

**INFLUENCE OF INDIAN OCEAN ON STRUCTURE AND
VARIABILITY OF MONSOON LOW LEVEL JET IN THE
PRESENT AND FUTURE CLIMATE PERSPECTIVES**

by

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(2018 - 20 – 022)

THESIS

**Submitted in partial fulfilment of the
requirements for the degree of**

B.Sc. – M.Sc. (Integrated) Climate Change Adaptation

Faculty of Agriculture

Kerala Agricultural University



COLLEGE OF CLIMATE CHANGE AND ENVIRONMENTAL SCIENCE

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2023

DECLARATION

I, Neha Johnson (2018-20-022) hereby declare that this thesis entitled "**Influence of Indian ocean on structure and variability of monsoon low level jet in the present and future climate perspectives**" is a bonafide record of research work done by me during the course of research and the thesis has not previously formed the basis for the award to me of any degree, diploma, associateship, fellowship or other similar title, of any other University or Society.

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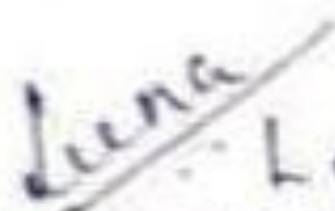
We, the undersigned members of the advisory committee of Ms. Neha Johnson, a candidate for the degree of B.Sc. – M.Sc. (Integrated) Climate Change Adaptation agree that the thesis entitled “Influence of Indian ocean on structure and variability of monsoon low level jet in the present and future climate perspectives” may be submitted by Ms. Neha Johnson in partial fulfilment of the requirement for the degree.



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ACKNOWLEDGEMENT

*I would like to express my deepest appreciation and gratitude to my major advisor, **Dr. Ruchith R. D.**, a distinguished Scientist at the CSIR – National Institute of Oceanography (NIO) in Dona Paula, Goa, India. Throughout my academic journey, Dr. Ruchith has been a pillar of support and guidance, without whom the successful completion of my thesis would not have been possible. His expertise, dedication, and unwavering commitment to the field of oceanography have not only shaped my research but also broadened my horizons. His mentorship has been invaluable in refining my ideas, shaping the direction of my thesis, and helping me navigate the complexities of the research process. His keen insights, rigorous feedback, and encouragement have been a constant source of inspiration. I am truly privileged to have had the opportunity to work under the tutelage of Dr. Ruchith. His patience and willingness to engage in in-depth discussions, even during the most challenging phases of my research, have been instrumental in my growth as a researcher.*

*I extend my sincere gratitude to the **Director of the National Institute of Oceanography (NIO)** for providing me with the invaluable opportunity to work within their esteemed institution and access the rich resources it offers. This opportunity has played a pivotal role in shaping my academic and research experiences, and I am deeply appreciative of the support and resources made available to me during my time at NIO.*

*I am deeply grateful to my advisory committee members, **Dr. P. O. Nameer**, Dean of the College of Climate Change and Environmental Science at Kerala Agricultural University, **Dr. Leena P. P.**, Scientist at the Indian Institute of Tropical Meteorology, and **Dr. E. A. Resmi**, Group Head at the National Centre for Earth Science Studies. Their expertise and guidance have been instrumental in shaping my research. Their commitment to advancing climate and environmental science has been a constant source of motivation, and I am privileged to have worked under their mentorship.*

*I would like to express my heartfelt appreciation to our dear Dean, **Dr. P.O. Nameer**, of the College of Climate Change and Environmental Science. Dr. Nameer has been a continuous source of inspiration for me and my fellow students, consistently encouraging us to reach our full potential. I am immensely grateful for the opportunity to study in this exceptional college, as it has not only shaped my career aspirations but also profoundly impacted my life. The knowledge and skills I have acquired here have not only prepared me for my future career but have also instilled a deep sense of responsibility towards our environment. I would also like to extend my heartfelt thanks for the wonderful memories we have created throughout these years, which I will cherish forever.*

*I would like to extend my sincere appreciation to the exceptional individuals who have been my labmates at NIO: **Adithyan, Alex, Febin, Sohan, and Imsang**. Their unwavering support, technical expertise, and collaborative spirit have been invaluable pillars of strength that I have relied upon throughout my research journey. They have not only been colleagues but also friends, and their dedication to our collective goals has fostered an atmosphere of teamwork and shared progress. Their assistance, whether it was in troubleshooting technical challenges, brainstorming ideas, or lending a hand during critical experiments, has played a pivotal role in the successful execution of our research projects. Their willingness to share knowledge, exchange ideas, and engage in open discussions has not only enriched our scientific endeavors but also created a positive and motivating environment in our research group. Furthermore, the camaraderie we have built goes beyond the lab, as they have offered friendship, unwavering support, and a willingness to patiently clear doubts. This collaborative and supportive atmosphere has not only enhanced our research but has also made our academic journey an enjoyable and memorable one. I am deeply grateful for their contributions which have been instrumental in our collective pursuit of knowledge and achievement. This collaborative and supportive atmosphere has not only enhanced our research but has also made our academic journey an enjoyable and memorable one.*

*I want to convey my deep appreciation to my wonderful classmates **Elysianz-2018** batch who have been an integral part of my journey. Throughout our*

academic journey, your steadfast support and unwavering camaraderie have played a vital role in making this experience truly special. Beyond the classroom, our interactions have given rise to countless cherished memories that I will forever hold close. Your willingness to assist, whether it was in engaging in stimulating discussions, offering valuable insights, or even taking the time to proofread my work, has been invaluable. The collaborative spirit we've cultivated has not only enhanced our collective learning but has also served as a wellspring of inspiration. Your moral support during challenging times has provided a source of strength, making this academic journey more manageable and enjoyable.

*I would like to acknowledge all my friends, with a special mention to **Vibin MB**, for his constant support. He has been a pillar of strength, standing by my side through the toughest of times, offering all moral support and a valuable friendship that has made a significant difference in my journey.*

*I am so grateful to my **parents** and **family** for their love, motivation, understanding, and constant support during this challenging time. Their love has given me strength and courage to face the challenges. Their motivation has kept me going even when I wanted to give up. Their understanding has helped me to cope with the difficult emotions. Their support has made me feel loved and supported. I am truly blessed to have such a loving and supportive family.*

*I would also like to thank the members of **College of Climate Change and Environmental Science, KAU** who have contributed to my academic growth and special thanks to **Mrs. Mini** for her timely help. The staff, faculty, and administrators who have provided resources, opportunities, and a supportive environment have made a significant impact on my development.*

I would like to express my sincere gratitude to the countless individuals who have contributed to this thesis work, whether in big or small ways. Your support has not gone unnoticed and has been essential to the success of this research. Thank you all!

Neha Johnson

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SYMBOLS AND ABBREVIATION

°C	Degree Celsius
AS	Arabian sea
ASMWP	Arabian Sea Mini Warm Pool
BoB	Bay of Bengal
CAPE	Convective Available Potential Energy
CDS	Climate Data Portal
CMIP6	Coupled Model Intercomparison Project phase-6
EIO	Equatorial Indian Ocean
ENSO	El Nino-Southern Oscillation
ESGF	Earth System Grid Federation
FGP	Food Grain Production
Fig.	Figure
GCM	General Circulation Model
GDP	Gross Primary Productivity
IITM	Indian Institute of Tropical Meteorology
IITM-ESM	Indian Institute of Tropical Meteorology-Earth System Model
IMD	India Meteorological Department
IO	Indian Ocean
IOD	Indian Ocean Dipole
IOWP	Indian Ocean warm pool

IS	Indian Subcontinent
ISM	Indian Summer Monsoon
ISMR	Indian Summer Monsoon Rainfall
ITCZ	Inter Tropical Convergence Zone
JJAS	June, July, August, and September
LLJ	Low Level Jet
LLJ	low-level Jetstream
MH	Mascarene High
MLLJ	Monsoon Low-Level Jet
mm	millimeter
MOK	Monsoon Onset over Kerala
MSLP	Mean sea level pressure
MT	Monsoon Trough
NE Monsoon	Northeast monsoon
RCP	Representative Concentration Pathway
SEAS	South Eastern Arabian Sea
SIO	Southern Indian Ocean
SSP	Shared Socioeconomic Pathways
SST	Sea surface temperature
SW Monsoon	Southwest monsoon
tcw	Total Column Water
TEJ	Tropical Easterly Jet

TH	Tibetan High
UI	Upwelling index
WCRP	World Climate Research Programme
WMO	World Meteorological Organization

CHAPTER 1

INTRODUCTION

2.1. GLOBAL MONSOON

The monsoon is a phenomenon characterized by the seasonal reversal of prevailing winds, accompanied by changes in atmospheric circulation, temperature, and precipitation. This seasonal shift is primarily driven by the movement of the Intertropical Convergence Zone (ITCZ). The term "Monsoon" has its origins in Arabic, specifically "Mausam," which translates to "season." Arab sailors were the first to use this term to describe the significant seasonal changes in wind direction. The monsoonal region encompasses a substantial portion of the tropics, spanning from 25 degrees south latitude to 35 degrees north latitude and from 30 degrees west longitude to 170 degrees east longitude. This region covers all tropical continents worldwide and the tropical oceans in the western North Pacific, eastern North Pacific, and southern Indian Ocean. Monsoon circulation affects over one-third of the world's population, providing the majority of annual rainfall to many countries in the tropics and subtropics (Geen et al., 2020).

The South Asian monsoon system, as established by Mooley and Parthasarathy in 1984, is the most extensive monsoon system worldwide. South Asia possesses unique geographical and physical characteristics, covering a vast continental area that spans from equatorial to polar latitudes in the northern hemisphere. It is bordered by oceans to the south, closer to the equator, which creates conditions favoring strong convection due to the contrast in temperature between the land and sea. Consequently, this region experiences concentrated rainfall during specific times of the year. Several factors, including the Tibetan Plateau, the Intertropical Convergence Zone (ITCZ), the Siberian high-pressure system, and the Pacific Ocean's El Nino-Southern Oscillation (ENSO) phenomenon, interact to shape the complex monsoon system. In the Asian monsoon region, the Indian Subcontinent and Indo-China peninsula are part of this system, extending northeastward into mainland China, Japan, and Korea. This monsoon system also encompasses the northwest Pacific Ocean and the South China Sea (Kelkar, 2012). The South Asian

Monsoon rainy season, lasting from June to September, contributes over 75% of the region's annual rainfall, particularly in areas such as the southern slopes of the central and eastern Himalayas (Krishnan et al., 2019; IPCC, 2021).

