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Unveiling Karnataka's Atmospheric Dynamics: A Comprehensive Study on Vapor Pressure Deficit

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Abstract

In numerous agricultural domains, primary factors contributing to diminished yield encompass elevated temperatures and inadequate water availability. Moreover, the water equilibrium within plants is significantly influenced by the escalating atmospheric Vapor Pressure Deficit (VPD), culminating in adverse effects on growth and productivity (1). The comprehensive evaluation of VPD in Karnataka over the preceding 35 years has been accomplished through multidimensional data analysis. Geospatial and temporal scrutiny of VPD was conducted employing the Mann-Kendall analysis, thereby corroborating its trends via Z-score, P-value, and Sen-slope measurements. This investigation aims to delineate the trajectory of VPD over the 35 years (1986-2020) in Karnataka, employing a multidimensional approach. As per the findings, notwithstanding seasonal fluctuations in VPD contingent upon vegetation dynamics in Karnataka, the overarching trend of annual VPD has exhibited a declining trajectory over the past three and a half decades.

Keywords: Multidimension; SpatioTemporal; VPD; MannKendall - S' Slope; PValue; Z Score

Introduction

As a cornerstone of societal structure and economic vitality, agriculture is paramount in alleviating poverty within burgeoning economies. Despite the pronounced influence of climate and weather risks on agricultural output, existing insurance schemes exhibit suboptimal market penetration and remain heavily reliant on governmental subsidies. Notably, adverse weather phenomena contribute substantially, accounting for 70% to 90% of crop loss [(1)] . The principal environmental factors identified to exert substantial influence on plant productivity and the quality of numerous cultivated crops are elevated temperatures and drought-induced stress [(2)] . During the vegetative phase, a VPD falling within the range of 0.8 to 1.1 kilopascals (kPa) is commonly perceived as optimal; conversely, in the flowering stage, a VPD range spanning from 1.0 to 1.5 kPa is frequently deemed as ideal.

Farmers employ the VPD as a technique to assess humidity levels within controlled environments such as greenhouses, facilitating the evaluation of its impact on plant growth and developmental processes. VPD computation involves quantifying the pressure differential between the atmospheric water vapor content and the air's saturation threshold, representing the maximum amount of water vapor the air can hold at its existing temperature. Additionally, the term "dew point" is synonymous with the point of complete saturation[3] . Elevated VPD levels, typically occurring mid-day and exacerbating plant water stress, significantly impact various aspects of plant physiology including photosynthesis, growth, and yield. The intensified atmospheric water demand affects plant hydraulic status, with stomatal behavior serving as the primary determinant. Regulating stomatal conductance during periods of high VPD enables control over transpiration, thereby facilitating water conservation and sustaining plant growth, particularly crucial during the later stages of the season when drought prevails. Numerous crop species, including wheat (*Triticum aestivum L.*), maize (*Zea mays L.*), sorghum (*Sorghum bicolor L.*), soybean (*Glycine max L.*), peanut (*Arachis hypogaea L.*), cowpea (*Vigna unguiculata L.*), chickpea (*Cicer arietinum L.*), and lentil, have demonstrated adaptations to mitigate the impacts of high VPD, notably through their response to transpiration reduction limits (TRlim)[2] .

The agricultural sector in Karnataka relies significantly on the southwest monsoon due to its geographical location within a tropical monsoon climate zone[4] . Karnataka, constituting the eighth-largest state in India by land area, spans approximately 2,190 square kilometers, representing 6.3% of the nation's total territory[4] . Owing to the expansive geographic expanse, VPD undergoes seasonal fluctuations influenced by changing climatic patterns, which have also evolved over the past 35 years. The employment of multidimensional data extracted from terra climate spanning three and a half decades has afforded a novel perspective on VPD dynamics within Karnataka.

Study Area

Karnataka (Figure 1), located on the western coast of India at coordinates 12.97°N 77.50°E, boasts Bengaluru as its capital city. It shares its borders with Goa and Maharashtra to the north, Telangana to the east, Tamil Nadu to the southeast, Kerala to the south, and the Arabian Sea to the west. The state's topography is characterized by four distinct physiographic zones: the coastal plain, hill ranges, the Karnataka Plateau to the east, and the black-soil tract to the northwest[5] . The total land area of Karnataka spans 2,190 square kilometers. As per the 2011 Census data, the state's population amounts to 96,21,551 individuals in total[6] . Karnataka comprises 31 administrative districts organized into four distinct administrative regions.

Karnataka experiences a subtropical climate characterized by four distinct seasons: the southwest monsoon (June through September), the post-monsoon (October through December), and winter (January and February). Daily temperatures range from the mid-80s F (around 30 °C) in winter to the low 100s F (about 40 °C) in summer. Precipitation varies across the state, with drier regions receiving approximately 20 inches (500 mm) of annual rainfall, while the wettest coastal areas receive up to 160 inches (4,000 mm). The majority of rainfall occurs during the southwest monsoon, with a lesser contribution from the northeast monsoon during the post-monsoon season. Winter is notably dry. Agriculture forms the backbone of the state's economy, with rice being the primary food crop cultivated on the coastal plain, followed by sorghum (jowar) and millet (ragi). Sugarcane is the principal cash crop, complemented by cashews, cardamom, betel (areca) nuts, and grapes. The Western Ghats' cooler slopes are conducive to coffee and tea plantations, making Karnataka one of the country's significant coffee-producing regions. Irrigation infrastructure in the eastern region facilitates the cultivation of sugarcane, rubber, and fruits such as bananas and oranges. Cotton, oilseeds, and peanuts thrive in the black soil of the northwest (groundnuts)[4,6] .

