Atmospheric Parameters and Their Influences on Precipitating Cloud Systems Over East Coastal Andhra Pradesh: A Decadal Analysis (2014–2023)

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ABSTRACT

This research provides a detailed understanding of the characteristics and processes governing precipitating cloud systems that are crucial for rainfall over the East Coastal districts of Andhra Pradesh (ECAP). By analyzing a diverse dataset including gridded precipitaion, temperature, pressure, and wind speed data from 2014 to 2023, the study seeks to uncover the complex interplay between atmospheric conditions, cloud microphysics, and precipitation development in this important region. In this study, we utilized multi-source data on aerosol, cloud properties, precipitation, and meteorological factors to investigate the impact of aerosols on precipitation efficiency (PE) over ECAP, where the differences between SW and NE monsoon were prominent. Because te ECAP, strategically located along the Bay of Bengal, receives rainfall from both the Southwest and Northeast Monsoons, and is significantly impacted by cyclonic disturbances. This paper investigates the spatiotemporal variability of rainfall, identifies dominant cloud types, and elucidates the atmospheric dynamics and thermodynamic structures conducive to heavy precipitation events. Furthermore, it explores the potential influence of aerosol-cloud interactions and other microphysical processes on precipitation efficiency. The findings contribute to a deeper understanding of ECAP's rainfall climatology, offering insights vital for improved hydrological forecasting, water resource management, and disaster preparedness in the face of a changing climate.

Keywords: Atmospheric Dynamics, Cloud Microphysics, Monsoon, Cyclonic Disturbances, and Rainfall Variability.

INTRODUCTION

Precipitating cloud systems are indispensable for water resources, agricultural productivity, and the overall health of ecosystems, particularly in regions like Andhra Pradesh where the agricultural sector is heavily dependent on rainfall. For instance, rice yields, a staple crop in the region, exhibit a direct correlation with observed rainfall and temperature patterns (Mall et al., 2006). East Coastal Andhra Pradesh possesses an extensive coastline, rendering it inherently susceptible to the multifaceted impacts of climate change, notably heatwaves, floods, and tropical cyclones originating from the Bay of Bengal (De et al., 2005). The Bay of Bengal is globally recognized as a major basin for the genesis of cyclonic disturbances, characterized by high mean precipitation, and significantly contributing to the dynamics of the Asian monsoon circulation (Goswami et al., 2006).

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Rainfall is a fundamental meteorological variable with profound implications for water resources, agriculture, and socio-economic well-being, particularly in a predominantly agrarian state like Andhra Pradesh (AP), India. The East Coastal districts of Andhra Pradesh (ECAP) (as shown in Fig.1) are a critical region in this context, susceptible to both water scarcity during deficient monsoon seasons and devastating floods during intense rainfall events, often associated with cyclonic activity in the Bay of Bengal. A comprehensive understanding of the precipitating cloud systems and the atmospheric processes that govern rainfall in this specific geographical area is crucial for effective planning and disaster mitigation. Precipitating cloud systems play a critical role in the hydrological cycle and are particularly important for monsoon-dependent regions like the East Coastal districts of Andhra Pradesh (Rao et al., 2019). Understanding the cloud processes and atmospheric drivers that govern precipitation is vital for improving forecasts and managing agricultural and water resources.

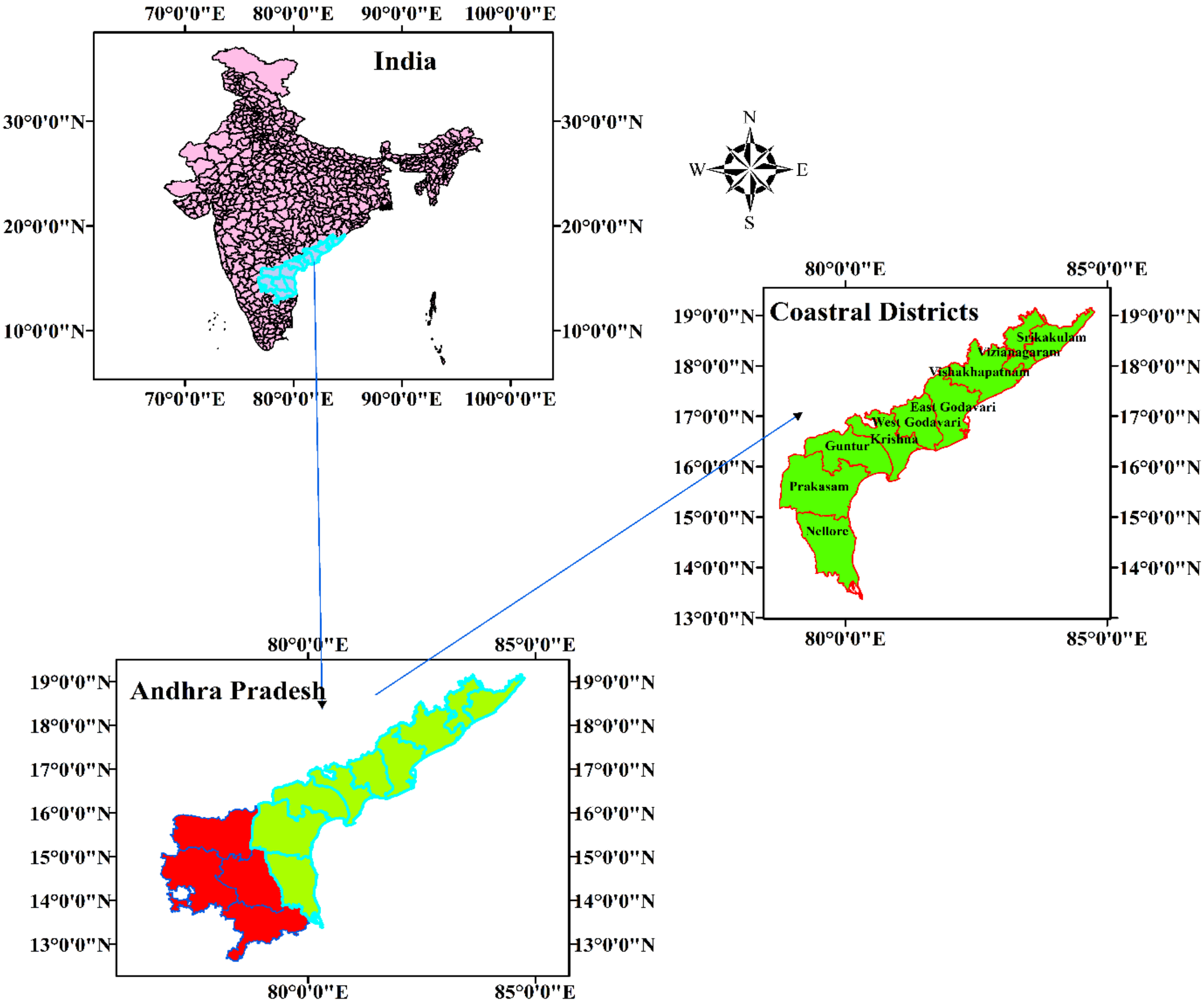

Fig.1 (a) India Map, (b) Andhra Pradesh Map, and (c) Map showing the East Coastal districts of Andhra Pradesh, located along the Bay of Bengal, include Srikakulam, Vizianagaram, Alluri Sitharama Raju, Visakhapatnam, Anakapalli, Kakinada, Konaseema, East Godavari, West Godavari,Eluru, Krishna, NTR, Guntur, Palnadu, Bapatla, Prakasam, and Nellore

This study undertakes a detailed decadal analysis spanning from 2014 to 2023, to provide a detailed understanding of the characteristics and processes that govern precipitation cloud systems crucial for precipitation in the East Coast of Andhra Pradesh (ECAP) region.

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To analyze the spatiotemporal variability of precipitation, identify the dominant cloud types, and elucidate the atmospheric dynamics and thermodynamic structures conducive to intense precipitation events.

To explore the influence of cloud microphysical processes and their interactions with aerosols on the efficiency of water vapor conversion into precipitation.

To investigate the role of atmospheric pressure systems, especially low-pressure areas and cyclonic circulations, as the main organizers of significant precipitation events.

To understand how wind patterns, including both speed and direction, influence moisture transport, convective lifting, and the distribution and intensity of precipitation.