2.2. INDIAN MONSOON

The Indian monsoon system, which is positioned at the center of the global monsoon region, exerts a profound influence on India and the adjacent water bodies. During the winter months, it originates from the northeast and is referred to as the Northeast monsoon (NE monsoon) or winter monsoon. In contrast, during the summer months, it shifts direction to come from the southwest, hence known as the Southwest monsoon (SW monsoon) or summer monsoon. Of the two monsoons, the Southwest monsoon is more significant, contributing to over 75% of India's annual rainfall (Mooley and Parthasarathy, 1984). India's economy relies heavily on agriculture and is greatly affected by the amount and distribution of rainfall during the monsoon seasons. According to a study conducted by Gadgil and Gadgil in 2006, declines in Gross Domestic Product (GDP) are associated with substantial deficits in Indian Summer Monsoon Rainfall (ISMR), and the impact of severe ISMR deficits on Food Grain Production (FGP) is considerably greater than that of surplus rains, especially since 1980.

The monsoon plays a pivotal role in India's climate and agricultural landscape, as it delivers a substantial portion of the country's annual precipitation, accounting for more than 70% of its total rainfall. The onset of the monsoon marks a momentous event, particularly in the southern state of Kerala, as it signals the commencement of a crucial four-month period of consistent rains that are vital for various sectors of the economy, with agriculture being of paramount significance. The specific date of the monsoon onset over Kerala, referred to as the Monsoon Onset Date (MOK), exhibits a notable degree of variability from one year to the next (Pai et al., 2020). Over a span of 100 years, the mean MOK date falls on the first of June, with a standard deviation of approximately 7.4 days. This means that while the average onset date remains consistent, there is a range from as early as May 28th to as late as June 5th for the

commencement of the monsoon rains (Gadgil and Gadgil, 2006). This variation in the onset of the monsoon holds immense importance, as it can have significant repercussions on agricultural planning, water resource management, and various economic activities that rely on the timely arrival of monsoon rains. The ability to predict and adapt to these variations is of utmost importance in ensuring food security and the overall well-being of the Indian population. Therefore, the study and understanding of the monsoon onset date and its fluctuations are critical for policymakers, farmers, and meteorologists alike. The monsoon's earliest arrival was observed on May 11, 1918, while its hindered onset was recorded on June 18th 1972 (Pai et al., 2020). According to Deshpande et al., (1986), the monsoon typically takes 8 days to travel from Kerala to Mumbai, which is about 1 degree of latitude per day. The standard deviation is 7 days, which means that in most years, the monsoon will arrive in Mumbai within 15 days of arriving in Kerala. However, there have been a few years when the monsoon arrived in Mumbai much earlier or much later than expected. In the most extreme cases, the monsoon arrived in Mumbai 29 days after arriving in Kerala, or even 7 days before arriving in Kerala. However, these extreme cases are very rare. In the 84-year record (1901 to 1984), there have only been 3 years when the monsoon arrived in Mumbai earlier than Kerala, and in each of those years, it arrived just one day earlier.

The monsoon in India follows a typical pattern, taking about 45 days to progress from its onset in Kerala on June 1 to covering the entire country by July 15. However, the duration of this advanced phase can vary considerably from year to year. On average, the duration of the advanced phase is about 38 days, with a standard deviation of 11 days. This means that in most years, the monsoon advances over India in approximately 38 days, but it can be as short as 17 days or as long as 78 days. The shortest recorded advanced phase occurred in 1953 when it took only 17 days for the monsoon to encompass the entire country after starting in Kerala. Conversely, the longest advanced phase was documented in 2002, taking a prolonged 78 days for the monsoon to extend its coverage across the nation (Joseph, 2012). The variability in the duration of the advanced phase of the monsoon is attributed to several influencing factors. These include the strength and position of the monsoon winds, the

temperature conditions in the Indian Ocean, and the presence of any weather systems that might disrupt the monsoon's progress (Deshpande et al., 1986). As the monsoon season progresses, it typically begins to withdraw from northwest India during the first half of September. However, the timing of this withdrawal can also fluctuate significantly from year to year. The monsoon withdrawal process starts with the cooling of the Asian continent as it transitions from summer to the post-monsoon period. As the landmass cools, the low-level westerly winds gradually lose their strength and eventually reverse direction. This reversal of wind direction marks the beginning of the retreating monsoon season, leading to drier conditions and reduced rainfall. It is a critical phase in the annual monsoon cycle, impacting agriculture, water resources, and climate patterns in the region (Joseph, 2012).

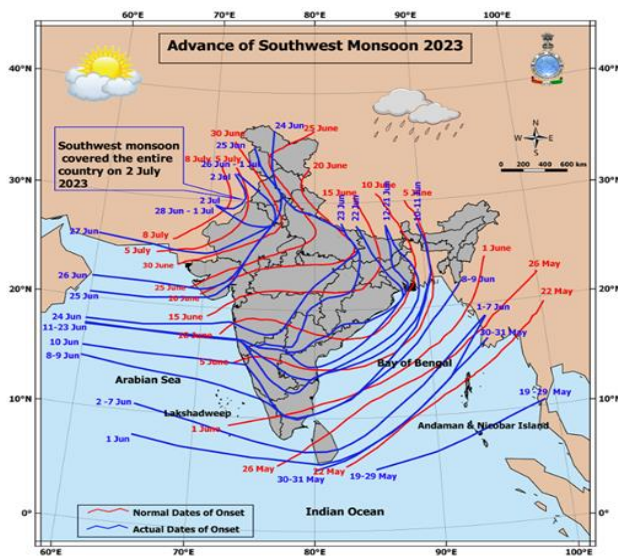


Fig. 1 Monsoon onset and advance 2023

(Source: https://mausam.imd.gov.in/imd_latest/contents/monsoon.php)

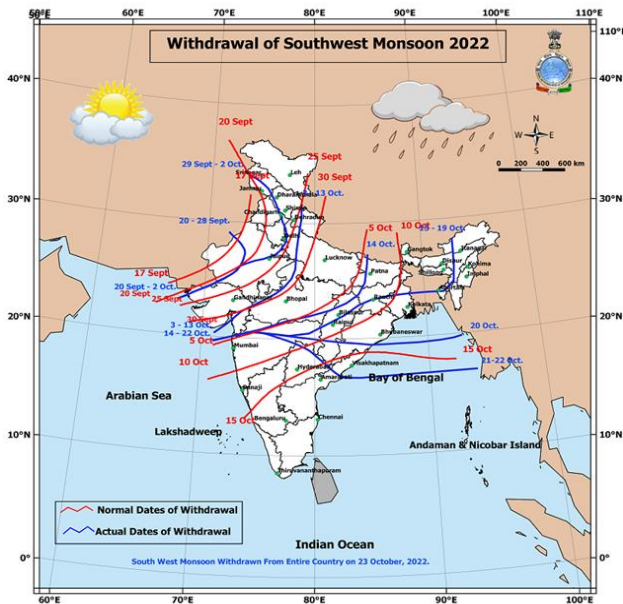


Fig. 2 Monsoon withdrawal 2023

(Source:

https://mausam.imd.gov.in/responsive/monsooninformation_withdrawal.php)

2.2.3. Semi-permanent systems associated with monsoon

Rainfall patterns in the Indian subcontinent are a consequence of distinct seasonal shifts in wind patterns. These shifts are driven by the contrast in temperatures between land and oceans, as well as the influence of the Coriolis force, resulting in well-defined and predictable meteorological changes that occur with the changing seasons. These patterns are interconnected and closely tied to the tropical circulation system. While some of these patterns persist throughout the summer monsoon season, their positions and intensity can vary from one year to the next and within the season itself. These variations are intricately linked to the strength of the monsoon circulation and how rainfall is distributed across India, both in terms of location and timing. The Indian Summer Monsoon is characterized by several semi-permanent meteorological features, including the Monsoon Trough (MT), heat low, Mascarene high, Low-Level Jet (LLJ), Tibetan High (TH), and Tropical Easterly Jet (TEJ). These features play a vital role in shaping the Indian Summer Monsoon and influencing the distribution of rainfall during the summer season, albeit with some year-to-year and seasonal variations (Khole, 2012).

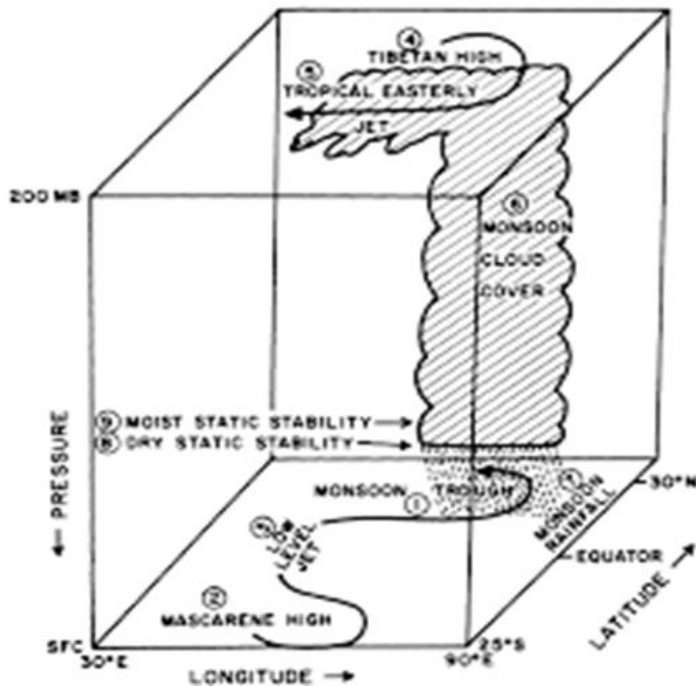


Fig. 3 Synoptic component of Indian summer monsoon

The Monsoon Trough (MT) is a notable meteorological feature that runs parallel to the Himalayan Mountains, stretching from west to east. It forms an elongated area of low pressure and is considered the equatorial trough during the northern summer in India and neighboring regions. As one moves upward, the Monsoon Trough tilts southward and extends to an altitude of approximately 5-6 kilometers above mean sea level. In the lower troposphere, temperatures tend to decrease as one moves southward from this trough (Koteswaram, 1960). The Monsoon Trough is associated with the development of monsoon depressions, each of which can bring a substantial amount of rainfall in a relatively short time. This feature becomes more prominent during July and August, and as September approaches, it gradually shifts its position to the south, with its western end becoming less well-defined (Khole, 2012). The Monsoon Trough also serves as a convergence zone where the prevailing wind patterns from the southern and northern hemispheres converge. In the equatorward part of this region, westerly monsoon winds dominate, while poleward of the trough, easterly trade winds prevail. Along the axis of the trough, heavy rainfall occurs, marking the onset of the peak rainy season for that location (Nanda, n.d.).