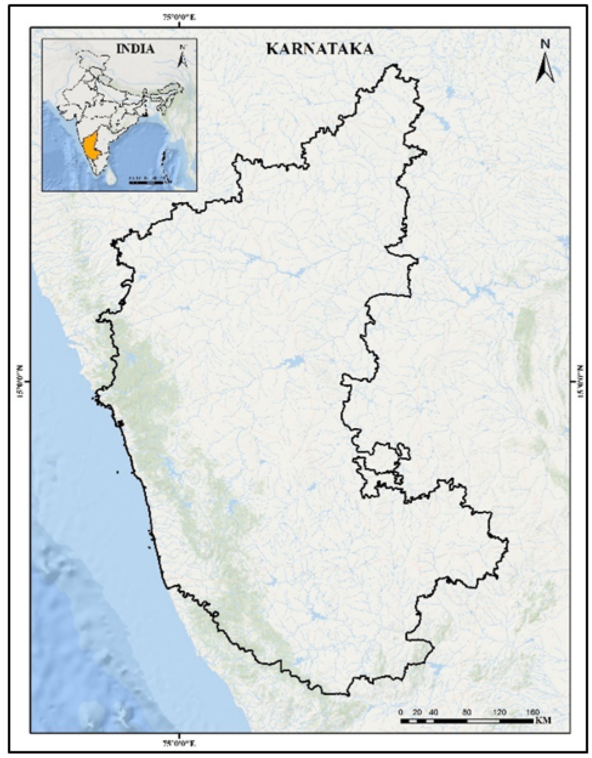

Fig. 1. Location map of Karnataka

Methodology

Over 35 years, VPD data for Karnataka was obtained from terra climate with a spatial resolution of 4km. The Mann-Kendall methodology was utilized to analyze VPD trends regionally and temporally, employing multidimensional data. A comprehensive methodology detailing this approach is depicted in Figure 2 .

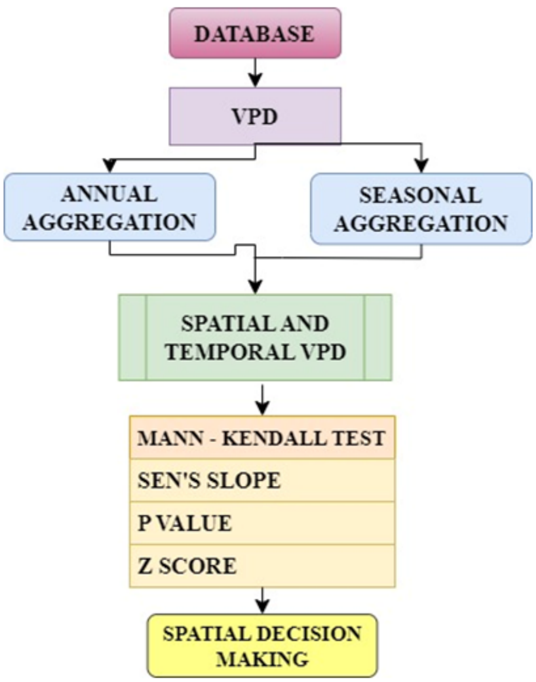

Fig. 2. Flow chart of Spatio-temporal analysis of VPD, Karnataka

Mann-Kendall

To ascertain whether a dataset exhibits a discernible trend of either increasing or decreasing values over time, as well as to determine the statistical significance of such trends, researchers commonly employ the Mann-Kendall statistical test for trend analysis[(7)] . The Mann-Kendall (MK) test, introduced by Mann (1945), Kendall (1975), and Gilbert (1987), serves as a statistical tool to ascertain whether a particular variable exhibits a monotonic trend of either increase or decrease over time. A monotonic trend, which may not necessarily be linear, indicates a consistent growth or reduction in the variable across time intervals. Unlike parametric linear regression analysis, which assesses whether the slope of the predicted regression line differs significantly from zero, the MK test offers a non-parametric alternative. It does not hinge on the assumption of normally distributed residuals from the fitted regression line. According to Hirsch, Slack, and Smith (1982), the MK test is particularly useful for identifying significant or substantial changes in data series, providing a means to quantify such alterations. Thus, it is most appropriately regarded as an exploratory analytical approach.

The Mann-Kendall (MK) test relies on several key hypotheses:

i) The measurements collected over time are independent and stem from an identical distribution in the absence of any trend. This assumption of independence entails no serial time correlation among the observations.

ii) The observations conducted over time accurately reflect the prevailing conditions at the time of sampling. The methodologies employed for sample collection, handling, and measurement yield objective and representative observations of the underlying populations across different time points.

iii) The distribution of measures does not necessarily need to follow a normal distribution, and any trend observed need not be linear. Even in scenarios involving missing data or values below detection limits (LD), the MK test can still be computed, albeit with potential performance degradation. To maintain the assumption of independence, there should be a significant time gap between samples to ensure no correlation between measurements taken at distinct time intervals.

Calculations:

The Mann-Kendall (MK) test aims to assess whether to reject the null hypothesis (H_0) or accept the alternative hypothesis (Ha), where H_0 implies the absence of a monotonic trend.

Ha posits the presence of a monotonic trend. Initially, the MK test assumes H_0 to be true, requiring the data to convincingly support the rejection of H_0 and acceptance of Ha beyond a reasonable doubt (Design Trend Mann-Kendall, n.d.).

Three bands of the Mann-Kendall test were examined in this study:

Sen's slope

Simple linear regression is a widely used method for detecting linear trends, but it relies on the assumption of residual normality. However, Viessman et al. (1989) noted that many hydrological variables exhibit significant right skewness, deviating from a normal distribution due to natural influences. Consequently, Sen's (1968) slope estimator has emerged as a valuable alternative for establishing linear relationships. Sen's slope offers advantages over the traditional regression slope by being less susceptible to large errors and outliers in extensive datasets. The mean of all pairwise slopes for each point pair within the dataset represents Sen's slope. Equation 1 below can be used to calculate each slope.

