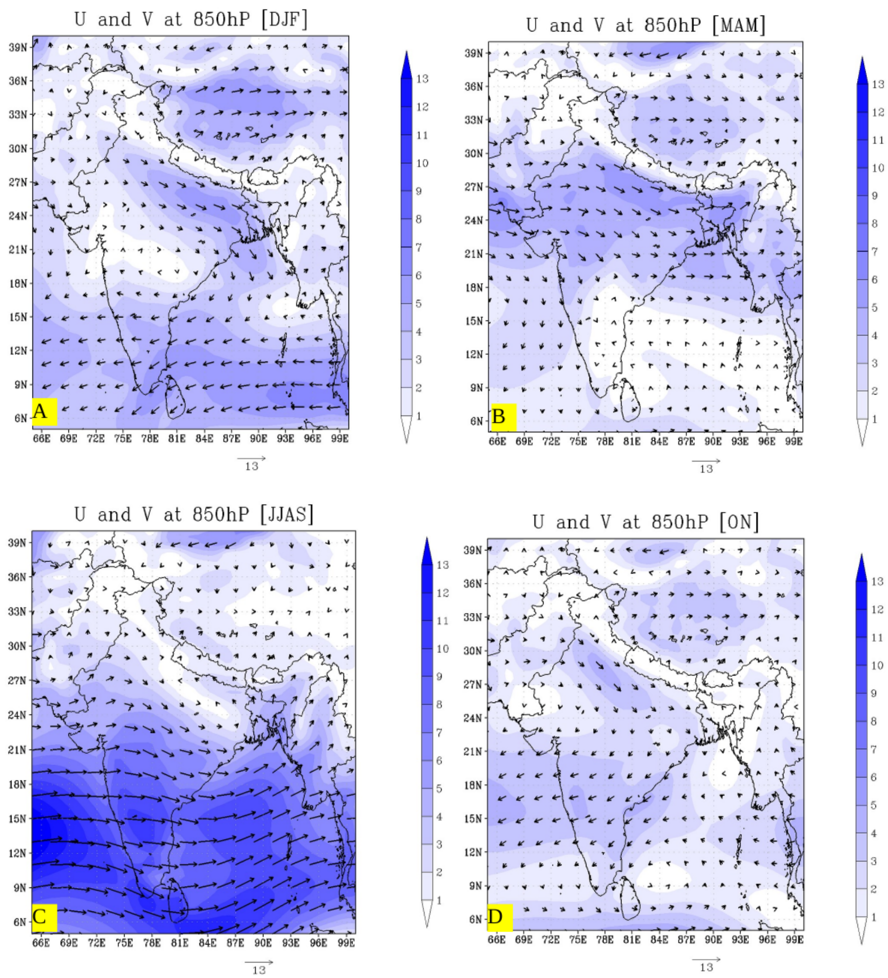

Figure 2. U and V wind component over the Indian subcontinent. In figure A, DJF = December-February, MAM = March-May, JJAS = June-September, and ON = October-November.

4. Results and Discussion

4.1. Temperature and precipitation trend analysis

The analysis of average temperature and precipitation patterns across the different blocks reveals interesting insights into regional climate variations.

In terms of average temperature, the East Block (Block 1) consistently experiences higher minimum and maximum average temperatures compared to the other blocks. It has both the highest minimum average temperature (12.24°C) and maximum average temperature (13.82°C) over the 30-year period (Table 1). The Center Block follows with slightly lower temperatures, having a minimum of 10.94°C and a maximum of 12.9°C. The Western Block exhibits the lowest temperatures, with a minimum of 6.42°C and a maximum of 8.96°C. The Far Western Block falls in between, with a minimum temperature of 10.41°C and a maximum of 12.88°C.