The heat low is a notable meteorological phenomenon in the Indian subcontinent resulting from the intense heating that occurs in the pre-monsoon months. This heating leads to the creation of a low-pressure belt spanning from North Africa to northwest India, passing through regions like Arabia and Pakistan. The most prominent low-pressure area within this belt, located over Pakistan and neighboring parts of northwest India, is commonly referred to as the heat low (Khole, 2012). The presence of the Himalayan mountain range significantly influences the formation of this heat low during the Indian summer monsoon season. During the monsoon season, the Himalayas play a crucial role in directing moisture-laden winds to ascend their slopes, causing the air to release most of its moisture on the southern side of the mountains. Consequently, the heat low is positioned over areas like Sindh and its neighboring regions, while the monsoon trough is established across northern India. The precise locations of these low-pressure centers are determined by the topography of the mountains and hills in the region (Nanda, n.d.). Mountains have a profound impact on atmospheric circulation due to two key factors: mechanical lifting and heating resulting from condensation. As air ascends over mountain barriers, it undergoes mechanical lifting, leading to changes in atmospheric pressure and wind patterns (Murakami, 1987). Additionally, as the rising air cools and experiences condensation, latent heat is released, further influencing atmospheric dynamics and contributing to the formation of the heat low and the monsoon trough during the Indian summer monsoon season.

The Mascarene High is a surface-level high-pressure system located in the Western Indian Ocean, typically positioned to the east or southeast of Madagascar, with its center near 30°S and 50°E. This high-pressure system generates a northward outflow that gathers moisture from the Indian Ocean and the Arabian Sea. This moisture-laden flow ultimately reaches India's west coast and further extends to the southeast coast of Bangladesh, manifesting as the south-westerly monsoon current (Nanda, n.d.). Additionally, the Mascarene High influences the low-level westerly jet in the Arabian Sea and subsequently in the Bay of Bengal. A robust Mascarene High is usually associated with an active monsoon in India, Bangladesh, and nearby regions (Khole, 2012). During the summer monsoon, the position of the Mascarene High

exhibits variations around its typical location, both longitudinally and latitudinally. According to Feng et al. (2003), the Mascarene High plays a pivotal role in influencing the broader atmospheric circulation between the two hemispheres. Their research indicates that the strengthening of the Mascarene High results in a significant enhancement of the Somali Low-Level jet and the summer monsoon circulation in tropical Asia and the western Pacific region. In essence, the intensification of the Mascarene High has substantial impacts on these meteorological phenomena, affecting wind patterns and monsoon activity in India.

The Tibetan high, a prominent feature of the Indian summer monsoon, plays a dominant role in shaping the region's weather patterns. Situated over the southwestern part of China, the Tibetan plateau is a vast landmass with dimensions of approximately 2000 kilometers from east to west and 600-1000 kilometers from north to south, characterized by an average elevation of 4 kilometers. The substantial heating of this plateau triggers intense thermal convection, causing the ascending air to disperse both northward and southward from the plateau. This divergence of air leads to the formation of a high-pressure system over Tibet, typically found at altitudes of around 300 or 200 hPa, commonly known as the Tibetan high. The existence of this phenomenon is upheld by the radiation balance over the Himalayan region (Khole, 2012). The air pressure at the plateau's surface ranges from 700 to 500 hPa. As described by Murakami (1987), the Tibetan plateau exerts a significant influence on the atmosphere by serving as a high-level heat source and acting as a mechanical barrier. The strength, position, and orientation of the Tibetan high are strongly impacted by the monsoon circulation across South Asia. Ramaswamy's work (1965) illustrates that a well-defined anticyclone over Tibet, extending from east to west at the 500 and 300 hPa levels, along with a well-defined high-pressure circulation over regions such as Siberia, Mongolia, and northern China, are associated with evenly distributed rainfall patterns over India.

The Tropical Easterly Jet (TEJ) is characterized by strong easterly winds, typically blowing at speeds ranging from 60 to 80 knots. These winds are observed in the higher troposphere, between the 150 and 100 hPa levels, and they form as a jet stream above Asia's subtropical ridge. The core of this jet is generally situated around

13.5°N over the Indian subcontinent. Over the Indian Ocean, the TEJ is most pronounced at an altitude of approximately 15 kilometers, with a speed of around 40 meters per second (Khole, 2012). The position of the core of the Tropical Easterly Jet varies during different months. In June and September, the core is typically found near Trivandrum, and in July and August, it is situated between Trivandrum and Chennai (Joseph and Raman, 1966). The formation of the TEJ is a consequence of the temperature gradient from south to north over India during the southwest monsoon. It makes its initial appearance over Kerala at the onset of the monsoon and gradually diminishes by October when the summer monsoon is largely concluded (Hastenrath, 1991, and Khole, 2012). In the South Asian region, there are substantial pressure and temperature variations between subtropical and equatorial latitudes, primarily due to the proximity of the equator and the presence of the high Tibetan plateau at approximately 40°N. Throughout the troposphere, temperatures are relatively high in the subtropics and lower in the equatorial zone. Consequently, this leads to a low-pressure zone in the subtropics and a high-pressure zone near the equator in the lower troposphere. In the middle and upper troposphere, this condition is reversed. The relatively low Coriolis force experienced in these latitudes means that even a slight pressure gradient can generate significant eastward flow, giving rise to the robust easterly jet stream observed over South Asia (Joseph and Sijkumar, 2004, and Khole, 2012).

2.2.3. Trends and Variations in Indian Summer Monsoon

The Indian summer monsoon exhibits a wide range of fluctuations on various time scales, including daily, sub-seasonal, interannual, decadal, and centennial variations. These fluctuations have significant implications for the Indian economy, particularly because critical sectors such as agriculture, allied industries, mining, and hydropower heavily rely on the monsoon's timing and intensity. Even slight alterations in the monsoon's behavior can lead to substantial economic and ecological consequences, including crop losses, droughts, and in severe cases, famine (Kumar et al., 2013 and Mohanty et al., 2023). For many centuries, it has been understood that the Indian monsoon rainfall exhibits both intra-seasonal and inter-seasonal variations (Gadgil and Joseph, 2003). Intra-seasonal variability results in active and break phases during

the monsoon season, with active phases characterized by significant rainfall and breaks marked by minimal precipitation (Mohanty et al., 2023). These fluctuations occur between June and September and significantly impact convection and precipitation over India.

Active and break events are identified based on the standardized deviation of precipitation over a key region, known as the monsoon core zone, exceeding 1 or falling below -1.0 for a minimum of three consecutive days during the peak monsoon months of July and August. An analysis by Rajeevan et al. in 2010, using data from 1951 to 2007, revealed that breaks tend to last longer than active spells, and prolonged breaks can lead to drought-like conditions. Approximately 80% of active spells lasted between 3 to 4 days, while only 40% of break spells were of such short duration. A small proportion (9%) of active spells and 32% of break spells extended for a week or more. While active events occurred nearly every year, 26% of the years examined had no occurrence of breaks. On average, there are 7 days of both active and break events from July to August, and there were no significant trends observed in the duration of these events. The study also highlighted a distinction between weak spells and extended, intense breaks. Weak spells were characterized by a weak, moisture-driven convective regime, while prolonged break events exhibited a circulation pattern akin to a heat trough over the Indian subcontinent before the monsoon onset. The evolution of rainfall patterns indicated that the revival from breaks was primarily due to the northward progression of the convective cloud zone. Significant differences were noted between the spatial patterns of active/break spells and those associated with interannual variability, particularly in their relationship with ENSO (El Niño-Southern Oscillation). This led to the conclusion that interannual variations in the Indian monsoon could not be primarily attributed to changes in intra-seasonal patterns. However, there were similarities in the signal over the eastern equatorial Indian Ocean on both intra-seasonal and interannual time scales.

Analyzing the trends in monsoon patterns is of great significance as it helps in understanding how monsoon rainfall has evolved over time. This information is invaluable for assessing the impacts of climate change, enhancing monsoon forecasting, facilitating water resources management planning, and mitigating the

consequences of droughts and floods. Through the examination of monsoon trends, scientists can gain deeper insights into how climate change is impacting the monsoon system and its effects on the region. This knowledge can be leveraged to improve monsoon forecasting models and formulate more effective adaptation strategies. Additionally, policymakers can use the insights from monsoon trend analysis to make informed decisions about water resource management, ensuring an adequate water supply to meet the needs of the population, especially in regions prone to droughts and floods. In a study conducted by Mohanty et al. in 2023, time series analysis and various nonparametric trend analysis methods were employed to detect significant trends in monsoonal rainfall patterns. The results revealed an overall positive trend in monsoonal rainfall across India as a whole. However, it was observed that in the past two to three decades, there has been an increased variability in seasonal rainfall, suggesting a rise in the occurrence of extreme rainfall years. Specifically, the northeastern region of India, known for heavy rainfall, showed a decreasing trend with a higher frequency of extreme rainfall years in recent times. In contrast, southern and central India exhibited a consistent trend in rainfall over the past century, with mean rainfall levels remaining relatively stable. These findings underscore the dynamic nature of monsoonal rainfall patterns and their regional variations.

The Low-Level Jet stream (LLJ) is a narrow band of wind with strong vertical and lateral wind shears, typically found in the lower atmosphere, at around 850 hPa. LLJ, plays a crucial role in carrying moisture from the nearby oceans to the Indian subcontinent, making it a significant factor in the Indian summer monsoon (ISM) (Sandeep and Ajaymohan 2015) LLJs are a regular component of the night time boundary layer and are commonly seen in areas with flat topography, such as the United States' Great Plains region (Holton, 1967). They are frequently connected with the transportation of heat and moisture and are generally strongest in the spring and summer months when temperature gradients are at their greatest. The topography, wind shear, temperature gradients, and other variables can all have a substantial impact on the strength and depth of LLJs. The monsoon low-level jet is one of the primary forces behind summer rainfalls. These powerful jets are typically cross-equatorial in character; they originate as easterly trade winds in the southern Indian

Ocean, pass the equator as southerlies, and then change to westerlies over the Arabian Sea before reaching the Indian subcontinent. Since its discovery, the jet's center has been located at 850 hPa and has been travelling at 20 to 30 m per second. (Joseph and Sijikumar 2004). The development and evolution of deep convection have been found to be correlated with the low level wind speed maxima, which are significant for both the horizontal and vertical fluxes of temperature and moisture. Ruchith et al. (2014) has shown that the LLJ core and intensity is varying within the day itself. The moisture transport influences the monsoon on a broad scale and the moisture transport depends on the core height and core speed of the LLJ (Wilson et al. 2019). They further concluded that the core height is higher in the Northern Hemisphere than in the Southern Hemisphere. In 2004, Joseph and Sijikumar conducted a study examining the fluctuations of the monsoon Low-Level Jet (LLJ) across the Indian sub-continent. They found that the central region of the LLJ is typically located between 10-15 °N latitude, but during the break condition of the monsoon, it tends to avoid passing directly over the Indian sub-continent. Additionally, their research highlighted the significant impact of convective heating over the Bay of Bengal on the strength of the LLJ in the Indian region. During periods of monsoon break, the intensity of wind is observed to be higher over the Southern Indian Ocean (SIO) while it decreases over the Arabian Sea. Similarly, wind speed over the southern Bay of Bengal (BoB) is greater during these break periods compared to active monsoon spells. Furthermore, the presence of a cyclonic circulation over northern India on days with active rainfall indicates the presence of the dynamic monsoon trough. (Wilson et al. 2019). On precession timescales, the Low-Level Jet (LLJ) undergoes alterations in its intensity, north-south position, and breadth. These changes have an impact on upwelling since upwelling relies on the wind stress curl, which, in turn, is influenced by these LLJ factors. (Jalihal et al. 2022) The connection between LLJs and deep convection shows that LLJ are significant regional climate factors. (Gimeno et al., 2016). The LLJ is strongly influenced by the Indian Ocean, and its structure and variability are closely linked to the oceanic conditions in the region. . LLJS undergoes significant changes in its vertical structure and intensity as it passes over different parts of the South Asian region. (Shinu et al., 2019). The MLLJ's moisture intake into the subcontinent has a significant impact on monsoon rainfall. Strong intra-seasonal

and inter-annual variations have also been observed in MLLJ. As a result, since MLLJ is a dynamic quantity, the variability of the Indian summer monsoon may be directly related to its fluctuations (Narayanan et al., 2016).