Data Sources and Methodological Approach

A robust decadal analysis of atmospheric parameters and their influences on precipitating cloud systems over East Coastal Andhra Pradesh necessitates the integration of data from multiple authoritative meteorological sources. The primary data sources utilized for this study include: ECMWF Reanalysis v5 (ERA5) represents the fifth-generation atmospheric reanalysis from the European Centre for Medium-Range Weather Forecasts (ECMWF). For this decadal analysis (2014–2023), data encompassing temperature, pressure, wind speed, and rainfall will be systematically collected from the aforementioned sources. ERA5 data is analyzed using a variety of statistical methods to assess its accuracy and characteristics. These include standard metrics like correlation coefficients, root mean square error (RMSE), and bias, as well as more advanced techniques like Empirical Orthogonal Functions (EOF) for spatial pattern analysis and Mann-Kendall tests for trend analysis (Hersbach et al., 2020).

India Meteorological Department's (IMD) gridded rainfall (0.25°x0.25°) and temperature data for India will form a foundational dataset, supplemented by their annual climate summaries and reports on extreme weather events, which often include state-level details for Andhra Pradesh. The India Meteorological Department uses a kriging-based spatial interpolation technique to generate gridded rainfall data from rain gauge observations. For temperature data, they utilize a distance-weighted averaging method, along with quality control measures and bias corrections, to create gridded products (Pai et al., 2014).

Data from different sources, often at varying spatial and temporal resolutions, will be re-gridded or interpolated to a common resolution to facilitate comparative analysis. Anomalies, missing values, and potential biases within the datasets will be identified and addressed using appropriate statistical methods (e.g., interpolation, outlier detection). Data will be precisely extracted for the East Coastal Andhra Pradesh region using geographical coordinates to define the study area.

Table 1: Climate/Weather based on Seasons according to India Meteorological Department (IMD)

Sl. No.	Season	Period/ Months	Climatic conditions
1	South-West (SW) Monsoon	Jun-Sep	The summer monsoon season brings the highest rainfall to the ECI, with the region experiencing a prolonged period of enhanced precipitation associated with monsoon depressions and other large-scale systems. This is the most important rainfall period for the region.
2	North-East (NE) Monsoon	Oct – Early Dec.	During the post-monsoon months of October to December, a different monsoon cycle, the northeast (or "retreating") monsoon, brings dry, cool, and dense air masses to large parts of India.[1] this period, after the

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			southwest monsoon has peaked in rainfall
3	Winter	Lat Dec. – Feb.	During the winter months, precipitation over the ECI is generally low, with occasional weak systems bringing isolated showers. The region experiences a relatively dry period as the monsoon winds subside.
4	Pre-monsoon	Mar. - May	As the seasons transition, the ECI starts to experience an increase in convective activity, with the formation of isolated thunderstorms and occasional pre-monsoon depressions. This period is marked by a gradual rise in precipitation amounts.

Trends and Variability in Temperature (2014–2023)

East Coastal Andhra Pradesh experiences a generally hot and humid climate, with summer temperatures typically ranging between 20°C and 41°C, and often exceeding 40°C in central parts of the state. Coastal areas tend to have higher temperatures during the summer months. As show in Fig. 2, the decadal analysis from 2014 to 2023 reveals notable trends and variability in temperature:

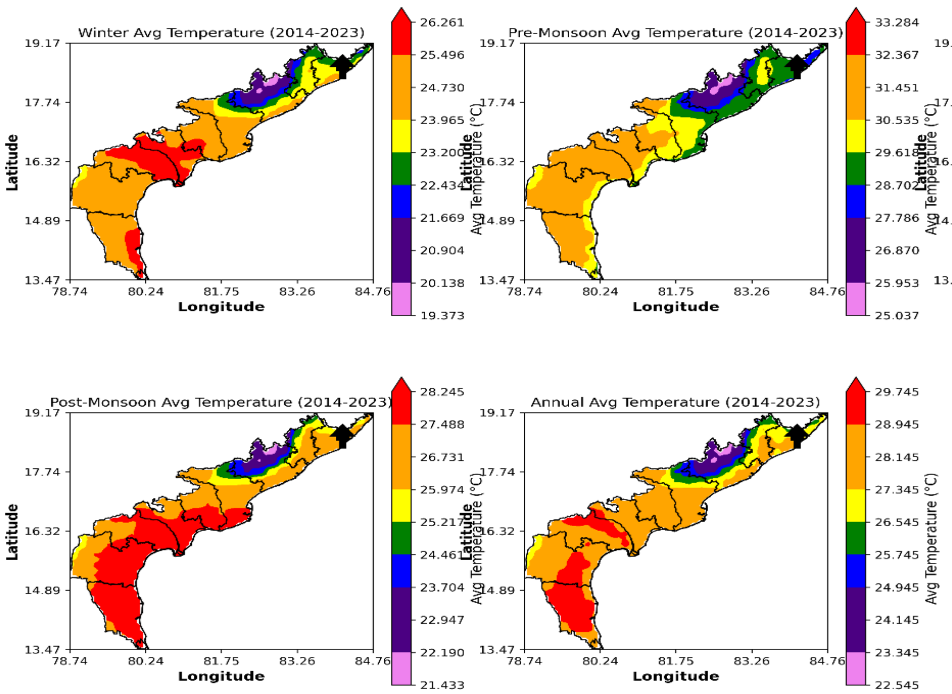

Fig.2: Seasonal and Annual average Temperature °C distribution over Coastal districts of AP in east coast of India.

The annual mean land surface air temperature averaged over India during 2023 was +0.65°C above the long-term average (1981-2010 period), making 2023 the second warmest year on record since 1901. This aligns with the broader Asian trend of warming at nearly twice the global average. As shown in Fig.3, during the pre-monsoon season (March-May) 2019, maximum temperature was above normal over parts of the peninsular region, and minimum temperature was above normal over parts of the eastern peninsula. The post-monsoon season (October-December) 2021 recorded the highest season-averaged minimum temperature anomaly (1.3°C, second warmest since 1901). The observed warming trends, particularly the increasing frequency of heatwaves, suggest a positive feedback loop where warmer ocean surfaces lead to increased evaporation, injecting more moisture into the atmosphere. This increased moisture, when lifted and cooled, can result in more vigorous cloud formation and potentially more intense, localized rainfall events, even as overall heavy rainfall frequency might fluctuate. This indicates that rising temperatures are not just a direct heat hazard but a significant underlying driver of the region's precipitation characteristics. This growing risk of compound hazards, where heat stress conditions can precede or coincide with conditions conducive to extreme rainfall and associated flooding, demands integrated adaptation strategies (IMD report, 2024)

As shown in Fig.3, the observed trends in temperature over the decadal period (2014–2023) indicate a significant increase in regional warming in the East Coastal Andhra Pradesh (ECAP) region. This rise in temperatures, particularly the observed increase in heatwave frequency and intensity, contributes to a greater atmospheric moisture-holding capacity. The document suggests that this enhanced moisture, when lifted through convective processes or by large-scale circulation, fuels the development of more intense, towering deep convective clouds, leading to more erratic rainfall patterns characterized by fewer overall heavy rainfall events but a sustained or even increased occurrence of extremely heavy, localized downpours. Therefore, the implications of these temperature trends include a heightened vulnerability to climate variability and extreme weather events in the region, necessitating region-specific climate action (Srivastava et al., 2009).