The observed temperature variations across different blocks in Nepal align with the influence of local geographical features and topography on regional climate. Studies have demonstrated that Nepal's diverse terrain—from the lowlands in the east to the high altitudes in the west—drives significant climatic gradients. Pokharel et al. (2020) and Karki et al. (2016a) highlight that temperature tends to decrease from east to west and with increasing elevation, aligning with the east-west and altitudinal gradient observed in this study. The East Block's higher temperatures can be explained by its lower elevation, which receives greater heat fluxes from solar radiation compared to the higher elevations in the west. However, the suggestion of increased proximity to the Bay of Bengal leading to higher solar radiation was indeed inaccurate and requires correc-

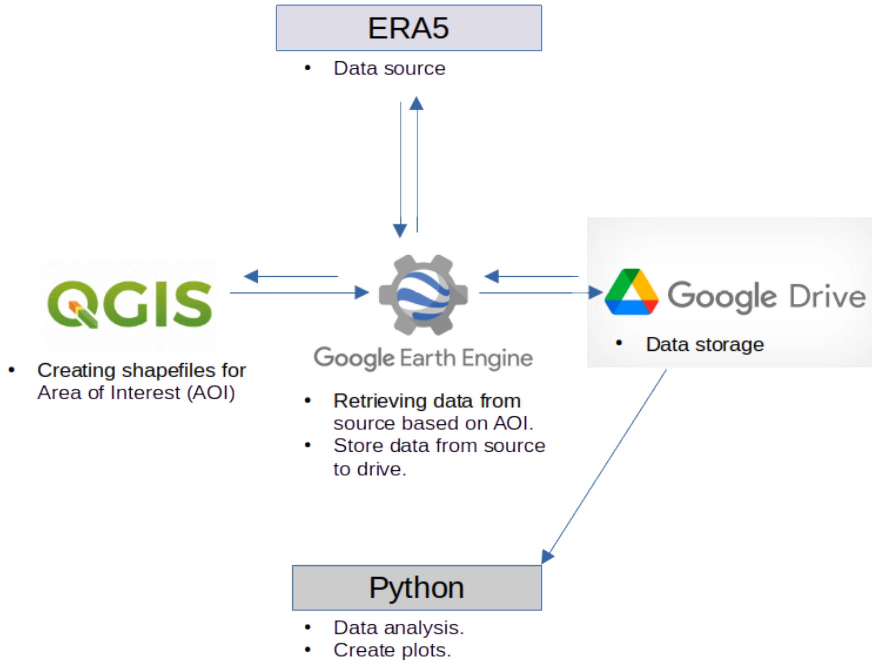

Figure 3. Flow chart for data retrieval and processing using Google-Earth-Engine.

tion. While the Bay of Bengal influences moisture and monsoonal dynamics, there is no established link between proximity to the bay and increased solar radiation intensity (Yihui and Chan, 2005). Therefore, the East Block's warmer conditions are more likely due to elevation and the influence of the subtropical climate than proximity to the Bay of Bengal.

In the Central Block, temperature variations are influenced by the intermediate elevation and terrain, consistent with the findings of Chand et al. (2021), who discuss the role of altitude and slope orientation in shaping local climatic conditions. The Western Block shows the lowest temperatures due to both its higher elevation and the presence of the rain shadow effect, as noted by Karki et al. (2017) and Islam et al. (2010). This effect reduces precipitation and results in drier conditions, leading to cooler temperatures in western Nepal. The Far-West Block, situated in a transitional zone, demonstrates intermediate temperature values, confirming the complex interactions of altitude, terrain, and distance from moisture sources like the Bay of Bengal, as described by Awasthi (2023).

Regarding average precipitation, the East Block also receives the highest amount of average precipitation. It has the highest minimum average precipitation of 1.844 meters and the highest maximum average precipitation of 2.90 meters. The Center Block receives slightly lower average precipitation, with a minimum of 1.63 meters and a maximum of 2.76 meters. The Western Block shows lower average precipitation levels, with a minimum of 1.29 meters and a maximum of 1.87 meters. The Far Western Block experiences intermediate average precipitation, with a minimum of 1.34 meters and a maximum of 2.07 meters.