Indian Summer Monsoon (ISM) is linked to many of the climate modes El Niño Southern Oscillation, North Atlantic Oscillation, Indian Ocean Dipole, etc. (Gadgil et al., 2004; Goswami et al., 2006; Krishnamurthy, 2014) El Niño often leads to inadequate Indian Summer Monsoon Rainfall (ISMR), while La Niña tends to bring about ample ISMR. (Walker 1923; Webster and Yang 1992; Kumar et al. 1999; Lau and Nath 2000; Wang et al. 2003; Shukla et al. 2011; Shukla and Kinter 2014). The Indian Ocean Dipole (IOD) mode is identified by a specific pattern of sea surface temperature anomalies (SSTA) characterized by a seesaw-like distribution between the western and eastern equatorial Indian Ocean. (Saji et al., 1999) has been shown to have a noteworthy impact on the variability of Indian Summer Monsoon Rainfall (ISMR) and can also influence the relationship between the Indian Summer Monsoon (ISM) and El Niño-Southern Oscillation (ENSO) (Juan Dou et al., 2016).

This research investigated the changes in the Monsoon Low-Level Jet (MLLJ) throughout the southwest monsoon season from 1979 to 2022. It enhanced our comprehension of the various aspects of LLJ characteristics on both spatial and temporal scales. Furthermore, the study contributed to a deeper understanding of Indian Ocean processes, which can significantly impact the variations in LLJ. Additionally, it shed light on the crucial role played by LLJ in extreme precipitation events on the Indian subcontinent, especially in the context of a warming climate, and how it influences mechanisms related to convection, cloud formation, and precipitation.

CHAPTER 2

REVIEW OF LITERATURE

2.1. LOW LEVEL JET STREAMS

The Low-Level Jet stream (LLJ) is a relatively narrow wind band characterized by strong vertical and lateral wind shears. It is typically situated in the lower atmosphere. The robust cross-equatorial low-level jet stream (LLJ), located around the 850 hPa level, associated with the Asian summer monsoon occurring from June to September, is existing over Indian sub-continent approximately around the 850 hPa level. The LLJ serves a vital function in transporting moisture from the adjacent oceans to the Indian subcontinent, thereby playing a pivotal role in influencing the Indian summer monsoon (ISM) (Sandeep and Ajaymohan 2014). The low-level jetstream (LLJ) is a significant and semi-permanent component of the Asian summer monsoon and is a part of the monsoon Hadley circulation (Krishnamurti and Bhalme, 1976).

Bunker (1965) identified the presence of such a lower-tropospheric jet stream, which is less intense over the southwestern Arabian Sea. He created a vertical wind profile using Doppler radar data for a specific location (11 degrees North, 58 degrees East) in the Arabian Sea on September 1, 1964. Joseph and Raman (1966) provided a characterization of the monsoon low-level jet (LLJ). They described it as a wind current with its highest wind speed occurring below 6 kilometers in altitude. The wind velocity should follow an ascending and then descending pattern with height, encompassing a range of at least 10 knots (equivalent to 0.5 meters per second) while maintaining a wind direction change of no more than 40 degrees. Their investigation revealed that the low-level jet stream (LLJ) is typically observed over peninsular India, with its central region situated at approximately 1.5 kilometers above the Earth's surface and exhibiting wind speeds in the range of 20 to 30 meters per second (equivalent to 40 to 60 knots). The winds exhibit a well-defined seasonal pattern, and their behavior varies in opposite phases in two specific altitude ranges, below and above 4-5 kilometers. . Findlater (1966, 1967) conducted a study on the cross-

equatorial jet stream at lower altitudes over the eastern regions of Kenya during the summer monsoon. This research indicated that wind speeds reached levels between 25 and 50 meters per second at altitudes ranging from 1.2 to 2.1 kilometers above mean sea level. Findlater (1969a) conducted an examination of the cross-sectional characteristics of the cross-equatorial jet stream over Kenya and the East African coast, utilizing methods involving pilot balloons, radio techniques, and aircraft measurements. He demonstrated that this LLJ is cross-equatorial and originates from the easterly trade winds in the south Indian Ocean. The LLJ winds originating in the south Indian Ocean crossed the equator within a narrow longitudinal region near the east African coast, forming a southerly jetstream. Subsequently, the LLJ changed direction to the west over the Arabian Sea, traversing peninsular India and the Bay of Bengal.

Krishnamurti et al. (1976) employed a single-level primitive equation model, emphasizing the significance of factors such as the East African Mountains, land-sea thermal variations, and the beta effect in simulating the behaviour of the LLJ. A time-dependent model based on primitive equations, which incorporated specified zonal flow, mountainous terrain, and adiabatic heating, was employed in a study conducted by Hoskins and Rodwell in 1995. Their research revealed the LLJ's high sensitivity to variations in convective heating over the Indian Ocean. Joseph and Sijikumar, in 2004, discovered a strong correlation between the intensity of convective heating over the Bay of Bengal and the strength of the LLJ, particularly its zonal wind component at 850 hPa over peninsular India, with a lag of 2-3 days, with convective heating leading the changes. A similar connection was observed for the western Pacific Ocean in a study by Joseph and Sabin in 2008.

Intra seasonal variability of Monsoon Low level Jet is studied widely by many researchers. Joseph and Sijikumar 2004 analysed during active and break times. They found that the central region of the cross-equatorial Low-Level Jet (LLJ) traverses the equator within a specific and consistently narrow longitudinal zone near the East African coast, manifesting as a southward current. Upon reaching India, it transforms into a westward current, covering latitudes ranging from the equator to 25.8 degrees

North. During active monsoon periods, the central core of the Low-Level Jet (LLJ) traverses peninsular India at approximately 15.8 degrees North latitude. In contrast, in break monsoon conditions, the LLJ originating from the central Arabian Sea takes a southeastward trajectory, passing near Sri Lanka within the latitude range from the equator to 10.8 degrees North. During this period, a less pronounced LLJ axis is frequently observed in northern India, situated around 25.8 degrees North latitude. During break monsoon periods, two branches of the Low-Level Jet (LLJ) are observed over India. However, it's worth noting that the northern branch is situated around 25.8 degrees North, deviating from the approximately 17.8 degrees North position identified by Findlater. (Joseph and Sijikumar 2004). Sam and Murthy (2002) also explored the dynamics of the Monsoon Low-Level Jet (MLLJ) and its variations during the transition from the active phase to the break phase of the monsoon. Their study included assessments of turbulence characteristics both above and below the MLLJ. Their key observation was that the strength of the Monsoon Low-Level Jet (MLLJ) serves as a reliable indicator of monsoon activity, exhibiting changes in intensity between the active and break phases of the monsoon.

Interannual and long-term variability of the low-level jetstream was investigated by Shynu et al. in their 2018 study. To examine this variability, the researchers divided the LLJ domain, covering the Indian and west Pacific Oceans, into six regions or boxes based on their physical characteristics. The study also analyzed the long-term changes in the LLJ and its associations with Indian monsoon rainfall and the El Niño index. An essential discovery from their research is that the Low-Level Jet (LLJ) component south of the equator in the Indian Ocean (ITz) exhibits a notably low correlation with the Indian Summer Monsoon Rainfall (ISMR), N3.4, and wind components on the interannual time scale. Contrary to the general concept, where trade winds in the ITz region are believed to cross the equator and veer right to transform into the monsoon flow their findings challenge this conventional understanding. The intensity of the westerly Low-Level Jet (LLJ) across the Arabian Sea is directly influenced by the strength of the monsoonal heat source, (Chakraborty et al., 2009). Convective heating of the atmosphere enhances LLJ winds, with stronger LLJ winds correlated with heightened cyclonic vorticity in the

atmospheric boundary layer, leading to increased convection and rainfall. This establishes a positive feedback loop between convection and wind on the intra-seasonal time scale, as discussed by Joseph and Sijikumar (2004) and Joseph and Sabin (2008). The study finds that the Low-Level Jetstream (LLJ) over India exhibits reduced strength on days characterized by a break in the monsoon. This weakening trend is correlated with a growing frequency of break monsoon days observed in recent decades (Wilson et al., 2018). In the past few decades, there has been a notable decrease in the strength of the Low-Level Jet (LLJ) flowing through peninsular India. Simultaneously, the flow south of peninsular India has shown an opposite trend, becoming stronger. This shift is closely linked to the rising occurrence of break monsoon days. They also find that during break monsoon spells, the axis of the Low-Level Jet (LLJ) shifts towards the equator, particularly east of longitude 70 degrees East.