Mij : Yj-Yi/j-1 (1)

Where,

I = 1 to n –1,

j = 2 to n,

In a time series comprising n values of Yj, where j >i, the number of estimates for the slope is determined by N = n(n-2)/2. The average of these N slope values represents the slope of the Sen Estimator. A positive trend observed in Sen's slope indicates an upward trend, whereas a negative trend signifies a downward trend[8] .

Value. The p-value serves as a metric to evaluate the strength of evidence supporting the null hypothesis. Lower p-values indicate stronger evidence against the null hypothesis. In the context of deciding whether to accept or reject the null hypothesis for Kendall's coefficient of concordance:

H0: The appraiser agreement is due to chance.

H1: There is no chance behind the appraiser agreement.

Comparing the p-value to the significance level, typically set at 0.05, helps determine the association between ratings. A significance level of 0.05 implies a 5% risk of erroneously concluding an association between ratings when none exists.

If the p-value is less than or equal to the significance level, the null hypothesis is rejected, suggesting a correlation between appraiser ratings. Conversely, if the p-value exceeds the significance level, the null hypothesis cannot be ruled out due to insufficient evidence, indicating that chance may be responsible for the appraiser agreement (Kendall's coefficients for Attribute Agreement Analysis - Minitab).

Z-Score

The Z-score, also referred to as the standard score, quantifies the deviation of a specific data point from the mean in terms of standard deviations. The mean is computed by summing all values within a group and dividing by the total number of items. To calculate the Z-score, subtract the mean from each data point and then divide the result by the standard deviation. A Z-score of zero indicates equivalence between the data point and the mean. Negative Z-scores occur when data points fall below the mean, while a Z-score of one signifies that the point is one standard deviation above the mean. In most sizable datasets, approximately 99% of values have Z-scores ranging from -3 to 3, denoting that they fall within three standard deviations of the mean. Analysts utilize Z-scores to compare data to a standard, enhancing the significance of the data. A Z-score of 0 suggests that the analyzed data point is average and within the expected range. A Z-score of 1 indicates a deviation of one standard deviation from the mean, with -1 representing a deviation of one standard deviation below the mean. Higher Z-scores suggest greater deviation from the norm in the data. In investment analysis, a higher Z-score suggests that the anticipated returns are likely to exhibit greater variability or divergence from the expected values(https://www.investopedia.com/ask/answers/021115/what-difference-between-standard-deviation-and-z-score.asp).

Result & Discussion

Spatial analysis

Annual average VPD of Karnataka

There has been a decrease of approximately 0.0026 in VPDover the past year, with minimal changes otherwise. In 2021, the VPD recorded was 1.16, while 2016 marked the highest VPD value at 1.50. This indicates that the surrounding air's humidity levels are too elevated to facilitate efficient transpiration, hindering the plant's ability to release moisture adequately. Consequently, the plant's metabolic processes may decelerate, rendering it more susceptible to diseases. Areas with high VPD exhibit drier air (Figure 3), potentially leading to excessive evapotranspiration rates from the leaf stomata, ultimately resulting in leaf desiccation. This represents another adverse consequence of elevated VPD levels (Figure 4).

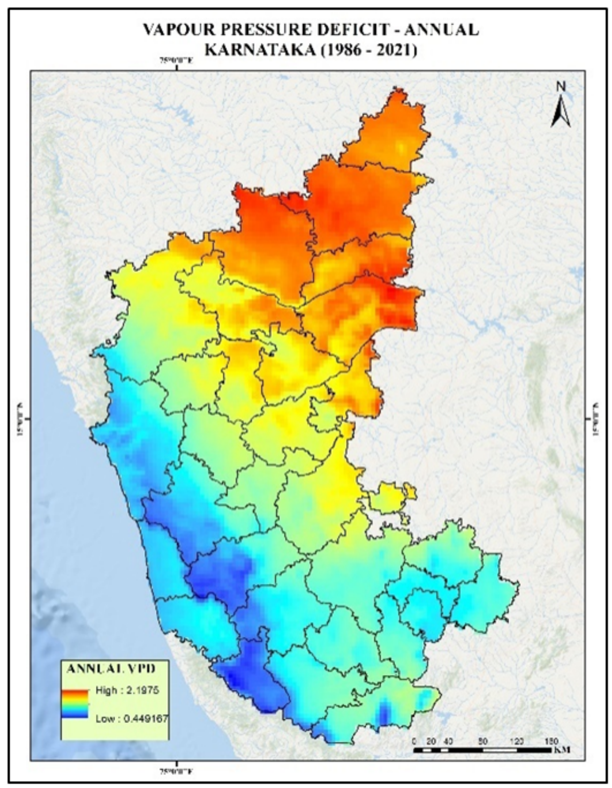

Fig. 3. Annual average VPD in Karnataka

Seasonal analysis of VPD in Karnataka

The seasonal variation in VPD is given in a graphical representation (Figure 9).

Summer. During the summer months (Figure 5), there is a decline of 0.0056 percentage points in VPD. As per

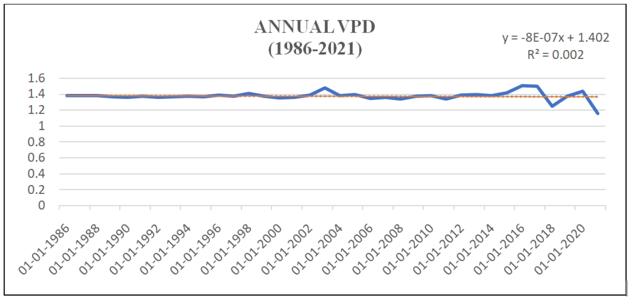

Fig. 4. Graphical representation of annual average VPD in Karnataka

the Indian Meteorological Department (IMD), the summer season extends from March to May. In 2007, the VPD reached its lowest level at 1.38, whereas it peaked in 2017 at 2.40. This suggests that an excess of moisture in the air can potentially lead to desiccation in plants up to a certain extent, rendering them more susceptible to diseases. Over ten years, there exists a variation exceeding 0.01 percent between the highest and lowest VPD values.