Sharma et al. (2020) also reported the similar results analysing monsoon and climatic extremes in Nepal having significant variations from east to west. The eastern region experiences distinct monsoon patterns and climatic extremes compared to the western region similarly mention by Subba et al. (2019). These variations are influenced by the diverse topography, geographical features, and atmospheric dynamics present across the country (Singh et al., 1995). This region receives abundant precipitation during the summer monsoon season, which results in lush vegetation, fertile agricultural lands, and dense forests. On the other hand, the Western and Far-Western region, encompassing block 4, may exhibit different monsoon characteristics and climatic extremes due to its unique geographic and atmospheric conditions (Kansakar et al., 2004).

Results shows that, towards the central and western regions of Nepal, including blocks 2 and 3, the climate gradually transitions to a more arid and semi-arid regime (mostly in Northern part of the region) (Meier et al., 2022). These areas lie in the rain shadow of the Himalayas, leading to reduced rainfall and drier conditions. Previous study carried out by Islam et al. (2010) in their research. The climate becomes more continental in nature, characterized by hot summers and relatively cooler winters. The westernmost

Table 1. Average minimum and maximum temperature and precipitation over the different study blocks (See: Figure 1)

	$Temperature$(°C)		$Precipitation(m)$	
	Min	Max	Min	Max
East	12.24	13.84	1.84	2.9
Center	10.94	12.9	1.63	2.76
West	6.42	8.96	1.29	1.87
Far-West	10.41	12.88	1.34	2.07

regions, such as Karnali and Sudurpashchim Province particularly in Blocks 3 and 4, are known for their arid landscapes and limited precipitation which is also shown by less precipitation in blocks 3 and 4 (Table 1), contributing to a unique climatic and ecological setting.

The observed trends in temperature, as revealed by the regression analysis (Fig. 4, align with findings from the study conducted by Chand et al. (2021), adding credibility to the evidence of a gradual warming trend across the Himalayan region. The positive slopes in the temperature regression equations for the East, Centre, and West Blocks, ranging from 0.021°C to 0.023°C per unit of time, mirror the broader consensus in the scientific community regarding the impacts of global warming on mountainous terrains. The coherence in temperature trends suggests a region-wide response to the changing climate, influenced by global climate patterns and greenhouse gas emissions. The warming trend is particularly noteworthy, considering its potential implications for glacial melt, water resources, and ecosystem dynamics, as emphasized by Immerzeel et al. (2010), Salerno et al. (2016) and Singh and Bengtsson (2005) in their research on the Himalayan cryosphere.

However, the precipitation trends exhibit intriguing variations across the different blocks, adding nuance to the climate change narrative. The positive slopes in the regression equations for the East and Centre Blocks indicate an increasing trend in precipitation over the 30-year period. This aligns with studies by Subba et al. (2019), who emphasized the intensification of the Indian Summer Monsoon and its impact on regional precipitation patterns, especially in eastern Nepal. Contrastingly, the Far Western Block shows a negative slope in its precipitation trend, suggesting a slight decrease in rainfall over time. This finding echoes the concerns raised by Saini et al. (2023) regarding changing monsoon dynamics and potential shifts in rainfall patterns in the western Himalayan region.

The comprehensive examination of extreme precipitation values and trends across the four distinct study areas, as depicted in Fig. 5, reveals nuanced characteristics that contribute to our understanding of regional climate variations. In the eastern region (Block 1), the identified extreme precipitation threshold stands at 0.0163 m, accompanied by a positive trend, indicating a gradual increase over the 30-year period. Similarly, the central region (Block 2) exhibits a slightly lower threshold of 0.0156 m, coupled with a comparable increasing trend. Conversely, the western region (Block 3) displays a lower threshold of 0.0109 m and a smaller increasing trend, emphasizing the spatial variability in extreme precipitation dynamics.