Wilson et al. (2019) conducted a study on the cross-sectional structure of the Low-Level Jet (LLJ) during the Asian summer monsoon season. Their research reveals that the core wind speed of the LLJ undergoes spatial and temporal variations. The Arabian Sea experiences the highest wind speeds within the LLJ. Furthermore, the altitude at which the maximum wind speed occurs varies, with the core height of the LLJ influenced by the physiography of the location. Over the oceanic region, the peak wind speed is found at a lower altitude of 925 hPa, while over the land region, it occurs at a higher level of approximately 850 hPa. Additionally, the study reveals that, influenced by convective forcing and lower boundary effects, the core height of the Low-Level Jet (LLJ) is elevated to greater altitudes over continental regions. Observations indicate that the core speed of the LLJ in the Southern Indian Ocean (SIO) experiences a decrease (increase) during active (break) spells, attributed to the zonal pressure gradient. The shift of the LLJ poleward over the Arabian Sea on break days is potentially linked to the repositioning of the monsoon trough to the foothills of the Himalayas during this period. The strength of the monsoon Low-Level Jet (LLJ) demonstrates an upward trend during years characterized by excess rainfall, while it experiences a decline in intensity during deficient years. (Wilson et al., 2019). Ruchith et al.'s 2014 study, using high-resolution measurements from a Doppler wind lidar,

found pronounced diurnal variations during the monsoon season. The research highlighted that both the height and speed of the jet core exhibit distinct patterns. In the evening, the jet core descends to an altitude between 600 meters and 900 meters above the surface, while it ascends after sunrise, reaching heights exceeding 1800 meters by the afternoon. The study also revealed that the jet core's speed strengthens during the night, peaking in the early morning hours before decreasing when the core is at its maximum height. Simultaneous variations in surface temperature, heat flux, and the Richardson number showed that daytime heating and turbulence in surface layers promote mixing in the daytime boundary layer, aiding the ascent of the jet core. Additionally, turbulence generated by shear and momentum fluxes significantly contributes to the diurnal changes in the Monsoon Low-Level Jet (MLLJ). These findings underline the close connection between factors influencing the evolution of the convective boundary layer and the formation of the nocturnal boundary layer and the diurnal variations observed in the MLLJ during the monsoon season over the south Indian peninsula. A study focused on how the intensity of the low-level jet (LLJ) and its impact on upwelling in the Arabian Sea revealed that changes in LLJ wind speed, jet width, and its meridional (north-south) position all influence upwelling (Jalihal et al., 2020). On a yearly basis, wind speed changes primarily determine the average upwelling. On much longer timescales related to Earth's precession, variations in the width and position of the jet become crucial. These variations are influenced by convective heating in the western equatorial Indian Ocean and northeastern Africa, as described in the works by Jalihal, Bosmans, et al. (2019) and Jalihal et al. (2020). The convective heating sources are a result of precessional forcing. The changes in LLJ strength, width, and position lead to a more pronounced wind stress curl during periods of weaker summer insolation. Consequently, the spatial extent of upwelling becomes significantly larger in such climates, even when the summer monsoon is not as strong. As a result, proxies indicate increased productivity (upwelling) during these climate conditions.

Research conducted by Purwar et al. (2022) on the connection between the Monsoon Low-Level Jet (MLLJ) and rainfall reveals that changes in the MLLJ's strength and altitude serve as valuable indicators for predicting variations in the

Indian Summer Monsoon Rainfall (ISMR). Notably, the impact of the MLLJ on rainfall across the Indian subcontinent is most pronounced during the onset and withdrawal stages of the monsoon. The upward trend in the altitude of the MLLJ suggests the potential for increased rainfall in various Indian regions, with a particular focus on Western Ghats and Central India (Purwar et al. 2022).

A study conducted by Ramesh Kumar in 2009 investigated the characteristics of convective systems, including their frequency, geographic location, duration, and movement patterns, in relation to breaks in monsoon conditions over the Indian subcontinent during contrasting monsoon years. The study observed that, during excess monsoon years, the low-level wind flow at 850 hPa was notably stronger and directed towards the Indian subcontinent, whereas in deficit monsoon years, it was weaker and directed towards the equatorial region. Furthermore, during deficit monsoon years and prolonged breaks in monsoon conditions, approximately 69% of these convective systems formed further south compared to excess monsoon years. The study also identified a significant shift in the latitude (5.4°) and longitude (6.9°) of these systems, particularly in the peak monsoon month of July. This shift indicated a substantial influence of convective systems over the northwest Pacific Ocean on monsoon activity over the Indian subcontinent. This shift in the genesis of cyclones over the northwest Pacific Ocean could be attributed to changes in the low-level jet and convective activity over the equatorial eastern Indian Ocean (Rameshkumar et al., 2009). In a 2015 study by Sandeep and Ajaymohan, it was observed that the Indian Summer Monsoon's low-level circulation, especially the Low-Level Jetstream (LLJ), shifts poleward due to increased land-sea temperature contrasts. This shift in the LLJ is accompanied by a corresponding shift in the latitude where absolute vorticity reaches zero, primarily over the Arabian Sea. Due to the poleward shift, the Low-Level Jetstream (LLJ) strengthens to the north and weakens to the south of 15°N over the Arabian Sea. This shift in the LLJ corresponds to a wet pattern in the northern regions and a dry pattern in the southern regions, notably affecting the Western Ghats and adjoining areas of India (Sandeep and Ajayamohan, 2015). In a 2020 study conducted by Viswanadhapalli et al., the variability of the monsoon low-level jet (MLLJ) was examined using dynamically downscaled simulations spanning a 37-year

period (1980–2016). The study employed the Weather Research Forecasting (WRF) model. Key findings include the systematic diurnal variation of the MLLJ: maximum winds from the large-scale monsoon jet, driven by synoptic factors, occur during the daytime, while orographic channelled winds through geographical features like the mountains of East Africa, Hejaz, and Western Ghats dominate during the night. These diurnal shifts in monsoon winds play a crucial role in modulating the moisture convergence process and subsequently influence the evolution of rainfall over India. Furthermore, the study's seasonal and monthly climatology of monsoon winds indicates that the model effectively replicates the spatial wind patterns while slightly overestimating the mean monthly winds over the Bay of Bengal and Arabian Seas by 2–3 meters per second. The analysis of wind variability indicates that the Monsoon Low-Level Jet (MLLJ) experiences a consistent increase in wind speed on both seasonal and monthly scales, with the exception of August. The weakening of the MLLJ during August has significant implications. It leads to a decrease in the formation of monsoon depressions over the Bay of Bengal and an increase in the number of break days. These changes are associated with a reduction in precipitation over the central Indian region (Viswanadhapalli et al., 2020).

Sankar Prasad Lahiri's 2022 study explores the connection between upwelling, the Indian Summer Monsoon (ISMR). Specifically, the research examines the relationship between ISMR and the intensity of upwelling over the Somalia and Oman Coasts, using a sea surface temperature (SST)-based upwelling index. The findings indicate that both upwelling regions show a significant relationship with Mean Sea Level Pressure (MSLP) and ISMR in different parts of India. However, these relationships do not necessarily coincide with each other. While the upwelling index (UI) correlates well with ISMR, other factors like changes in Indian Summer Monsoon (ISM) circulation, SST gradient, and moisture gradient may also play a crucial role in influencing ISMR. And also Oman's Upwelling Index (UI) correlates with reduced wind speed and increased upwelling, while Somalia's UI is linked to the monsoon trough's movement. These relationships impact the Indian Summer Monsoon (ISMR). Oman's UI relates to future wind changes, while Somalia's UI influences ISMR through monsoon trough movement (Lahiri et al., 2022). According to Jalihal et al.'s 2022 study, upwelling in the Arabian Sea under contemporary

climate conditions is strongly connected to the low-level jet's strength and the South Asian summer monsoon. Over longer timeframes, changes occur not only in the low-level jet's strength but also in its position and width. These changes impact the intensity and spatial extent of upwelling, which, in turn, has implications for how proxies of upwelling should be interpreted.

So the objective of this study is to investigate the structure and variability of the monsoon low-level jet (LLJ) across various regions of the Indian Ocean and its intricate interactions with processes within the Indian Ocean. Additionally, the research aims to assess the influence of the LLJ on the interaction between convective clouds and precipitation patterns in the context of a warming climate.

CHAPTER 3

MATERIALS AND METHODS

3.1 STUDY AREA

The study region encompasses the extensive stretch of the Indian Ocean, stretching from the northern boundary at approximately 40 degrees north latitude to the southernmost limit around 50 degrees south latitude. This vast area extends from the eastern longitude of about 20 degrees east to the western boundary at approximately 120 degrees east. Geographically, it encompasses a substantial portion of the Indian Ocean, including diverse marine ecosystems, maritime territories, and key oceanographic features spanning across this extensive longitudinal and latitudinal range.

The study employed vertical cross-sections, known as transects, to analyze the LLJ's structure and behavior at different locations along its path over the Indian Ocean region. These transect were drawn perpendicular to the wind flow and represented meteorologically sensitive regions, such as (Shinu et al., 2019) in (Fig.4), the shaded portion is windspeed.

1. Indian Ocean (20°S - 5°S, 60°E - 90°E)
2. Equatorial Indian Ocean (5°S - 5°N, 35°E - 55°E)
3. Arabian Sea (5°N - 18°N, 50°E - 70°E)
4. Indian subcontinent (5°N - 20°N, 72°E - 80°E)
5. Bay of Bengal (5°N - 20°N, 82°E - 100°E)