Monsoon. According to the IMD, the monsoon season extends from June to September, exhibiting a mild declining trend (OD = 0.0063). The lowest VPD value was recorded in 2018 (0.63), while the highest occurred in 2013 (0.89). With relatively minimal fluctuations in VPD (Figure 6), it becomes evident that the monsoon season significantly benefits plant growth compared to the Kharif season. During the monsoon, crops can thrive with ample nutrient supply and are less susceptible to diseases.

Post-Monsoon. In the post-monsoon period (Figure 7) spanning from October to November, the trend remains consistent at 0.0018. The peak VPD occurred in 2016 (1.41), while the lowest was observed in 2019 (0.77). Despite the unchanged trend, there exists a notable 1.4 percent difference between the highest and lowest points over three years. This illustrates how the elevated VPD levels during the post-monsoon period of the Rabi cropping seasons lead to reduced transpiration rates in plants. Consequently, this phenomenon may give rise to various disorders affecting plant growth and development.

Winter. Following the IMD classification, the Winter season spans from December to February, characterized by typically substantial atmospheric moisture levels. There is a rising trend of 0.0013 points during this period. The lowest VPD value was recorded in 2020 (1.37), while the highest occurred in 2016 (1.75). With VPD levels exceeding 1.0 kPa, the air retains considerable moisture content. Consequently, there exists a significant gradient between the air and the plants, facilitating transpiration and eventual desiccation of the plants (Figure 8).

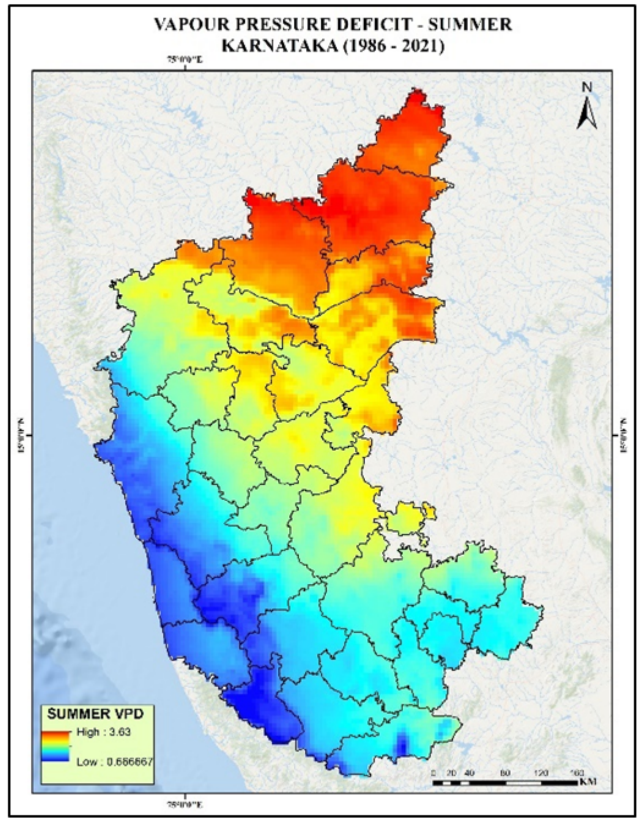

Fig. 5. Summer average of VPD in Karnataka

Temporal analysis of VPD in Karnataka

The temporal analysis of VPDis conducted using the Mann-Kendall test, which incorporates parameters such as the Sen slope, P-value, and Z-score (**Supplementary Table 1**).

Annual

Sen Slope

Sen's slope, depicted in Figure 10 , serves as a critical indicator for assessing the strength of trends within a dataset. Notably, Kolar exhibits a Sen's slope of 0.001913, while Dakshina Kannada demonstrates a value of -0.0016. This disparity can be attributed to the geographical characteristics of these regions within Karnataka. Kolar, situated in the eastern part of Karnataka, experiences higher temperatures and lower VPD, contributing to the observed increase in VPD. Conversely, Dakshina Kannada, located along the Western Ghats, features distinct environmental conditions, resulting in a decrease in VPD.

Value

In Figure 11 , P-values exhibit a lower value in Bengaluru (Urban) at 0.011024, contrasting with a higher value in Koppal at 0.82914, indicating a more significant trend in