The far-western region (Block 4) presents a higher threshold of 0.0128, but notably, it experiences a decreasing trend, highlighting a distinctive climatic pattern. These findings underscore the importance of recognizing spatial variability, with Blocks 1 and 2 sharing similar increasing trends, Block 3 showing a lower threshold and smaller trend, and Block 4 demonstrating a higher threshold with a decreasing trend. This understanding becomes crucial for enhancing preparedness and planning strategies tailored to the specific challenges posed by extreme precipitation events in each study area. Furthermore, the identified patterns align with research conducted by Bohlinger (2018); Pokharel et al. (2020); Shrestha and Sheikh (2008), emphasizing the significance of regional variability in extreme precipitation trends and supporting the broader scientific discourse on climate resilience and adaptation.

4.2. Extreme wind and its trend

The analysis of extreme wind values in different study blocks reveals distinct patterns across the regions (Fig. 6. The Block 1 exhibits the highest maximum extreme wind value, reaching 1.963 m/s, accompanied by a significant positive trend of 0.0026 m/s per year. This indicates a pronounced increase in extreme wind events, highlighting the potential for heightened risks in the East Block.

In contrast, the Block 2, displays a lower maximum extreme wind value of 1.278 m/s, accompanied by a smaller positive trend of 0.0016 m/s per year, suggesting a gradual increase in extreme winds over time. The West Block demonstrates a slightly higher maximum extreme wind value of 1.627 m/s, but with a negligible negative trend of -9.31e-05 m/s per year, indicating a possible stabilization or decrease in extreme wind events. The Block 4, shows the lowest maximum extreme wind value of 1.368 m/s, with a modest positive trend of 0.00053 m/s per year, implying a moderate rise in extreme wind events. These findings provide valuable insights into the spatial variability and trends of extreme wind patterns, enabling a better