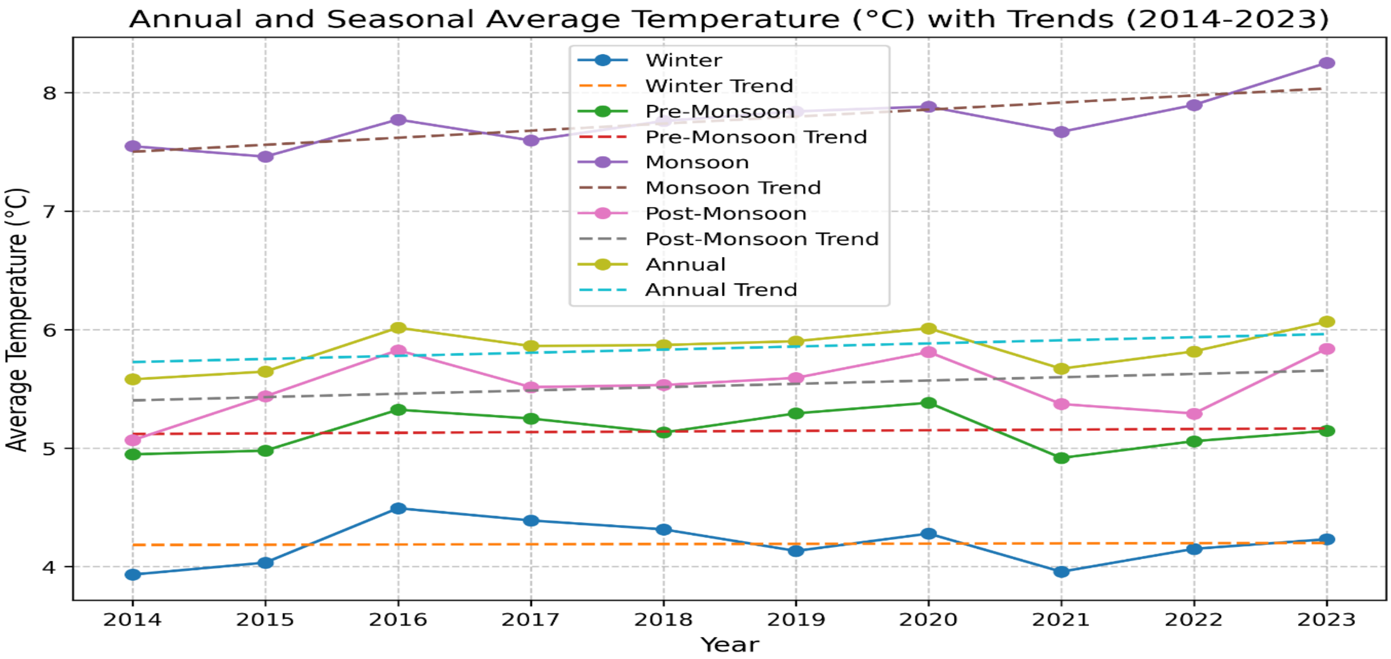

Fig.3: Time series of seasonal & Annual average Temperature, °C with Trends

Trends and Variability in Atmospheric Pressure (2014–2023)

The role of atmospheric pressure systems, especially cyclonic disturbances, in organizing significant precipitation events in the East Coastal Andhra Pradesh (ECAP) region is crucial. Low-pressure areas and cyclonic circulations originating in the Bay of Bengal act as the primary organizers of precipitation. These systems induce strong vertical air motions, leading to rapid cooling, condensation, and the formation of extensive precipitating cloud systems. The frequent occurrence of severe cyclones during the decade underscores the direct link between strong pressure gradients and extreme rainfall events. Therefore, cyclonic disturbances play a fundamental role in orchestrating the significant precipitation events observed in the ECAP region.

Atmospheric pressure variations are intrinsically linked to vertical air motions, which are fundamental to cloud formation and dissipation. Low-pressure systems are associated with rising air and cloud development, leading to increased rainfall, often accompanied by strong winds due to air convergence. As show in Fig.4, over the decadal period (2014-2023), the influence of atmospheric pressure on precipitating cloud systems in ECAP has been predominantly observed through the genesis and movement of cyclonic disturbances in the Bay of Bengal. These cyclonic systems are characterized by intense low-pressure cores that drive significant uplift and condensation, leading to heavy precipitation.

The Bay of Bengal is a major basin for cyclonic activity, which directly impacts East Coastal Andhra Pradesh. In 2023, 6 cyclonic disturbances developed over the Bay of Bengal as shown in Fig.5. consistent observation that cyclonic disturbances, inherently low-pressure systems, frequently develop over the Bay of Bengal and directly impact East Coastal Andhra Pradesh highlights these pressure systems as the major orchestrators of precipitating cloud events and associated extreme weather in the region. The genesis, intensification, and movement of these synoptic-scale low-pressure systems fundamentally dictate the timing, intensity, and spatial distribution of heavy rainfall and strong winds along the coast. This underscores that accurate monitoring and forecasting of the genesis, track, and intensity of low-pressure systems, particularly cyclonic circulations, over the Bay of Bengal are paramount for effective disaster preparedness and early warning systems in East Coastal Andhra Pradesh.

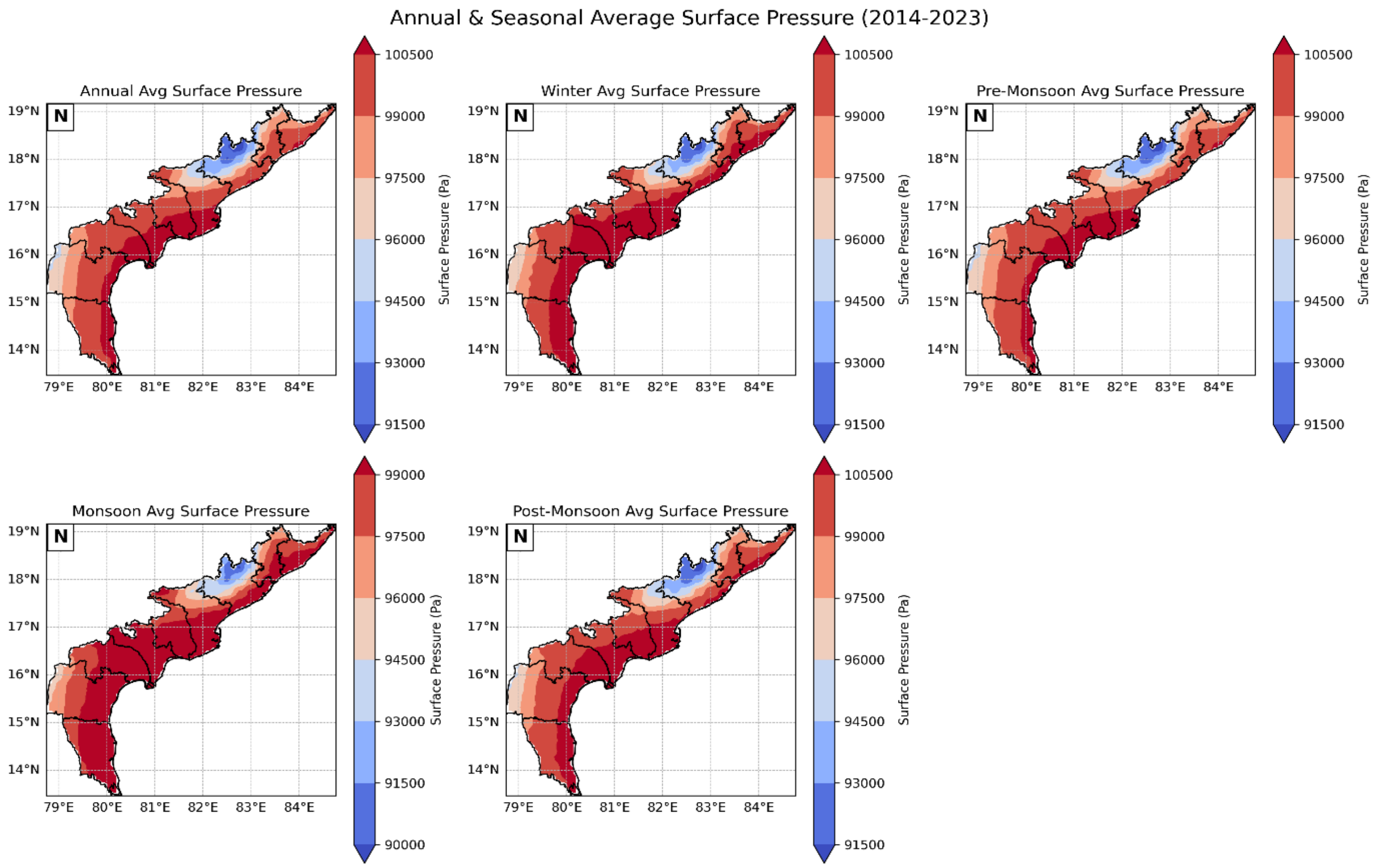

Fig.4: Seasonal and Annual average Pressure(hPa) distribution over Coastal districts of AP in east coast of India.