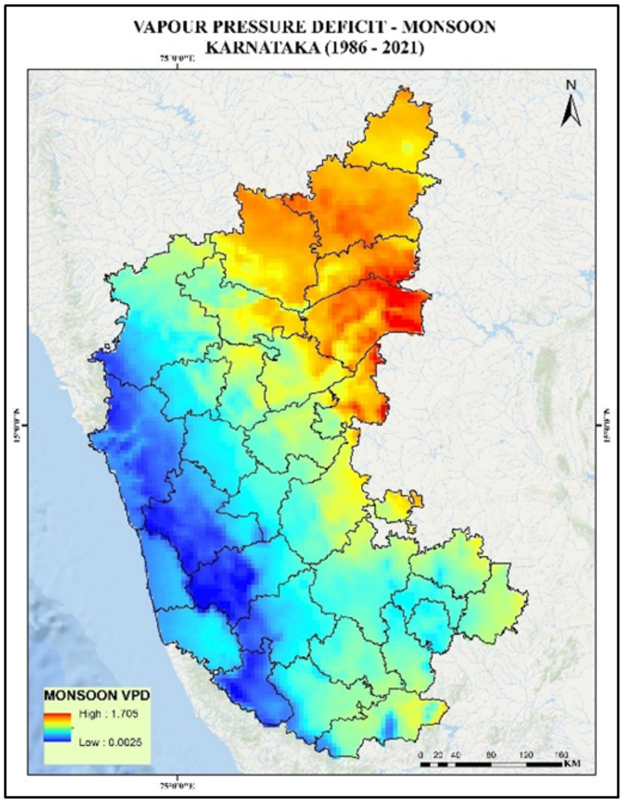

Fig. 6. Monsoon average of VPD in Karnataka

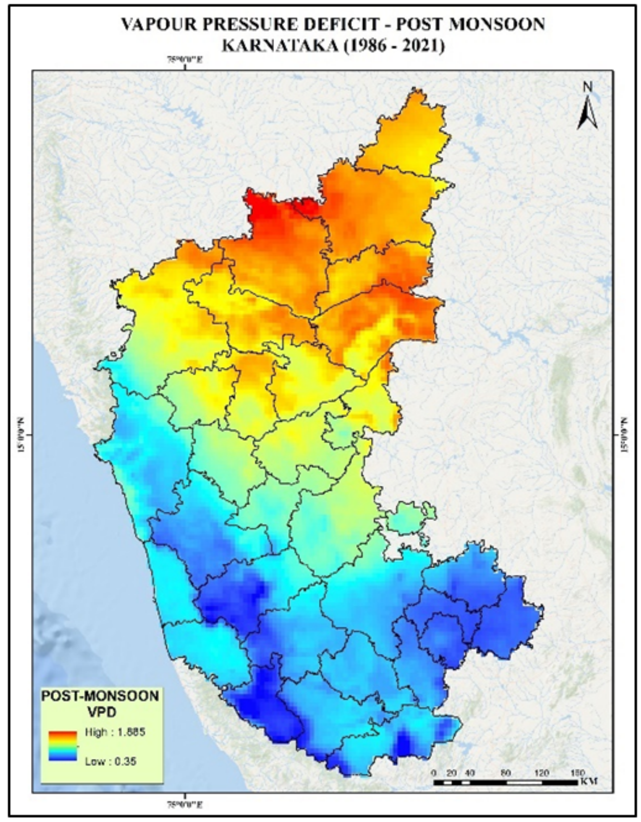

Fig. 7. Post-monsoon average VPD in Karnataka

VPD. The heightened relevance of Bengaluru, being a major city, contributes to the observed trend, as urbanization leads to decreased vegetation coverage and subsequent drying out of plants. Conversely, Koppal, situated in Karnataka's central-eastern region, displays a consistently high P-value, suggesting a relatively stable level of VPD in the area.

Score

By utilizing the Z-score (Figure 12), it becomes feasible to discern the apparent trend within a time series. Notably, the readings vary from -1.69801 in Dakshina Kannada to 2.552466 in Bengaluru (Urban), indicating a shift from a negative to a positive trend. Through the interpretation of the Z-score and P-value, it can be inferred, with a confidence level of up to 31 percent, that the trend in Karnataka over 35 years has exhibited a substantial increase.

Summer

Sen's Slope

In Figure 13 Dakshina Kannada registered the lowest Sen's slope value of -0.00246, while Bengaluru (Rural) recorded the highest at 0.002414. The observed magnitude of change implies a shift of -0.004 percent, indicating a significant reduction in VPD during the summer season over the past 35 years.

Value

Ballari exhibits a significance level of 0.914925, whereas Dakshina Kannada demonstrates the least significant P-value (Figure 14) at 0.111382. This discrepancy highlights how seasonal variations influence vegetation dynamics. The annual analysis of P-values indicates a rising trend with an 80% confidence level. However, focusing solely on the summer months, the confidence level increases to 53%, underscoring the seasonal vegetation dynamics within Karnataka.

Z-score

The trend in VPDhas transitioned from the western to the eastern regions of Karnataka, as evidenced by Kolar recording a value of 1.536759 and Dakshina Kannada registering -1.6088 (Figure 15). This positive trend illustrates a high significance level and an upward trajectory in VPD.