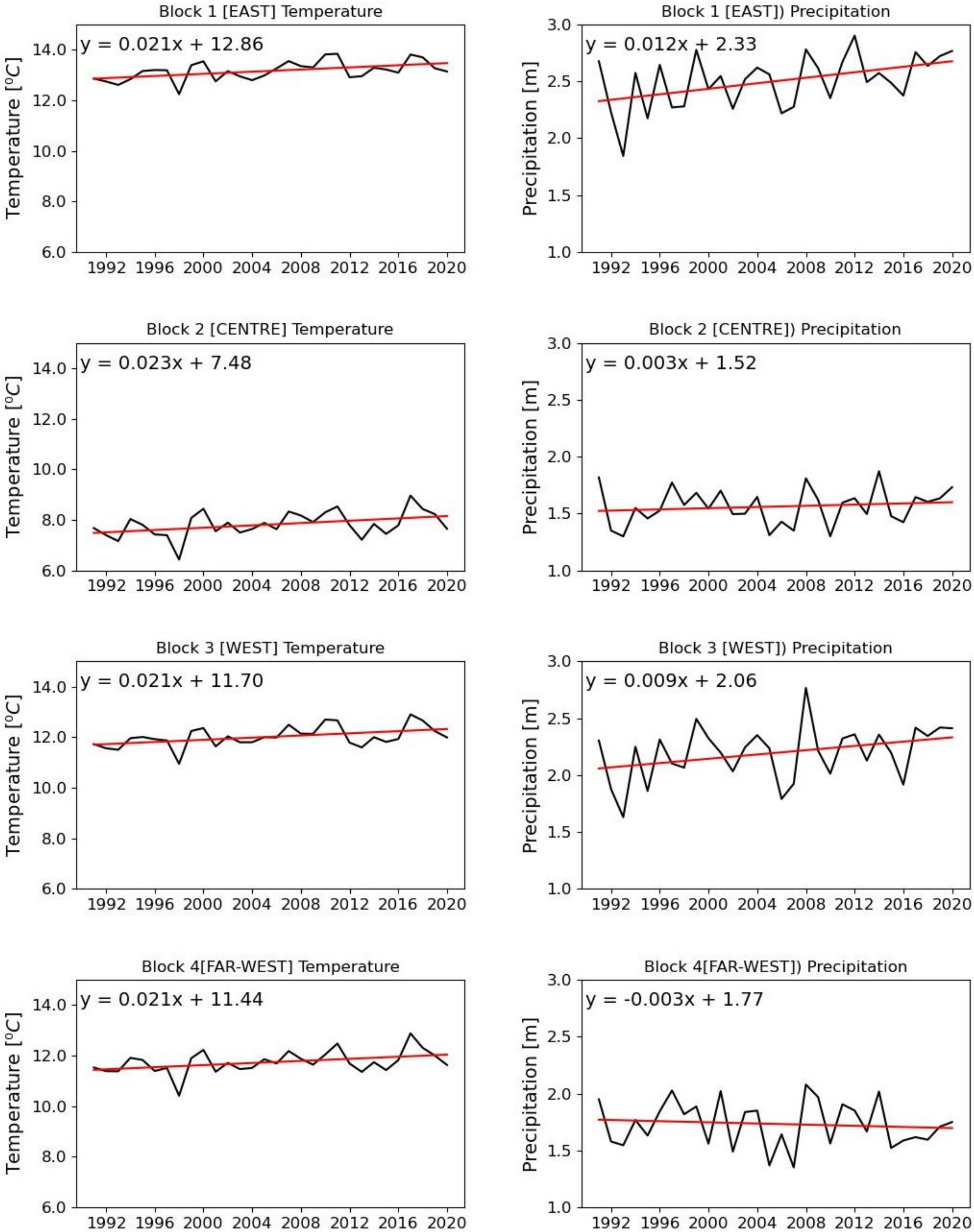

Figure 4. Temperature and precipitation trend with regression equations for different study blocks in the study area.

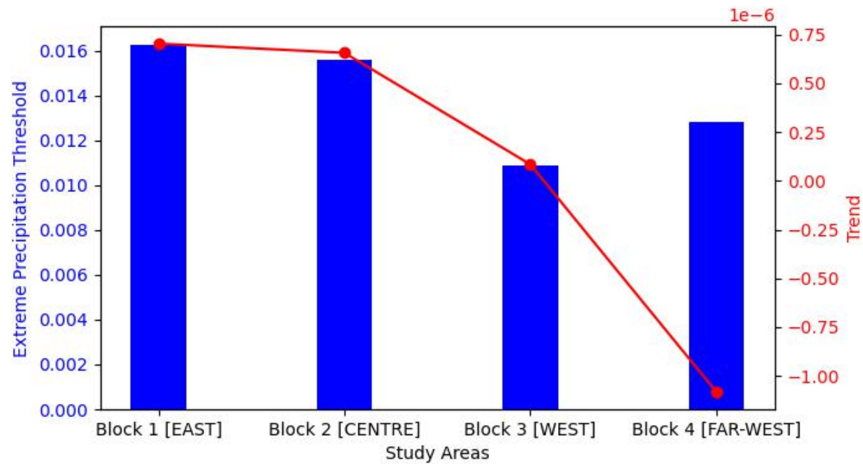

Figure 5. Extreme precipitation threshold and extreme precipitation trend in the study area. Units are in meters.