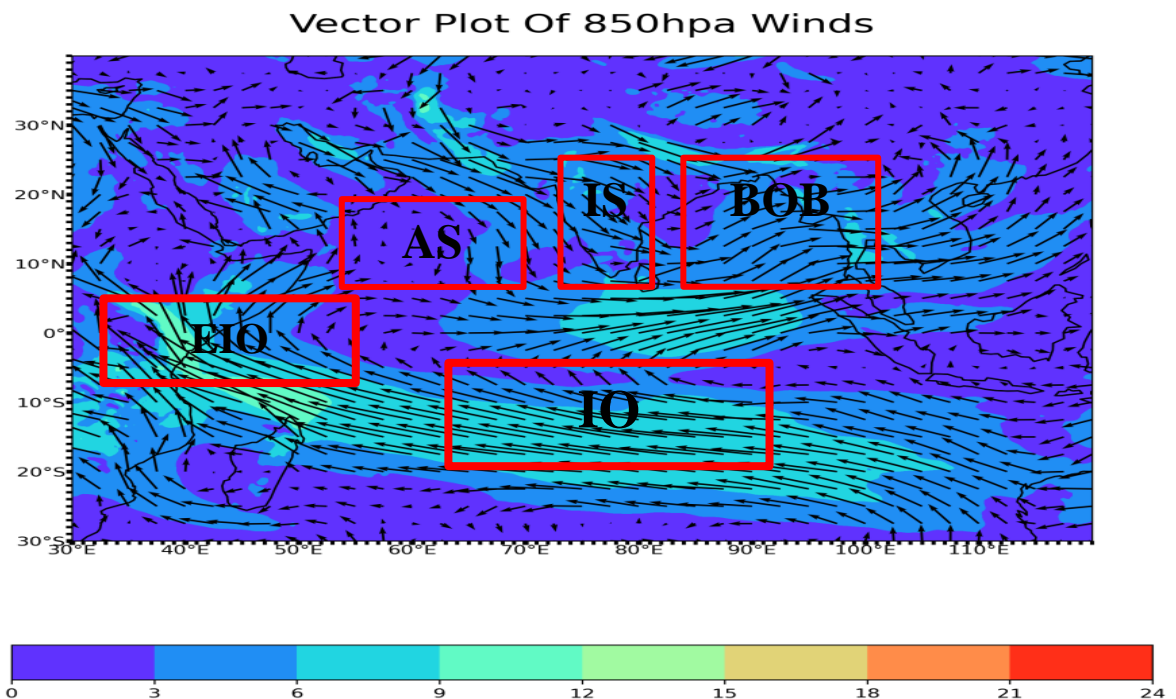


Fig. 4 Vector plot of 850 hPa winds in Indian ocean

The present study utilizes daily zonal and meridional wind profiles over the Indian Ocean region of 44 years (1979 to 2018) from reanalysis datasets obtained from the fifth-generation ECMWF (European Centre for Medium-Range Weather Forecasts) reanalysis ERA-5. (Hersbach et al. 2020); (<https://cds.climate.copernicus.eu>) . This dataset has a spatial resolution of 0.25 degrees latitude and longitude and the pressure levels ranging from 1000 hpa to 500 hpa. To analysis, the hourly data is converted into daily mean. The ERA 5 Interim dataset, developed by ECMWF, represents the most recent global atmospheric reanalysis. Notably, this dataset exhibits improved accuracy in capturing low-frequency variations compared to earlier ECMWF reanalyses. Additionally, it is integrated with data from conventional climate datasets that rely solely on observational data. We have taken radiosonde as the reference data. The radiosonde data over Goa station is used for comparison. The NOAA Optimum Interpolation Sea Surface Temperature Version 2 (NOAA OI SST V2) High-Resolution Dataset, (<https://psl.noaa.gov/>) for daily sea surface temperature data spanning from 1982 to 2021, is utilized to calculate the upwelling index within the geographical regions of Oman, Somalia, and the Southeastern Arabian Sea. This dataset features a spatial resolution of 0.25 degrees latitude and longitude. The Met Office Hadley Centre Global Sea Ice and Sea Surface Temperature (SST) monthly dataset with 0.5×0.5 spatial resolution, (<https://www.metoffice.gov.uk/hadobs/hadisst>) (Rayner et al., 2003), is used for the determination of key climate indices, including the Indian Ocean Dipole (IOD), Subtropical Indian Ocean Dipole (SIOD), and El Niño-Southern Oscillation (ENSO) index. We used 0.25° × 0.25° gridded daily rainfall data for Indian summer monsoon season (June to September) spanning from 1979 to 2018. This dataset was sourced from the India Meteorology Department (IMD) (<https://cdsp.imdpune.gov.in>) (Purwar et al., 2022) and is derived from the daily cumulative rainfall measurements collected at 6995 rain gauge stations (Pai et al., 2014). To analyze the future perspective of the structure and variability of the monsoon low-level jet, you can use CMIP6 (Coupled Model Intercomparison Project Phase 6) modeled historical data from 1850 to 2014 and projection data from 2015 to 2096. The data source is from the CMIP6 data portal, which is accessible at

<https://wcrp-cmip.org/> CMIP is a global effort that provides climate model simulations and data to better understand climate change and its impacts.

3.3 METHODOLOGY

In this study, a comprehensive analysis of reanalysis data was undertaken as zonal wind for the selected regions IO, AS,IS,BOB and meridional wind for the EIO to investigate the structural transformation of the monsoon Low-Level Jet (LLJ) across the entire Indian Ocean region. The study determines the core height of the Monsoon Low-Level Jet (MLLJ) by computing the average zonal wind speed within the MLLJ domain and then identifying the highest value among various vertical pressure levels, typically spanning from 1000 to 500 hPa. This maximum speed is referred to as the core speed. (Purwar et al., 2022; Shynu et al., 2019). In accordance with the structure of the Low-Level Jet (LLJ), the core speed denotes the altitude at which the wind velocity decreases on either side. We assess the reliability of reanalysis data sets by utilizing a comparative approach with radiosonde data as the reference. The radiosonde data over Goa station is used for comparison. The jet speed and core height were calculated for both radiosonde and ERA 5 data sets and were compared. This comparison involved the analysis of scatter plots, bias, spread, and Root Mean Square (RMS) error. The spread was assessed by quantifying the differences between the radiosonde and ERA5 measurements. This was followed by the finding the difference between the wind speed values at the 84th and 16th percentiles for each altitude.(Ruchith et al., 2014) The bias and RMS error is calculated by:

Bias = (Mean of Observed Data) - (Mean of Reanalysis Data)

RMS Error = $\sqrt{[\sum(\text{value_observed} - \text{value_reference})^2 / N]}$

To gain insights into the vertical structural features, the study analyzed the seasonal variability of zonal and meridional wind during June to August for the chosen regions. In addition, trend properties of the Jet characteristics were examined for each region on a monthly and seasonal basis, and these analyses were conducted over three distinct time periods: the entire study period (1979-2022), the pre-20 epoch

(1979-2000), and the post-20 epoch (2001-2022). The Mann-Kendall (MK) test, a robust and non-parametric statistical method, was used for the significance of trend analysis (Mann, 1945; Kendall, 1948) This test is used to verify whether there is a consistent monotonic increase or decrease in the trend of the variable within the specified time domain. Importantly, the MK test does not rely on any specific data distribution. In this test, the initial value of the MK statistics is set to zero, and if a positive trend is detected, this value is incremented by one. (Salami et al., 2016; Lahiri et al., 2019; Vissa and Tyagi, 2021)) Furthermore, the study encompassed the assessment of the percentage of occurrence and the analysis of the mean and variability of the jet properties, both on a monthly and seasonal scale. To examine the relationship between core height and core speed, scatter plots and correlation coefficients were calculated as part of the comprehensive analysis.

To investigate the relationship between jet properties and sub-seasonal ocean processes, the study analyzed the upwelling index for the Somali region (2–10°N, 46–52°E), Oman region (16–22°N, 54–60°E), South Eastern Arabian Sea (SEAS) (7–15°N, 70–78°E). The calculation of this index involved determining the temperature difference between the initial sea surface temperature (SST) value near the coastline and one located 5° away from the coast. The choice of a 5° difference is based on the consideration that upwelling regimes can influence ocean conditions up to 350-400 km offshore (Antony et al., 2002). To assess the correlation between the jet properties and upwelling in the Oman and Somalia regions, a Pearson's correlation test was conducted. Additionally, a lag and lead correlation analysis with a 6-day interval was performed. (Lahiri and Vissa , 2022). The Arabian Sea Mini Warm Pool (ASMWP), part of the Indian Ocean Warm Pool, forms in the eastern Arabian Sea just before the summer monsoon. It's located in the southeastern Arabian Sea, between 4°–14°N and 68°–78°E, with SST exceeding 30°C in April and May (Neema et al., 2011) is analysed and correlated with the jet properties of all five regions.

To understand the relationship between jet properties and cloud precipitation properties, Convective Available Potential Energy (CAPE) data is used. CAPE represents the amount of energy available for a parcel of air as it ascends vertically within the atmosphere. It is a crucial parameter used to quantify the energy necessary

for convection to occur (Al-Taai and Abbood , 2020). We calculated the daily spatial correlation between the properties of the Monsoon Low-Level Jet (MLLJ) and CAPE and we also conducted lag and lead correlation analysis with a 15-day interval. Furthermore, these analyses were performed over three distinct time periods: the entire study period (1979-2022), the pre-20 epoch (1979-2000), and the post-20 epoch (2001-2022). We also conducted a sliding correlation analysis over all regions with a 15-day lag and lead.

Then this study utilized Total Column Water (tcw), which is the vertical integral from the Earth's surface to the nominal top of the atmosphere. It quantifies the total amount of water in the column, encompassing water vapor, cloud water, and cloud ice, while excluding precipitation. We calculated the daily spatial correlation between the properties of the Monsoon Low-Level Jet (MLLJ) and water transport. Furthermore, we conducted lag and lead correlation analyses with a 15-day interval. The same procedures were applied to convective precipitation, which is a type of precipitation occurring when warm, moist air ascends rapidly in unstable atmospheric conditions. As the air rises, it cools, leading to the condensation of water vapor and cloud formation. The resulting water droplets or ice crystals increase in size and eventually fall as precipitation, such as rain or hail, under the influence of gravity. Convective precipitation is typically caused by the natural ascent of warmer, lighter air in colder, denser surroundings.

To examine the characteristics of the Monsoon Low-Level Jet (MLLJ) during various ocean-atmospheric coupled processes, we analyzed the Indian Ocean Dipole (IOD), the Southern Indian Ocean Dipole (SIOD), and the El Niño-Southern Oscillation (ENSO) indexes. The Indian Ocean Dipole (IOD) is defined by the variation in sea surface temperature between two distinct areas, creating a dipole pattern. It comprises a western pole located in the Arabian Sea, part of the western Indian Ocean, and an eastern pole situated in the eastern Indian Ocean, south of Indonesia. The IOD index is computed based on the anomalous sea surface temperature (SST) gradient between the western equatorial Indian Ocean (50E-70E and 10S-10N) and the southeastern equatorial Indian Ocean (90E-110E and 10S-0N). The Subtropical Indian Ocean Dipole (SIOD) features sea surface temperature

(SST) oscillations, with the southwest Indian Ocean south of Madagascar experiencing alternating warm and cold phases relative to the eastern part. The SIOD index is determined by the difference in sea surface temperature (SST) anomalies between two regions: (55°E–65°E, 37°S–27°S) and (90°E–100°E, 28°S–18°S) (Behera and Yamagata, 2001). And El Niño/Southern Oscillation (ENSO) represents the atmospheric-ocean interaction in the tropical Pacific causing periodic shifts in sea surface temperatures and alternating dry and wet conditions over several years. Through the computation of these indexes, we were able to discern the years associated with both positive and negative phases of IOD, SIOD, and ENSO. These indexes were then compared with the core height and core speed.

In this study, we investigate the interannual and intraseasonal variations in MLLJ speed and height along with rainfall data for different months within the Indian summer monsoon. The spatial correlation is assessed by comparing MLLJ height and speed with rainfall data for JJAS (June, July, August, and September). The correlation analysis is performed with a 28-day lag to capture the relationship between MLLJ height and rainfall (Purwar et al., 2022).

IITM Earth System Model

IITM-ESM, from IITM, enhances the US CFS model into a long-term climate model. IITM-ESM1.0 improved sea surface temps and monsoon links. IITM-ESM2.0 is a balanced global climate model with aerosol effects, sea ice, and monsoon rainfall improvements. It's India's first model for IPCC CMIP6. The IITM Earth System Model (IITM-ESM) employs four tier-1 scenario runs for the late 21st century, which include SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5. These scenarios encompass a broad spectrum of potential future socio-economic advancements, land use patterns, and emission trajectories, each associated with different levels of global warming. The numbers 2.6 to 8.5 indicate the stratospheric-adjusted radiative forcing in Wm^{-2} expected by the end of the 21st century. The IITM-ESM also incorporates the emissions scenario RCP 8.5 and the socioeconomic scenario SSP 5. Representative Concentration Pathways (RCPs) are used to depict various climate change scenarios. Higher RCP values signify elevated greenhouse gas emissions, leading to higher

global temperatures and more severe climate change impacts. Conversely, lower RCP values are more favorable for human well-being but necessitate more rigorous climate change mitigation measures to attain them.