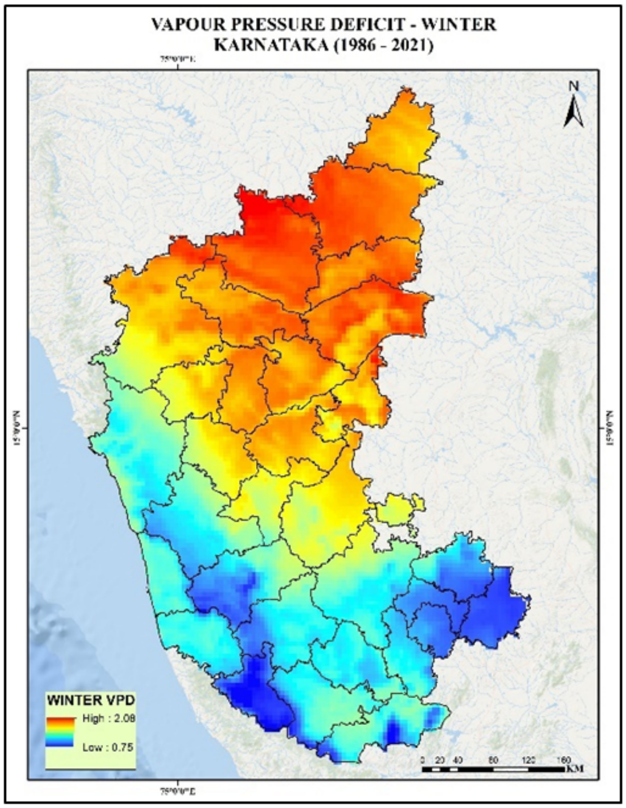

Fig. 8. Winter average VPD in Karnataka

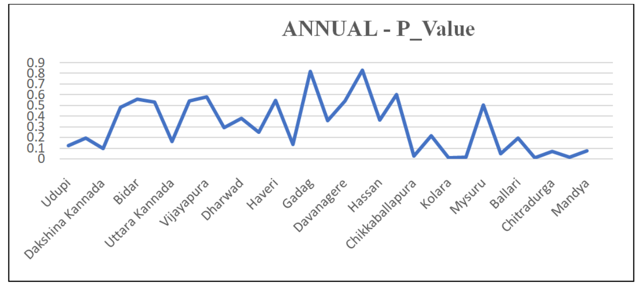

Fig. 11. P Value of annual average VPD of Karnataka

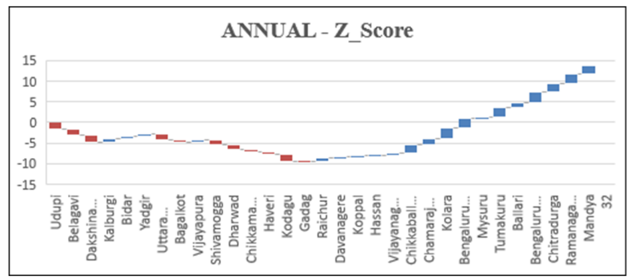

Fig. 12. Z Score of annual average VPD of Karnataka

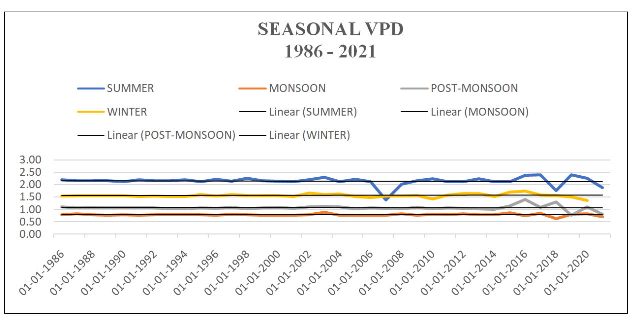

Fig. 9. Graphical representation of seasonal variations of VPD in Karnataka

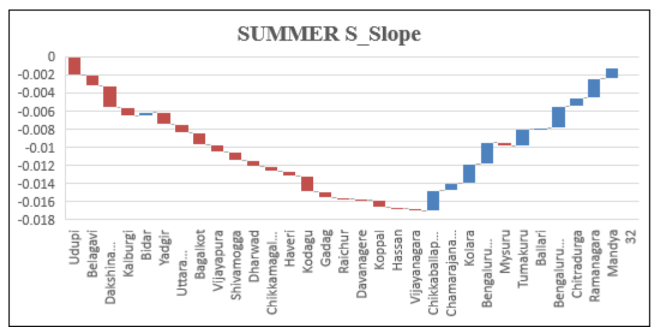

Fig. 13. Sen's Slope of Summer average of VPD in Karnataka

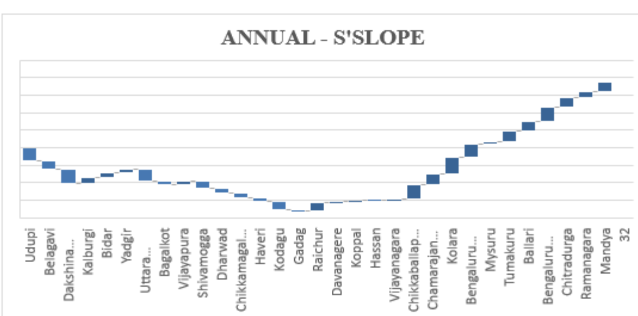

Fig. 10. Sen's slope for annual average VPD of Karnataka

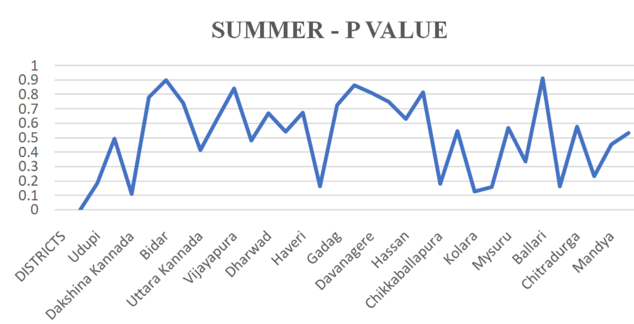

Fig. 14. P Value of Summer average of VPD in Karnataka

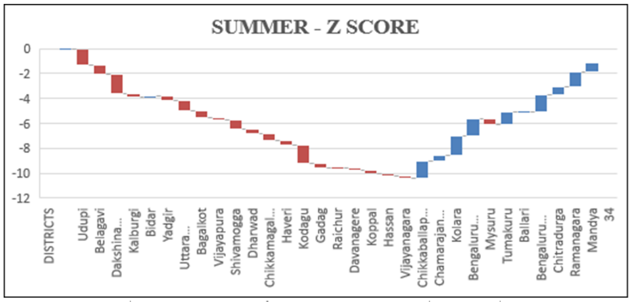

Fig. 15. Z Score of Summer average VPD in Karnataka

Monsoon

Sen's slope

The magnitude of change (Figure 16 District-level) has increased from -0.00076 in Bagalkot, the lowest recorded value, to 0.001967 in Kolar, the highest observed value. This significant variation indicates a decrease in VPDfrom the northern to the southern regions of Karnataka during the monsoon season.

Value

In Figure 17 , Kolar demonstrates a P-value significance of 0.011382, whereas Chitradurga displays a significance of 0.890645, accompanied by a confidence level of 49%. This observed trend indicates a growth in significance from the southeastern to the central-eastern regions of Karnataka.

Score

The trend is most pronounced in Ramnagarama, recording a value of 2.700149, while Bagalkot exhibits the lowest trend at -1.11095 (Figure 18). With a confidence level of 49%, this trend demonstrates an upward trajectory from the northern to the southern regions of Karnataka.