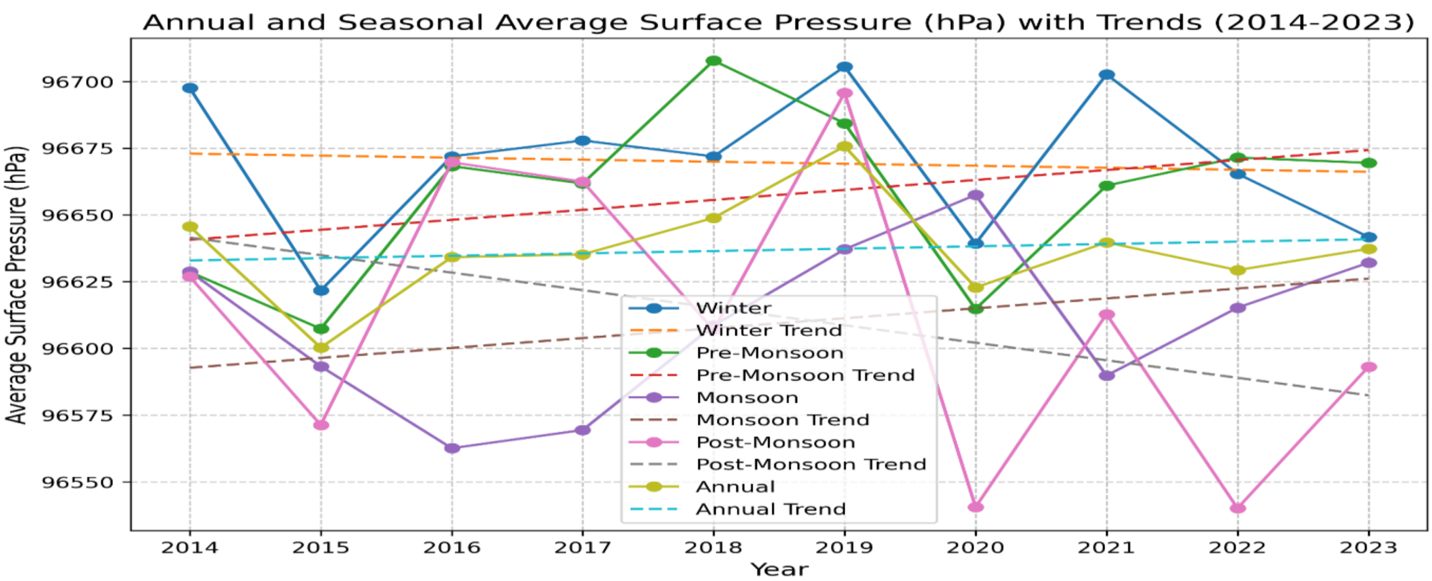

Fig.5: Annual and Seasonal average Surface Pressure (h Pa) with trends

Trends and Variability in Wind Speed and Direction

Wind plays a crucial role in atmospheric dynamics, influencing moisture transport, convection, and rainfall distribution. Stronger winds can accelerate air ascent, leading to faster cooling and enhanced cloud formation, often resulting in heavier rainfall. Wind direction is also vital, as oceanic winds bring moisture to coastal areas, while dry land winds reduce precipitation.

The Indian monsoon is characterized by a seasonal reversal of winds. The Southwest Monsoon (June-September) brings moist, southwesterly winds from the Indian Ocean, which are drawn inland by low-pressure systems, leading to widespread rainfall. The Northeast Monsoon (October-December) brings cold, dry winds from the Himalayas and Indo-Gangetic Plain, which pick up moisture from the Bay of Bengal to bring rain to peninsular India, including coastal Andhra Pradesh. As dipcted in Fig.6, Cyclonic disturbances are inherently associated with strong winds. Cyclone Hudhud (2014) made landfall in Visakhapatnam with winds exceeding 185 km/h, with gusts recorded up to 260 km/h. Cyclone Titli (2018) produced strong winds with gusts up to 165 km/h near its landfall point in Andhra Pradesh. Strong surface winds (40-60 kmph) are frequently observed over Coastal Andhra Pradesh during rainfall events, particularly those associated with cyclonic circulations.

The increase in height of deep convective clouds over the last two decades, fueled by warmer oceans, implies stronger updrafts and associated wind patterns within these towering systems, leading to more intense rainfall and stronger storms along the Eastern Coast.

Fig.7 shows that the active role of wind, both in its speed and direction, means that any observed changes in regional wind patterns could significantly alter both general monsoon rainfall distribution and the intensity/track of cyclonic events. For instance, changes in mid-level cyclonic circulations over the Bay of Bengal can favor the development of larger precipitating systems, especially under moister conditions. A detailed analysis of wind patterns, including speed, direction, and vertical profiles, is therefore critical for understanding and predicting both seasonal rainfall variability and the characteristics of extreme events in East Coastal Andhra Pradesh.

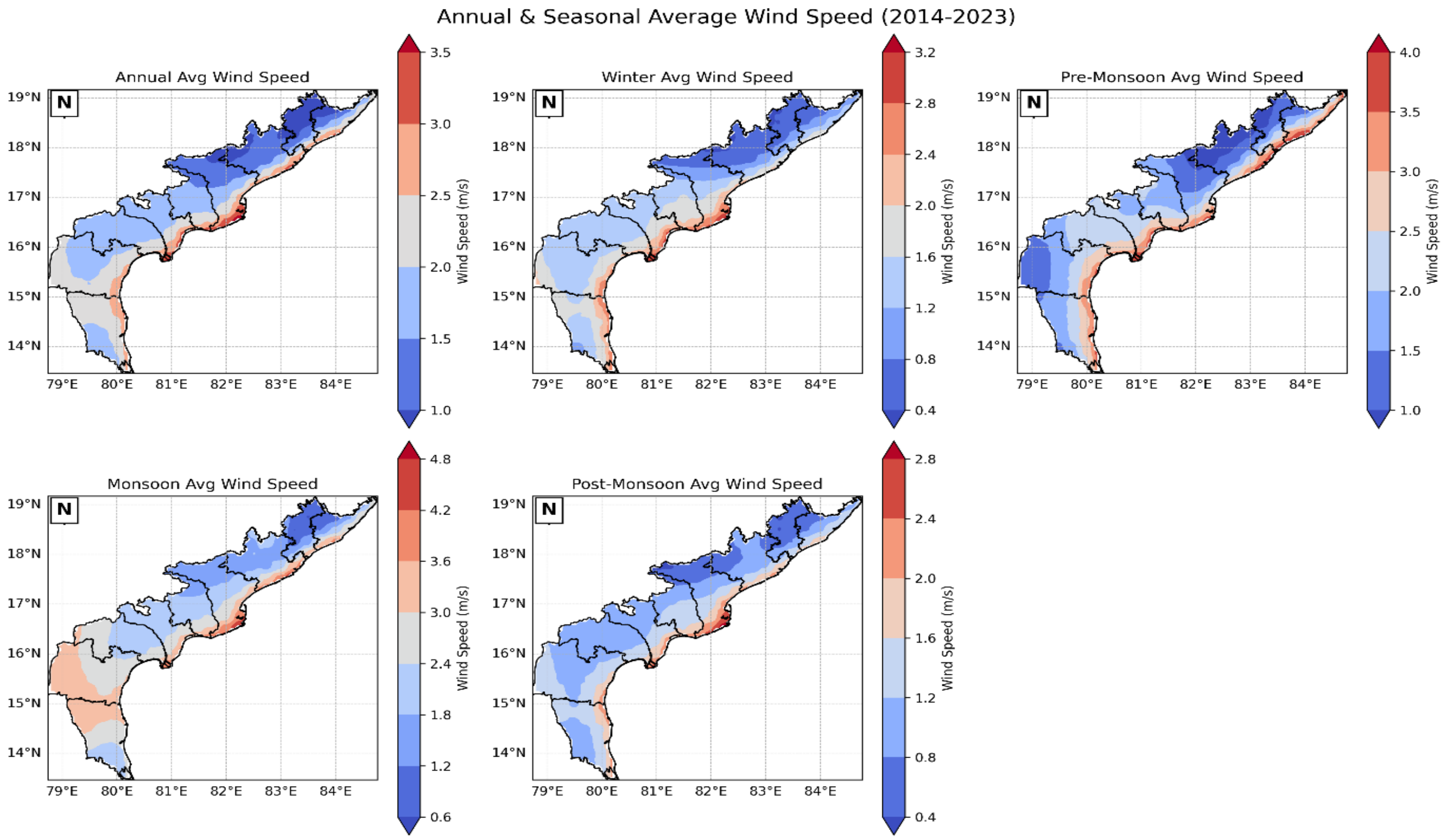

Fig.6 Seasonal and Annual winds over Coastal districts of AP in east coast of India.