IITM ESM historical and projection data is utilized for comparing LLJ (Low-Level Jet) characteristics. Core height and core speed are calculated for historical data from 1850 to 2014 and projection data from 2015 to 2098. The percentage of occurrence is then determined.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 COMPARISON OF ERA 5 REANALYSIS WITH RADIOSONDE DATA

Monsoon low level jets are important contributor in bringing and regulating the moisture supply to the Indian sub-continent during the south-west monsoon season. So the variability study will be more beneficial in fine detailing the cloud-precipitation process during that season. As mentioned in the previous chapter, the reanalysis data sets were using largely in the atmospheric and Oceanography fields in order to study the large scale features in a deeper manner. So it is important to see whether the used ERA-5 data sets were useful in capturing the LLJ characteristics. In order to get a general idea, monthly climatology of time-height variations of zonal wind for the selected regions IO, AS, IS, BOB and meridional wind for the EIO were plotted as shown in (Fig. 5).

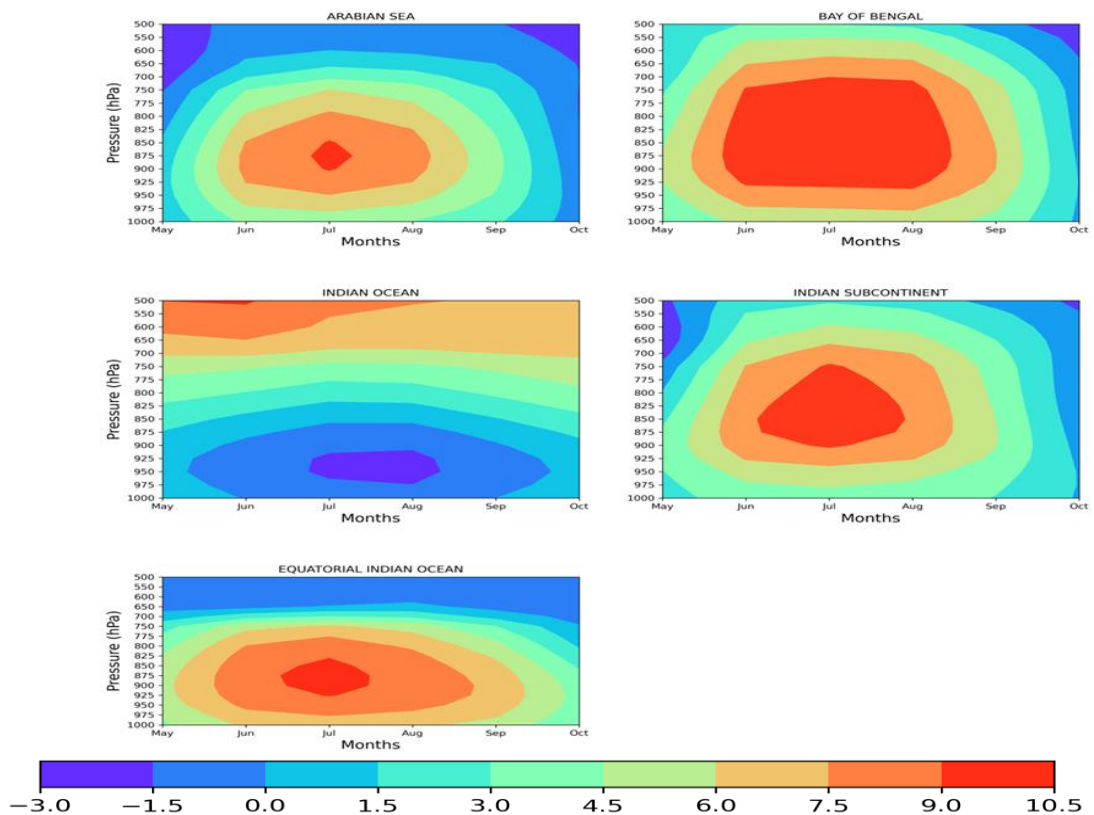
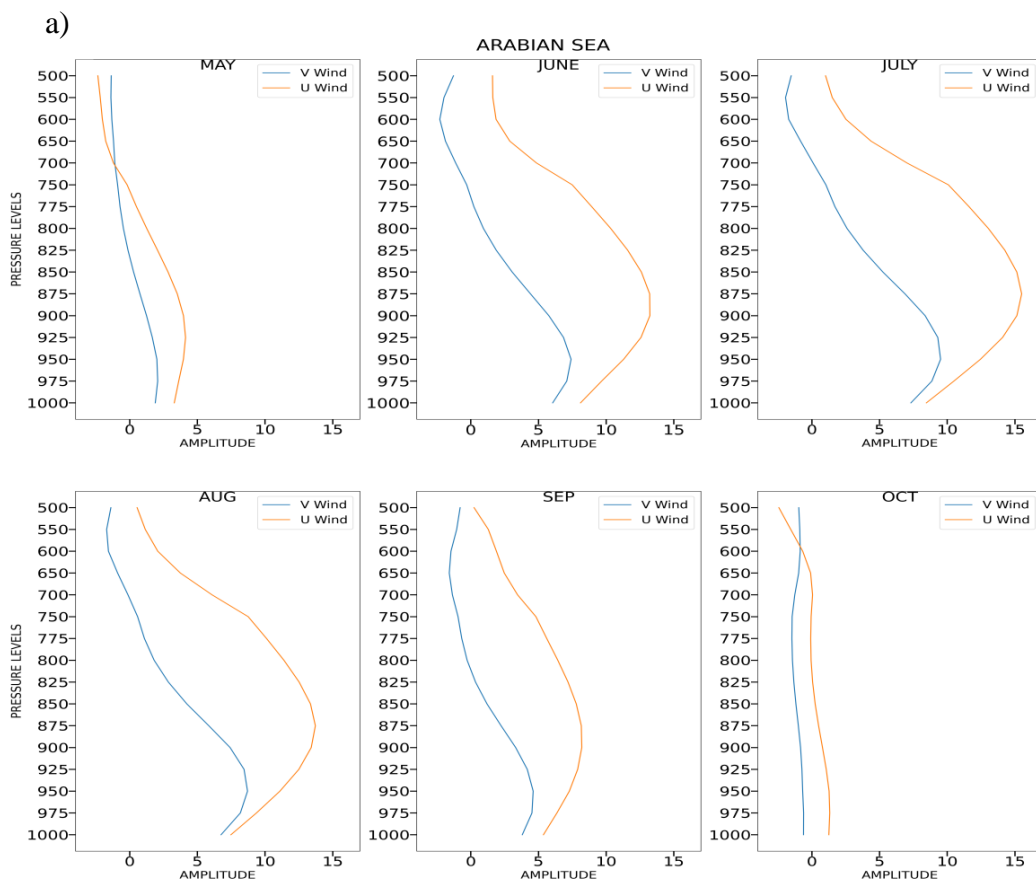
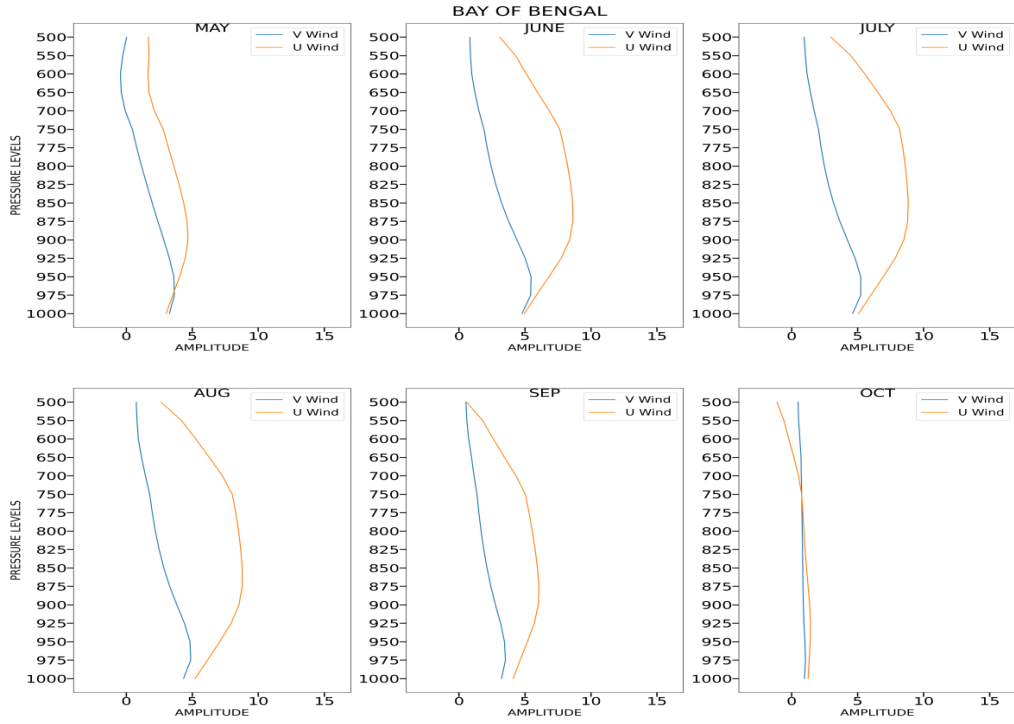


Fig. 5 Monthly climatology of time-height variations of zonal wind for the selected regions IO, AS, IS, BOB and meridional wind for the EIO