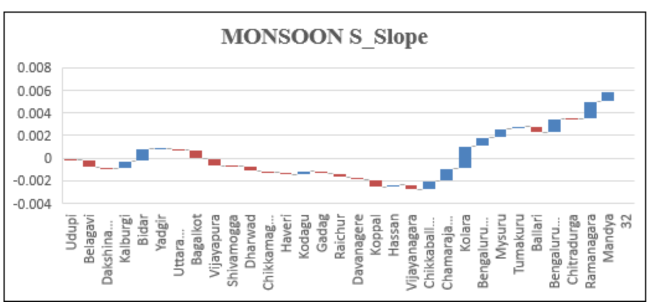

Fig. 16. Sen's Slope of Monsoon average of VPD in Karnataka

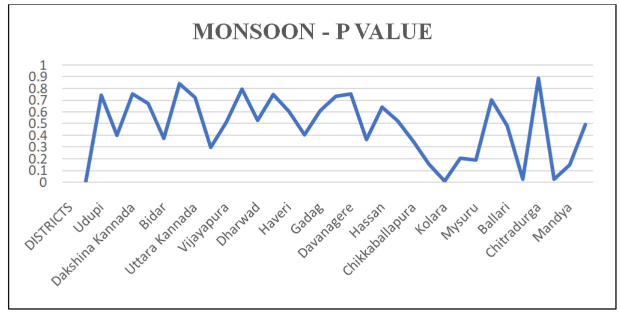

Fig. 17. P Value of Monsoon average of VPD in Karnataka

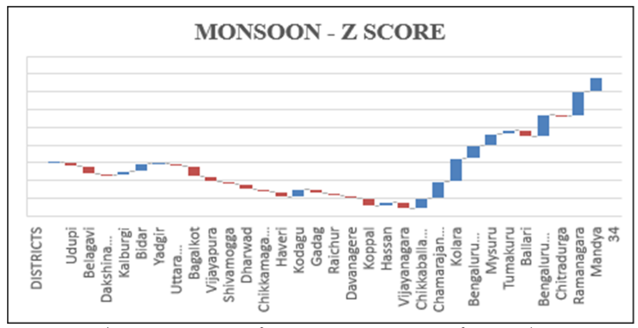

Fig. 18. Z Score of Monsoon average VPD of Karnataka

Post-Monsoon

Sen's slope

In Figure 19 Shivmogga exhibits a magnitude of -0.00271, while Raichur displays a magnitude of 0.001045. This suggests an expansion in the extent of VPDfrom the central-eastern to the northeastern region of Karnataka.

Value

Shivamogga exhibits a significance level of 0.066591, while Bengaluru (Urban) demonstrates a significance level of 0.886254 (Figure 20). This observation suggests an increase in VPD from the western to the southeastern region of Karnataka, with a 39 percent level of relevance.

Score

This indicates an upward trend of 0.897879 in Raichur, while Shivamogga exhibits a downward trend of approximately -1.89769 (Figure 21). This observation illustrates a decrease of -2.79 percent in VPD.Consequently, it suggests a shift in trend from the western to the eastern regions of Karnataka.

Winter

Sen's slope

Belagavi exhibits the lowest value of -0.00176, while Chitradurga demonstrates the highest value of 0.0028 for Sen's

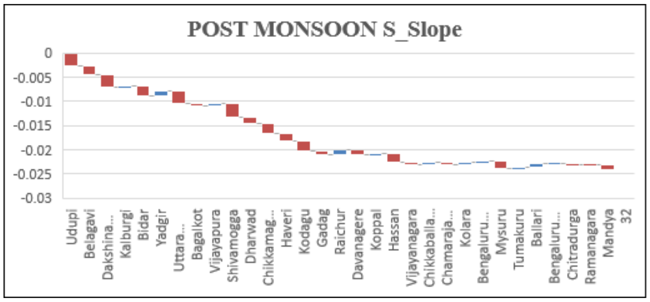

Fig. 19. Sen's Slope of Post Monsoon average VPD in Karnataka

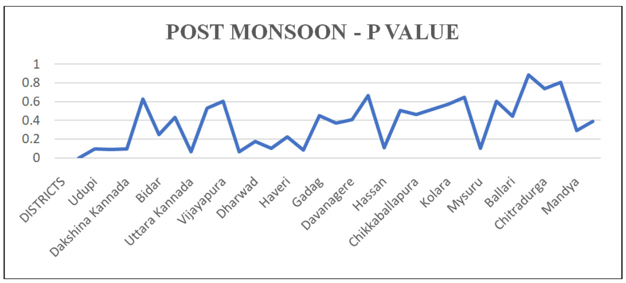

Fig. 20. P Value of Post monsoon average VPD in Karnataka

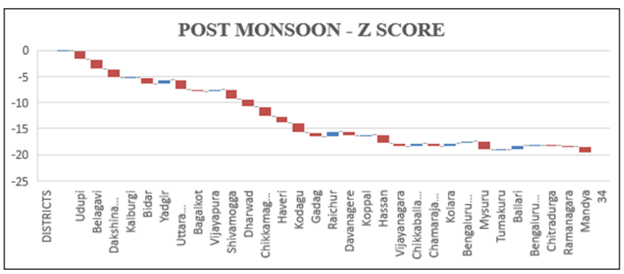

Fig. 21. Z Score of Post Monsoon average VPD in Karnataka

slope, indicating an increase in magnitude from the north-western to central-eastern regions of Karnataka (Figure 22).

Value

The P-value has shown improvement, with a confidence level of 34%, ranging from Mandya with the lowest value of 0.027734 to Dharwad with the highest value of 0.761554 (Figure 23). This trend signifies an increase in VPDfrom the southern to the northern regions of Karnataka.