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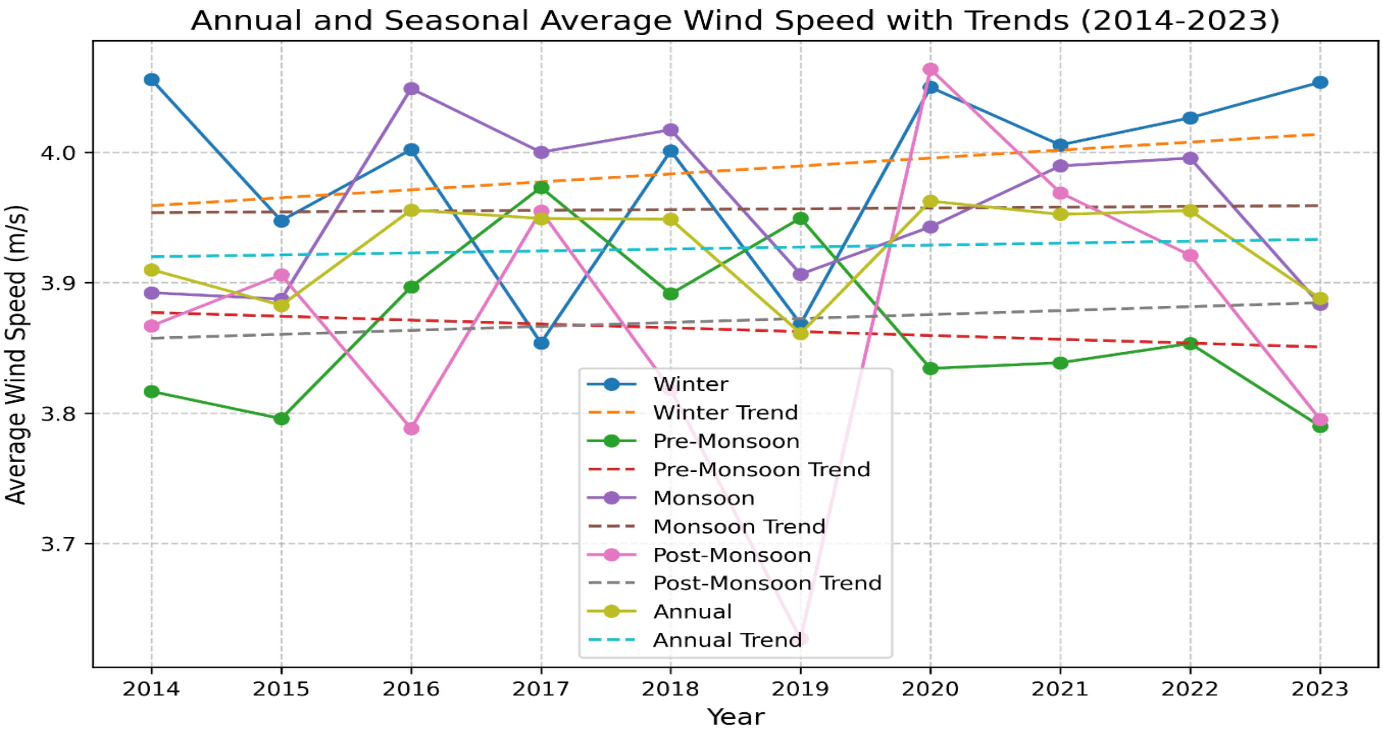

Fig.7: Annual and Seasonal average Surface Pressure (h Pa) with trends

Precipitation Distribution Over Ecap

Precipitation distribution refers to how rainfall varies across a geographical area (spatial distribution) and over different time periods (temporal distribution). It encompasses not just the total amount of rain but also its intensity, frequency, and duration. For a region like ECAP, which is highly dependent on monsoon rains and vulnerable to extreme weather events, characterizing precipitation distribution is more informative than merely looking at average totals.

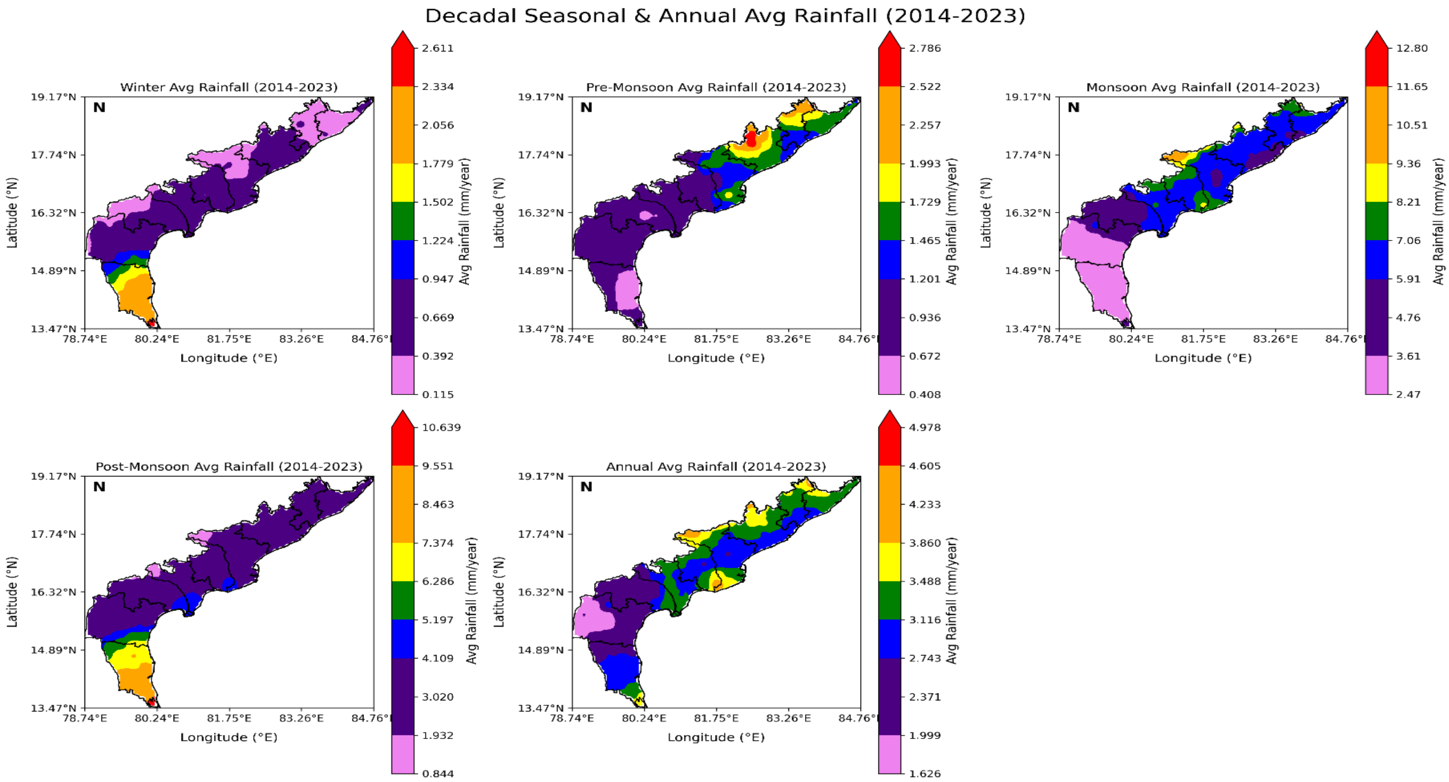

Fig.8: The distribution pattern of Annual mean monthly and seasonal distribution of precipitation, mm

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Fig.8 and 9 shows that the decadal analysis of rainfall over East Coastal Andhra Pradesh between 2014 and 2023 reveals critical seasonal precipitation patterns with significant implications for understanding climate variability and planning regional resilience strategies. The most prominent finding is the consistent dominance of monsoon rainfall, which contributes more than 70% of the total annual precipitation in most years (India Meteorological Department [IMD], 2023). This aligns with broader climatological patterns across India, where the Southwest Monsoon (June–September) is the principal source of rainfall, playing a vital role in agricultural productivity and water resource sustainability (Ramesh & Goswami, 2014).