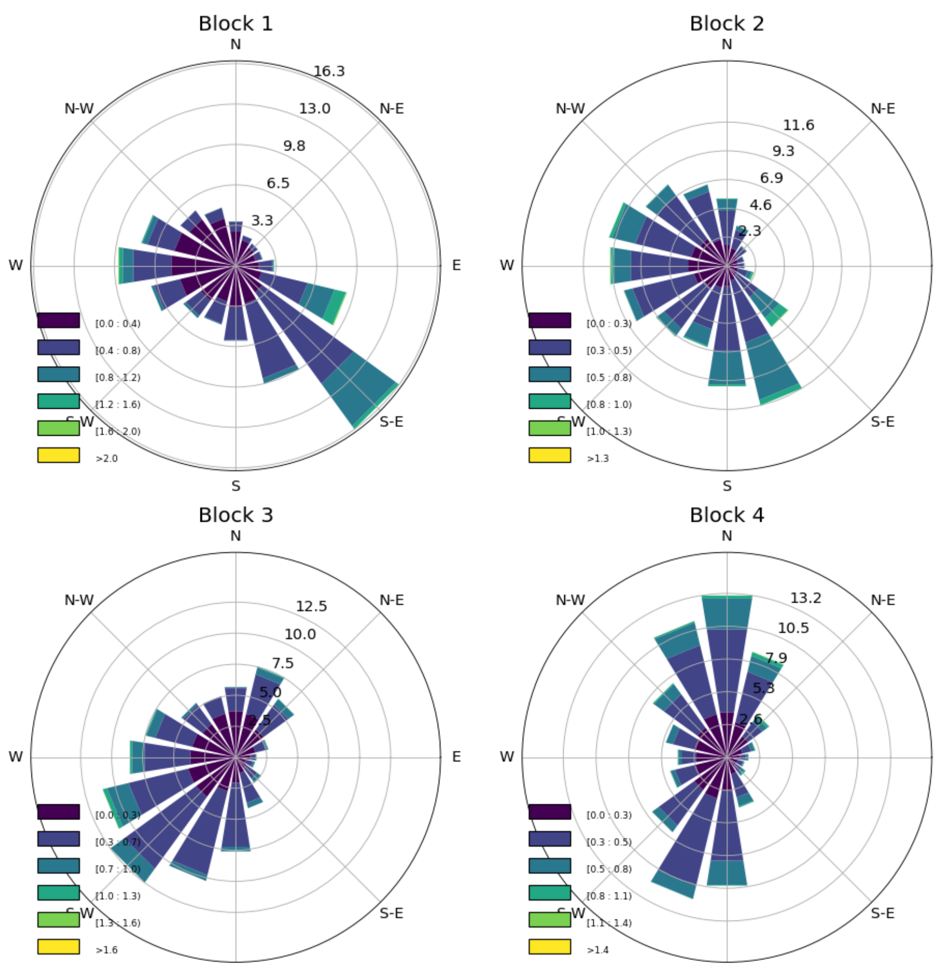

Figure 6. Wind rose diagram for four study blocks.

understanding of the potential risks and their implications for the respective study blocks.

The analysis of wind direction (Fig. 6) in different blocks reveals distinct patterns. In the Block 1, the prevailing wind direction is predominantly from the south-east. Moving to the center block, winds flow from the south-east to north-west. In the Block 3, the primary wind direction shifts to the south-west. Notably, the Block 4 exhibits a unique wind pattern, with winds mostly originating from the north.

5. Conclusions

The comprehensive analysis of temperature and precipitation patterns across distinct blocks in Nepal sheds light on the diverse regional climate variations. The East Block consistently experiences higher temperatures and receives the maximum amount of rainfall, marked by the influence of the summer monsoon. In contrast, the Block 3 (West) exhibits the lowest temperatures and less precipitation, contributing to a unique climatic and ecological setting.

The spatial variability in climate characteristics becomes evident as study were carried out from east to west, with the central (Block 1) and western regions (Block 2) transitioning to a more arid regime, influenced by the rain shadow effect of the Himalayas. The Far Western (Block 4) stands out with a climate that differs from both the eastern and western extremes.

Examining the temperature and precipitation trends over a 30-year period reveals a gradual warming trend across all four regions, while precipitation trends vary. The East and Centre Blocks show an increasing trend, while the Far Western Block indicates a slight decrease in precipitation. The Western Block demonstrates a relatively stable precipitation trend.

The analysis of extreme precipitation values and trends emphasizes the need for region-specific preparedness and planning. Spatial variability in extreme wind patterns further underscores the unique risks associated with each study block. The prevailing wind directions, as depicted in the wind rose diagram, exhibit distinct patterns across the blocks, highlighting the influence of local topography and geographical features.

Understanding these climate dynamics and trends is crucial for informed decision-making, especially in the context of climate change. The findings contribute valuable insights for policymakers, planners, and researchers, facilitating adaptation strategies and risk mitigation measures tailored to the specific challenges posed by the diverse climate patterns observed in different regions of Nepal.

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