Score

The trend has transitioned from the southern to the eastern regions of Karnataka, as evidenced by Mandya displaying the highest trend value of 2.296764 and Udupi recording the lowest at -1.51617 (Figure 24). This analysis suggests an elevation in VPDduring the winter season in Karnataka over 35 years, with a confidence level of 34 percent.According to the temporal analysis of VPDin Karnataka, the monsoon season is characterized by a consistent level of VPD, indicating that the air retains a considerable amount of moisture. This phenomenon results in a pronounced gradient between the air and the nearby vegetation, facilitating transpiration processes in plants. However, despite the favorable moisture levels, this period coincides with the Kharif cropping season, necessitating careful consideration to prevent plant desiccation. Conversely, during the winter season, VPD tends to be low, potentially leading to heat injury in plants. The reduced VPD levels result in elevated leaf temperatures, as transpiration rates decrease, disrupting the normal metabolic functioning of plants. Consequently, plants become more susceptible to infectious diseases during this period.

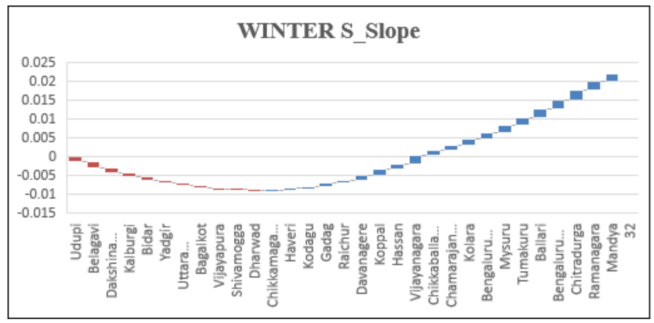

Fig. 22. Sen's Slope of Winter average VPD in Karnataka

This nuanced understanding of VPD dynamics during different seasons underscores the importance of strategic planning and management practices in agricultural systems. Proactive measures must be implemented to optimize crop yield and mitigate the risks associated with fluctuations in VPD, particularly during critical growth stages such as the monsoon and winter seasons. Such insights can inform targeted interventions aimed at enhancing crop resilience and ensuring sustainable agricultural practices in Karnataka.

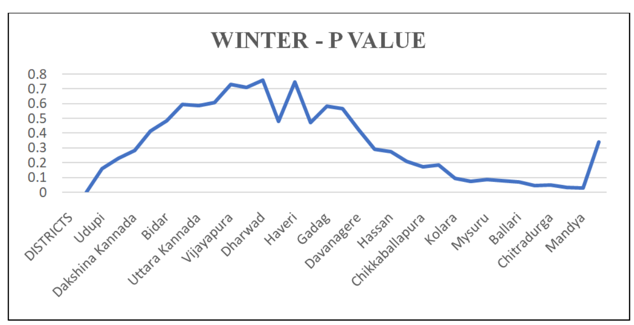

Fig. 23. P Value of Winter average VPD in Karnataka

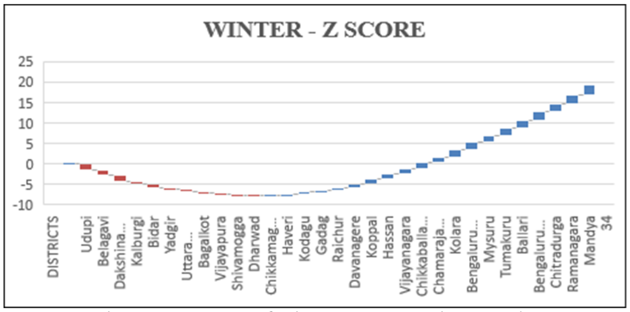

Fig. 24. Z Score of Winter average VPD in Karnataka

Conclusion

In this research, a comprehensive analysis of the 35-year trend of VPDin Karnataka was conducted using multidimensional data. The findings revealed a discernible upward trend in VPD across both seasonal and annual assessments, indicating fluctuations in the ideal VPD levels within the region. This underscores the dynamic nature of vegetation dynamics, which are influenced by both temporal and spatial variations in environmental factors. The seasonal analysis unveiled heightened plant metabolism and increased transpiration rates, suggesting favorable growth conditions and optimal physiological functioning. Conversely, the annual assessment depicted a concerning deterioration in VPD patterns over the past three and a half decades. This alarming trend signals a progressively challenging environment in Karnataka, characterized by elevated risks of plant desiccation and decay, leading to a notable decline in vegetation coverage.

Overall, these findings underscore the complex interplay between geographical and temporal dynamics in shaping VPD trends and their implications for vegetation health. The observed shifts in VPD patterns highlight the urgent need for targeted interventions to mitigate the adverse effects of environmental stressors on Karnataka's vegetation and promote sustainable ecosystem resilience in the face of ongoing climatic changes.

As per the temporal analysis conducted across various seasons, a notable increase in VPD trends during the monsoon season has been observed, indicating favorable conditions for plant health and growth. Conversely, a decrease in VPD trends during the winter season suggests a slowdown in plant metabolism and reduced transpiration rates, contributing to stable physiological processes. This underscores the significance of VPD in facilitating enhanced plant growth within the state. While higher VPD levels offer certain advantages, such as promoting plant growth, they also pose risks of heat damage, leading to elevated leaf temperatures and potential environmental repercussions. Conversely, lower VPD levels indicate near-saturation air and excessive ambient humidity, hindering effective transpiration processes. Therefore, agriculturalists must carefully consider VPD levels during each growing season to optimize crop yields and mitigate adverse environmental impacts.

The insights gleaned from this study offer valuable recommendations for government authorities to enhance planning strategies and foster long-term sustainable growth in Karnataka. By incorporating VPD considerations into agricultural policies and practices, policymakers can better address the challenges posed by fluctuating environmental conditions and promote resilience within the agricultural sector.

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