Over the ten-year period, a slight but consistent increase in total annual rainfall is observed. Though the interannual variability remains high—largely due to the influence of large-scale climate drivers like the El Niño–Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD)—the trend line indicates a gradual intensification of the hydrological cycle (Krishnan et al., 2020). The warming of sea surface temperatures in the Bay of Bengal has contributed to enhanced evaporation and increased atmospheric moisture content, thereby intensifying monsoonal and cyclonic rainfall events (Roxy et al., 2017).

Both the monsoon and post-monsoon seasons (October–December) show positive rainfall trends, especially in years with notable cyclonic activity. For instance, cyclones such as Hudhud (2014), Titli (2018), and Michaung (2023) significantly increased seasonal rainfall through high-intensity precipitation and prolonged wet spells (Rathore et al., 2021). These observations suggest that tropical cyclone frequency and intensity over the Bay of Bengal are key contributors to the increasing post-monsoon rainfall in the region (Dash et al., 2019).

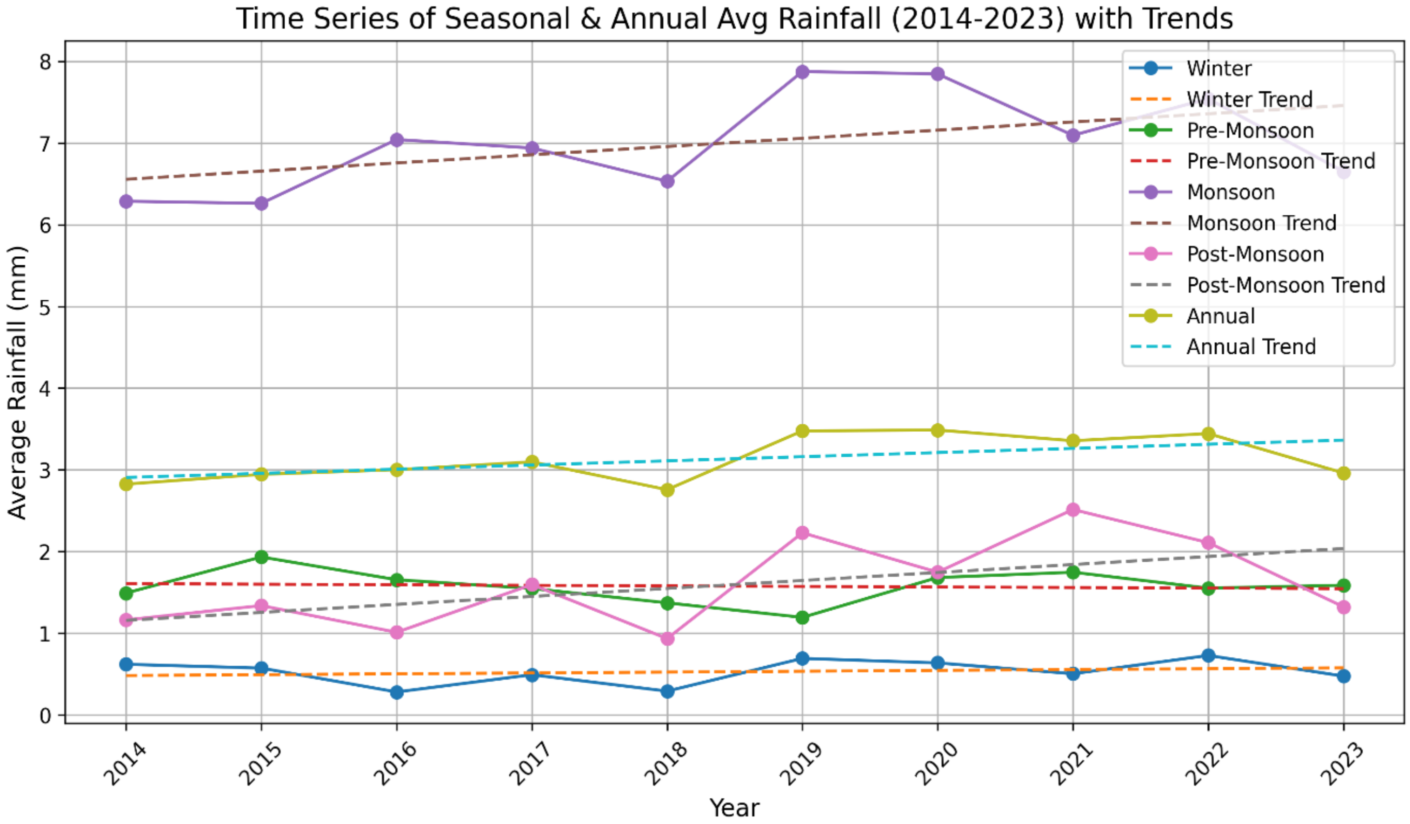

Fig. 9: Annual and Seasonal average rainfall/precipitation with trends between 2014 and 2023

In contrast, winter rainfall (January–February) remains minimal and stable, contributing less than 5% of the annual total, with no statistically significant trend over the decade. This is expected, as winter weather patterns over peninsular India are generally dry, influenced by the northeast monsoon winds and absence of moisture-bearing systems (Sahany et al., 2018).

The pre-monsoon season (March–May), although historically characterized by convective thunderstorms and localized rainfall events, shows a minor increasing trend in rainfall during the study period. This may be attributed to rising land surface temperatures and increased atmospheric instability, leading to enhanced convective activity (Mukherjee et al., 2018). The early onset of pre-monsoon rainfall could have important agricultural implications, particularly for crop planning and groundwater recharge.

In summary, the 2014–2023 period indicates a trend toward increased rainfall intensity and extended wet seasons, particularly during the monsoon and post-monsoon months. These findings highlight the growing influence of climate variability and cyclonic disturbances on seasonal precipitation and stress the importance of adaptive water management, disaster preparedness, and climate-resilient agriculture in the East Coastal Andhra Pradesh region.

Aerosol, Cloud Water, Precipitation and Precipitation Efficiency

Precipitation Efficiency (PE) is a critical concept in atmospheric science that quantifies how effectively the water vapor within a cloud system is converted into precipitation that reaches the surface. It is often defined as the ratio of surface precipitation rate to the total rate of water vapor condensation and/or convergence within the cloud system (Sui et al., 2007).

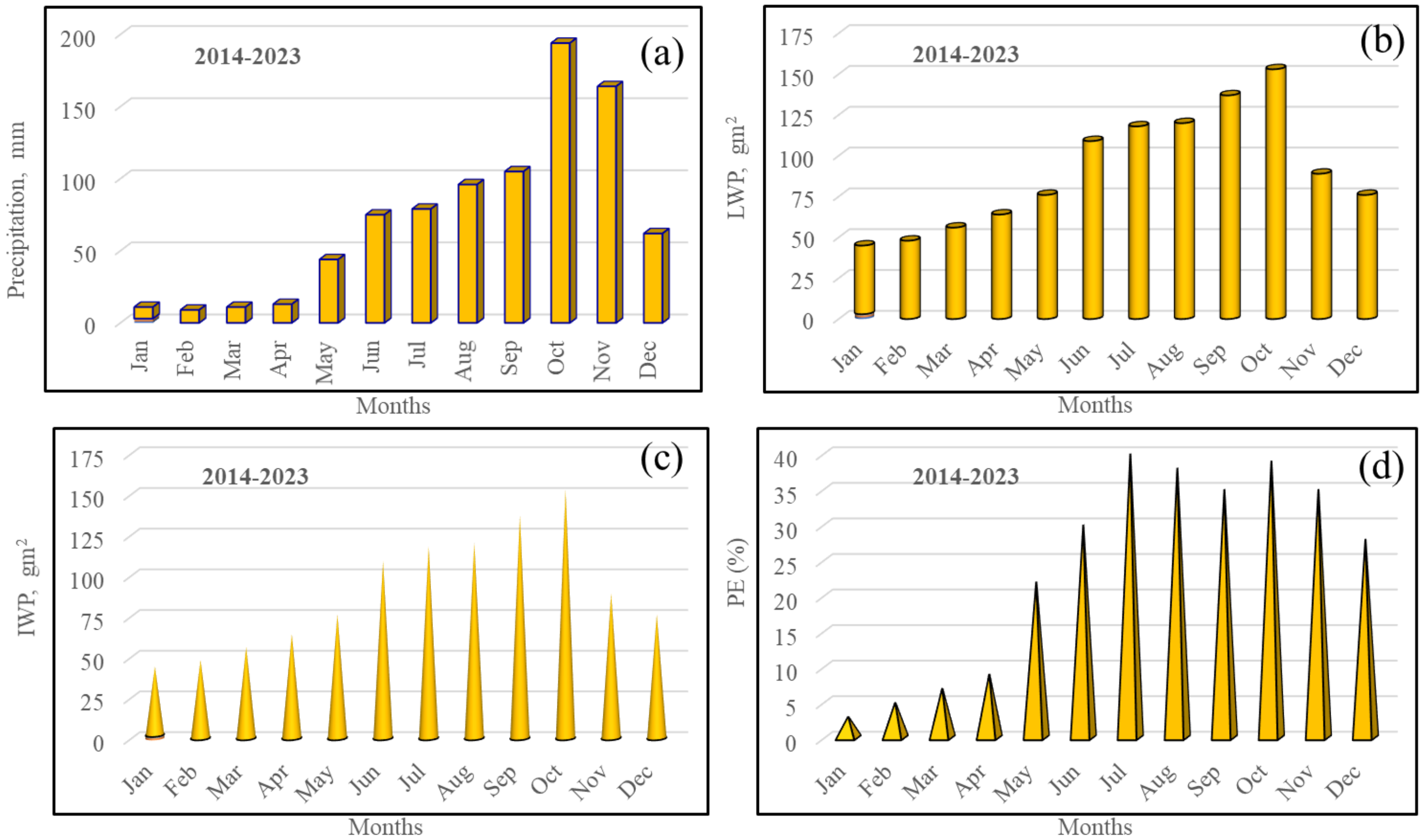

Fig.10: (a) monthly mean precipitation, mm; (b) monthly mean liquid water path (LWP) gm^2; (c) monthly mean ice water path (IWP), gm^2 and (d) monthly mean precipitation efficiency (PE) from 2014 to 2023 over East coast of AP

In this study, precipitation efficiency (PE) is used to represent the potential precipitation capacity of clouds. PE is defined as precipitation divided by the cloud water path (Market, et al., 2003; Zhao et al., 2022), as shown in Equation (1), Pre in the equation represents precipitation,

$$PE = \frac{Pre}{LWP + IWP} \qquad \text{........ (1)}$$

In Equation (1), Pre is the precipitation, LWP represents the liquid water path, and IWP represents the ice water path. LWP and IWP refer to the column content of liquid water and ice phase water above the unit area

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of the surface obtained based on satellite observation and retrieval, respectively. All cloud products were calibrated based on MODIS data prior to retrieval, and the cloud screening was effectively improved by utilizing CALIPSO-CALIOP data.

The aerosol index (AI) is defined as the product of the aerosol optical depth (AOD) and the Ångström exponent (AE), as shown in Equation (2). The AI is a dimensionless parameter. Previous studies (Karlsson, 2017) have suggested that the AI could better characterize aerosol concentration than the AOD,

$$AI = AOD \times AE \quad \text{........ (2)}$$

The AOD and AE from 2014 to 2023 derived from the MERRA-2 aerosol reanalysis product dataset, with an original resolution of 0.625° × 0.5° (Randles et al., 2017). To match with other datasets, the AOD and AE were interpolated to a spatial resolution of 0.25° × 0.25°.

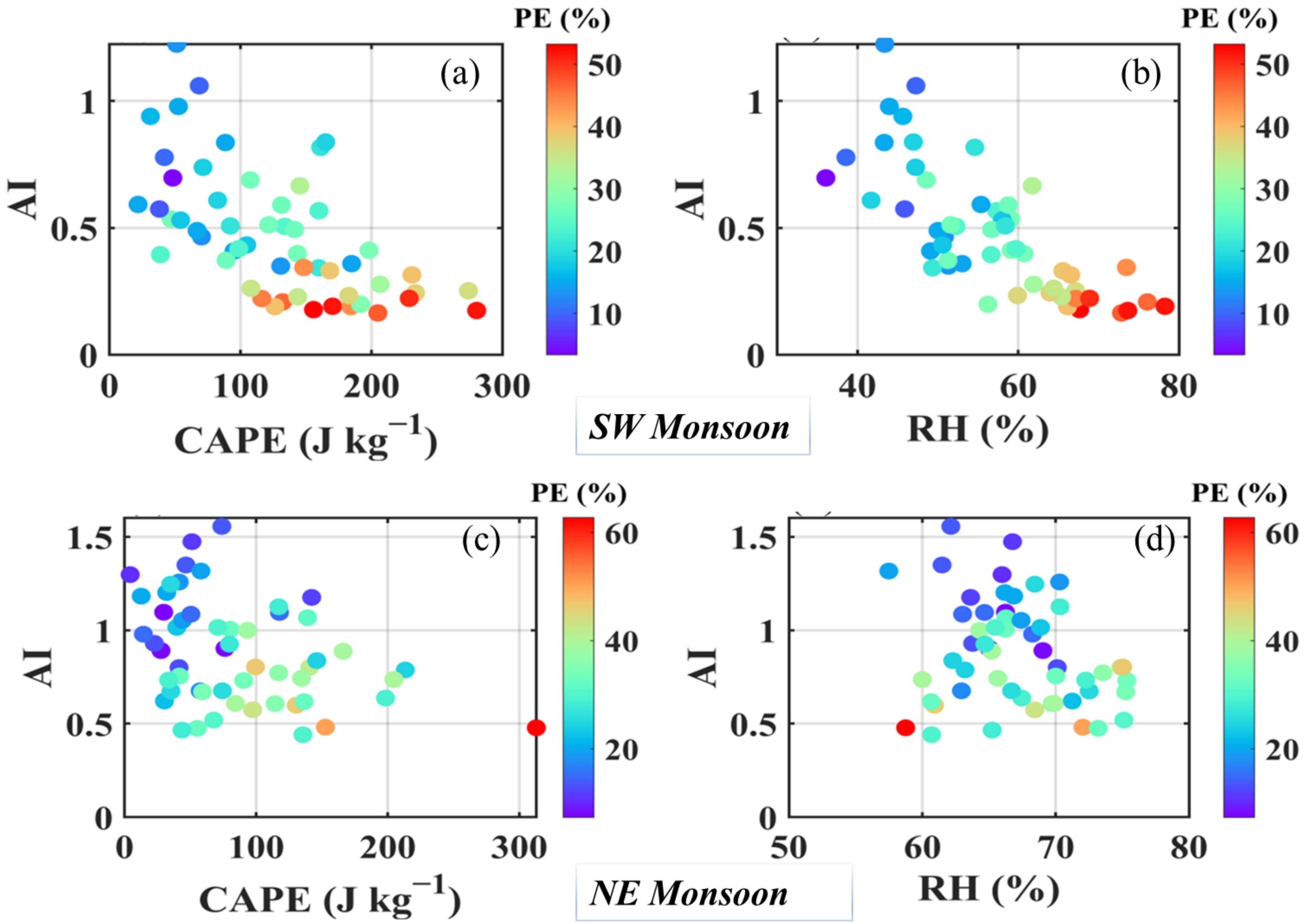

Fig.11: Co-modulation of PE by the AI and meteorological conditions (CAPE and RH). the CAPE and the AI (a), the RH and the AI (b) during SW monsoon, and the CAPE and the AI (c), the RH and the AI (d) during NE monsoon.

As discussed before, Precipitation Efficiency (PE) is a measure of how effectively water vapor is converted into precipitation that reaches the ground. Higher PE means more efficient rainfall. The Aerosol Index (AI) is a unitless measure derived from satellite observations that indicates the presence of UV-absorbing aerosols (like dust and smoke). Higher AI values generally mean higher aerosol loading in the atmospheric column. Convective Available Potential Energy (CAPE) is a meteorological parameter representing the buoyant energy available for convection. Higher CAPE values indicate a greater potential for strong updrafts and deep convection. It's often associated with instability. Relative Humidity (RH) is the amount of moisture in the air relative to the maximum amount it can hold at a given temperature. Higher RH indicates more moisture in the atmosphere, especially in the mid and lower troposphere, reducing evaporative losses from falling precipitation. Co-modulation term implies that the interaction between these factors (AI, CAPE, RH) collectively influences PE, rather than each factor acting in isolation. It suggests a complex, potentially non-linear relationship.

As shown in Fig.11 (a), the PE changes as both CAPE (instability) and Aerosol Index (aerosol loading) vary during the SW monsoon season. From these panels it is noticed that if the aerosols are small and hygroscopic (e.g., pollution), high AI might lead to more numerous but smaller cloud droplets. With high CAPE, these smaller droplets could be lofted to greater heights, promoting ice formation (mixed-phase and cold rain processes). This could potentially enhance PE if ice processes are efficient, or suppress warm rain if droplets are too small to coalesce effectively before freezing. If aerosols are dust (less hygroscopic but good ice nuclei at certain temperatures), high AI could directly enhance ice formation, potentially increasing PE. Conversely, extremely high AI (dense pollution) could reduce solar radiation reaching the surface, reducing surface heating and thus CAPE itself, or alter atmospheric stability, complicating the relationship. High CAPE, Low AI: With high instability and clean air, warm rain processes (collision-coalescence) would likely be efficient, potentially leading to high PE, especially in the lower troposphere. Low CAPE: Regardless of AI, low CAPE generally means weak convection, and thus PE is likely to be low, as there's insufficient energy to lift parcels to precipitable heights. Fig.111(a) helps discern if aerosols enhance or suppress precipitation efficiency in unstable conditions during the SW monsoon, and if there's an optimal range for AI given high CAPE.

In the Fig.11(b) it is inferred that high RH means abundant moisture, which reduces evaporative losses from falling precipitation, generally increasing PE. The combined effect with high AI is complex: In a very moist environment, even smaller droplets (due to high AI) might still have enough time to grow, or the abundance of moisture might mitigate some of the suppressive effects of aerosols on warm rain. High RH also fuels stronger convection if CAPE is available. Aerosol impact on PE in high RH conditions during SW Monsoon is critical: does it lead to invigoration (more intense convection, potentially higher PE) or suppression (reduced warm rain, lower PE)? This is a key research question.

High RH, Low AI values indicate that high moisture and clean air, PE is expected to be high due to reduced evaporation and efficient warm rain processes. Regardless of AI, low RH in the mid/lower troposphere often leads to significant evaporative cooling of falling precipitation, drastically reducing PE. Fig.11(b) it is found that the background moisture environment modulates the impact of aerosols on precipitation efficiency during the most vital rain-bearing season.

Fig.11 (c) is similar to (a), but specifically for the NE Monsoon (Oct-Dec). The nature of convection and aerosols might differ in this season. NE monsoon rainfall often comes from different types of systems: shallow convection, orographic enhancement, and crucially, tropical depressions and cyclones in the Bay of Bengal. CAPE might be lower on average compared to the SW monsoon for general convection, but very high during cyclonic periods. The interaction between CAPE and AI could reveal unique insights for this season. For example, if NE monsoon convection is often shallower, the warm rain suppression effect of aerosols might be more pronounced as droplets have less vertical distance to grow. If deep convection from cyclones is present, aerosol impacts could be complex. Helps understand if the aerosol-CAPE-PE relationship changes due to seasonal differences in convection type and aerosol characteristics.

From Fig.11(d) high RH in NE Monsoon is particularly critical, especially when associated with Bay of Bengal disturbances. These systems bring immense moisture. The interplay with AI would again be crucial. Given the potential for heavy rainfall events from cyclones in this season, how aerosols might modulate PE in such extremely moist, organized systems is highly relevant. Do aerosols act as invigoration agents (making rainfall more intense) or suppression agents (reducing the total amount reaching the ground)? Fig.11(d) provides insights into how the abundant moisture during NE monsoon, especially during cyclonic activity, interacts with aerosol loading to influence rainfall efficiency.

In essence, Fig. 11 allows for a multidimensional understanding of how the atmospheric environment (instability and moisture) and aerosol loading collectively shape the efficiency of rainfall formation over the East Coast of Andhra Pradesh.

DISCUSSIONS

The decadal analysis (2014-2023) of East Coastal Andhra Pradesh reveals a dynamic and interconnected system where atmospheric parameters—temperature, pressure, and wind—are the primary drivers of precipitating cloud systems and their associated rainfall patterns. The region's hot and humid climate, coupled with the influence of the Bay of Bengal, sets the stage for significant convective activity.

Rising temperatures, particularly the observed increase in heatwave frequency and intensity, contribute to a greater atmospheric moisture-holding capacity. This enhanced moisture, when lifted through convective processes or by large-scale circulation, fuels the development of more intense, towering deep convective clouds. This phenomenon explains the observed shift towards more erratic rainfall, characterized by fewer overall heavy rainfall events but a sustained or even increased occurrence of extremely heavy, localized downpours.

Atmospheric pressure systems, especially low-pressure areas and cyclonic circulations originating in the Bay of Bengal, act as the primary organizers of precipitation. These systems induce strong vertical air motions, leading to rapid cooling, condensation, and the formation of extensive precipitating cloud systems. The frequent occurrence of severe cyclones during the decade underscores the direct link between strong pressure gradients and extreme rainfall events.

Wind patterns, encompassing both speed and direction, play a multifaceted role. They dictate the advection of moisture from the ocean to the coast, providing the necessary water vapor for cloud formation. Additionally, stronger winds can intensify convective uplift, leading to more vigorous cloud development and heavier precipitation. The seasonal reversal of monsoon winds is the foundational mechanism for regional rainfall, while the intense winds associated with cyclonic systems are integral to their destructive precipitation output.

The influence of aerosol-cloud interactions and cloud microphysical processes on precipitation efficiency over the East Coastal Andhra Pradesh (ECAP) region played pivotal role. The paper highlights the need to explore the potential influence of aerosol-cloud interactions and other microphysical processes on precipitation efficiency in the ECAP region, as this can provide valuable insights into the region's precipitation dynamics and variability.

CONCLUSIONS

This decadal analysis (2014–2023) of East Coastal Andhra Pradesh underscores the region's heightened vulnerability to climate variability and extreme weather events, driven by a complex interplay of atmospheric parameters. Key findings reveal that:

East Coastal Andhra Pradesh experiences amplified climate vulnerability due to rapid regional warming and pre-existing coastal sensitivities, necessitating region-specific climate action.

The region's precipitation dynamics are shaped by a dual monsoon influence (Southwest and Northeast Monsoons) and a dominant role of cyclonic disturbances originating from the Bay of Bengal, which frequently orchestrate extreme rainfall events.

A concerning shift in cloud characteristics is evident, with deep convective clouds increasing in height, leading to more intense, localized downpours and a higher frequency of extreme weather events, even as overall heavy rainfall frequency might decrease.

Cloud microphysical processes and their efficiency in converting water vapor to precipitation are critical, with factors like aerosol loading potentially modulating regional rainfall intensity.

Rising temperatures contribute to a moisture feedback loop, where warmer oceans lead to increased atmospheric moisture, potentially intensifying convection and extreme rainfall.

Atmospheric pressure systems, particularly low-pressure cyclonic circulations, are the primary orchestrators of significant precipitating cloud events.

Wind dynamics, encompassing both speed and direction, actively influence moisture transport, convective uplift, and the distribution and intensity of rainfall, with any shifts potentially altering regional rainfall patterns and cyclone characteristics.

The paper recognizes the importance of understanding the role of aerosol-cloud interactions and cloud microphysical processes in modulating precipitation efficiency, as this can provide a more comprehensive understanding of the complex atmospheric drivers governing rainfall patterns in the East Coastal Andhra Pradesh region.

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