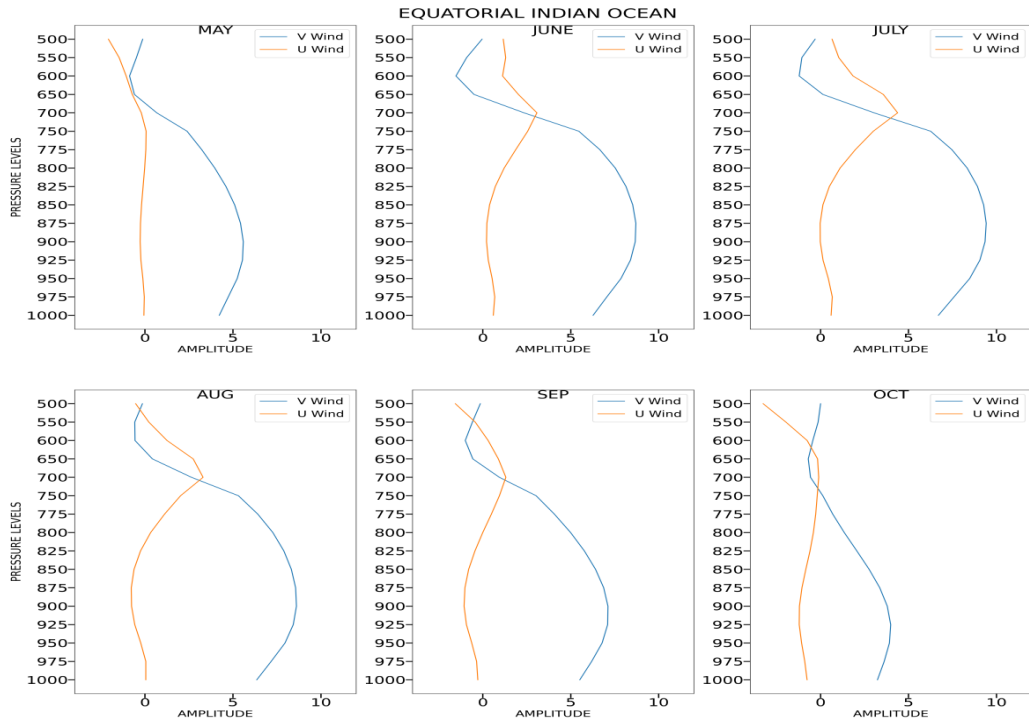
The evolution and persistence of Monsoon low level jet during the June-September months is clearly visible in these figures. For investigating further, the height profiles of zonal and meridional wind were plotted for the months May to October for the selected regions and were represented in (Fig 6. a,b,c,d,e) . This further elaborates the presence of monsoon Low level jet in the lower altitudes during the monsoon season.



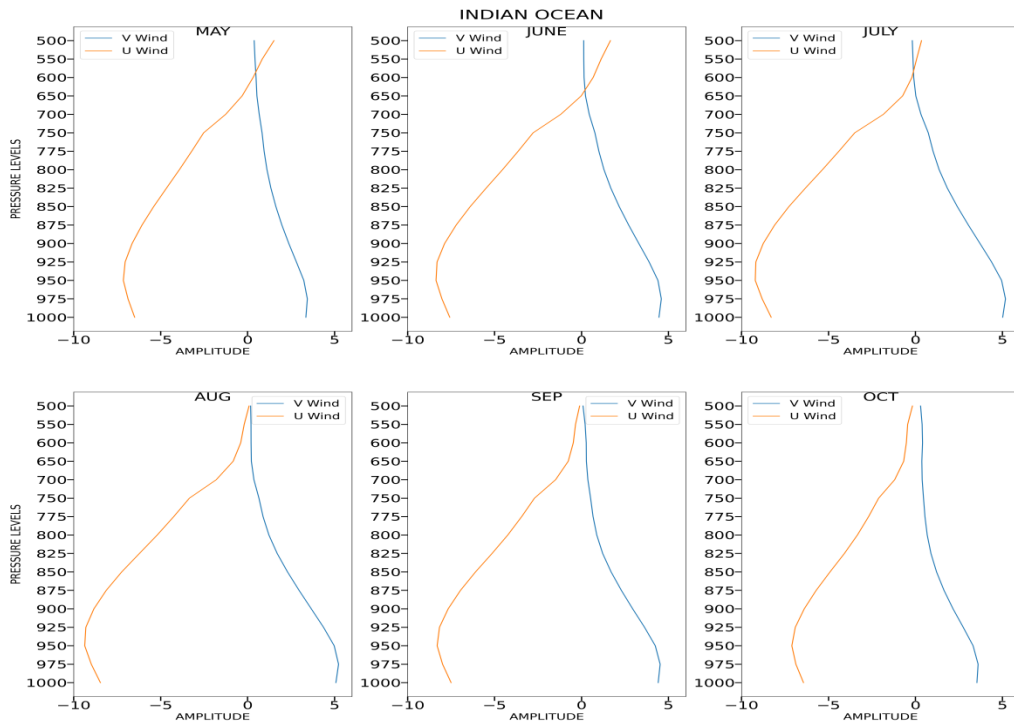
b)



c)



d)



e)

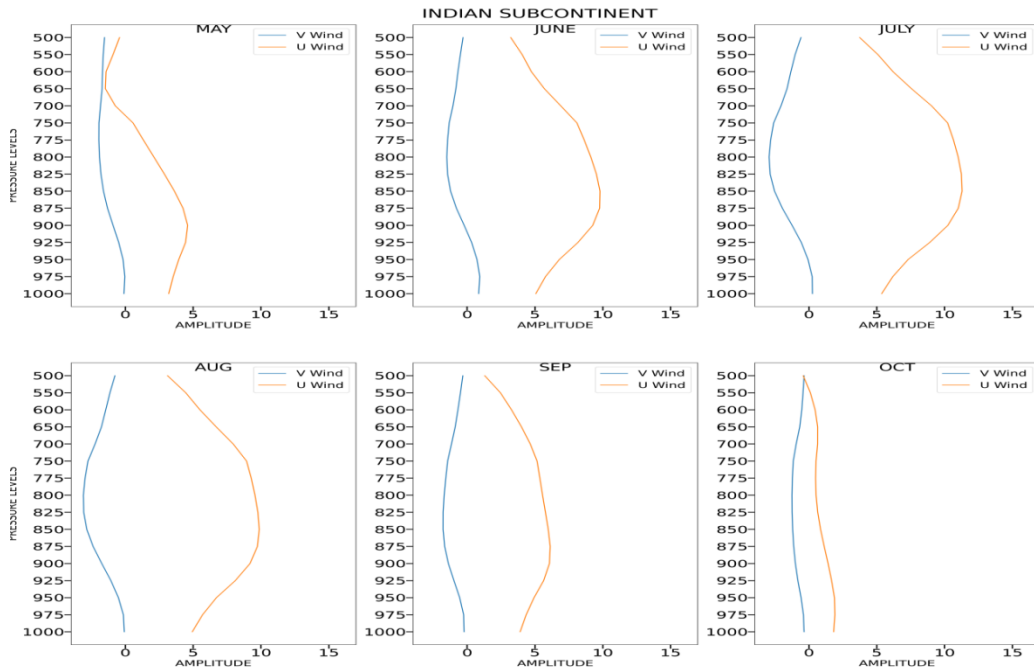


Fig. 6 Height profiles of zonal and meridional wind for the months May to October for the regions (a) Arabian Sea, (b) Bay of Bengal (c) Equatorial Indian Ocean, (d) South Indian Ocean, (e) Indian Subcontinent

Before going into the detailed discussion on the investigation of variability of monsoon low level jet by using the ERA 5 data sets, it is worthwhile to compare the fidelity of this data sets with a reference data set. Here in this study we have taken radiosonde as the reference data. The radiosonde data over Goa station is used for comparison. The jet speed and jet core height were calculated as mentioned in the methodology section from both radiosonde and ERA 5 data sets and were compared. The scatter plot made between these data sets were represented in (Fig. 7) The correlation values for core height and core speed were 0.54 and 0.85 respectively. This results indicates that both the data sets were showing good agreement. The calculation of bias for both the jet characteristics implies a slight underestimation of ERA 5 data sets with the in-situ measurements. The bias values are -40.53 hPa and -0.485 m/s respectively for core height and core speed. Spread values were tabulated as 90.58 and 11.08 respectively. RMSE values are also less implying the fidelity of ERA5 data sets for utilizing in the MLLJ characteristics investigation.

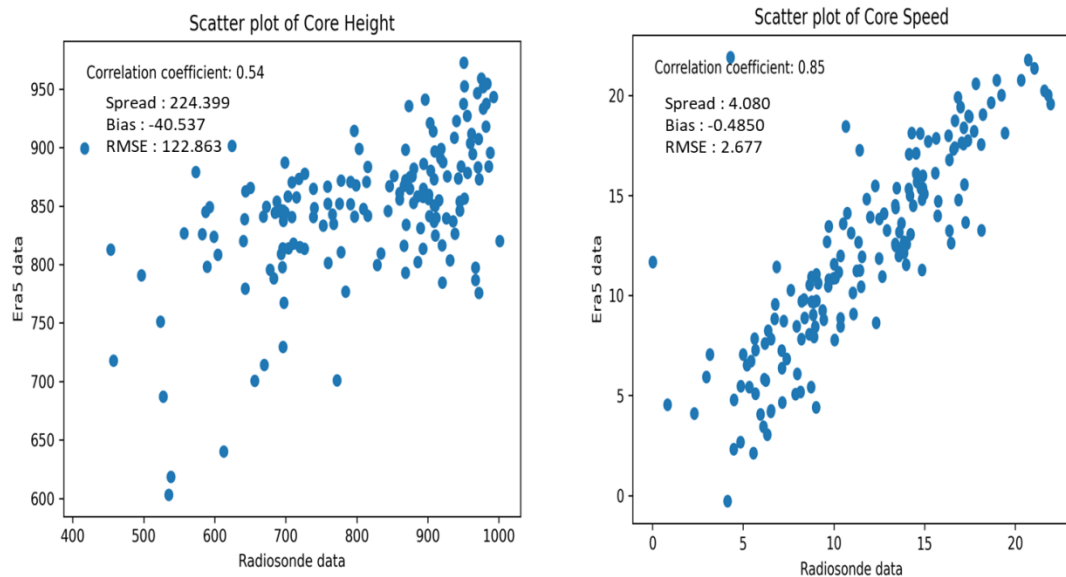


Fig. 7 Scatter plot of ERA5 and radiosonde wind data for core height and core speed

4.2 STRUCTURAL VARIABILITY IN MONSOON LOW LEVEL JET PROPERTIES

Monsoon low level jet characteristics are having pivotal role in atmospheric dynamics. So their characterization is so important in terms of atmospheric science aspects. The occurrence of Jet properties in the season (June-August) is portrayed as coreheight in (Fig.8) and corespeed in (Fig.9). In order to get an idea on the vertical structural characteristics, monthly variability (May-Oct) of jet properties were analyzed for selected regions is shown in Table (1,2,3,4,5). seasonal (June-August) variability of jet properties were analyzed as shown in (Fig. 10). On a seasonal scale, Higher core height is observed over EIO region and lower core height is observed over IO region. In case of variability, maximum variability is seen over IO region where as minimum is seen over EIO region and Jet core speed is seen maximum (minimum) in AS (IO) region. Mean Jet core height for this selected regions were found to be 973.07 ± 5.96 , 874 ± 16.9 , 849.62 ± 24.11 , 830.70 ± 39.85 , 832.47 ± 41.25 and mean jet speed were found to be 5.01 ± 0.6469 , 10.49 ± 1.07 , 15.79 ± 3.1 , 11.43 ± 3.4 and 9.857 ± 3.09 respectively for the selected regions.

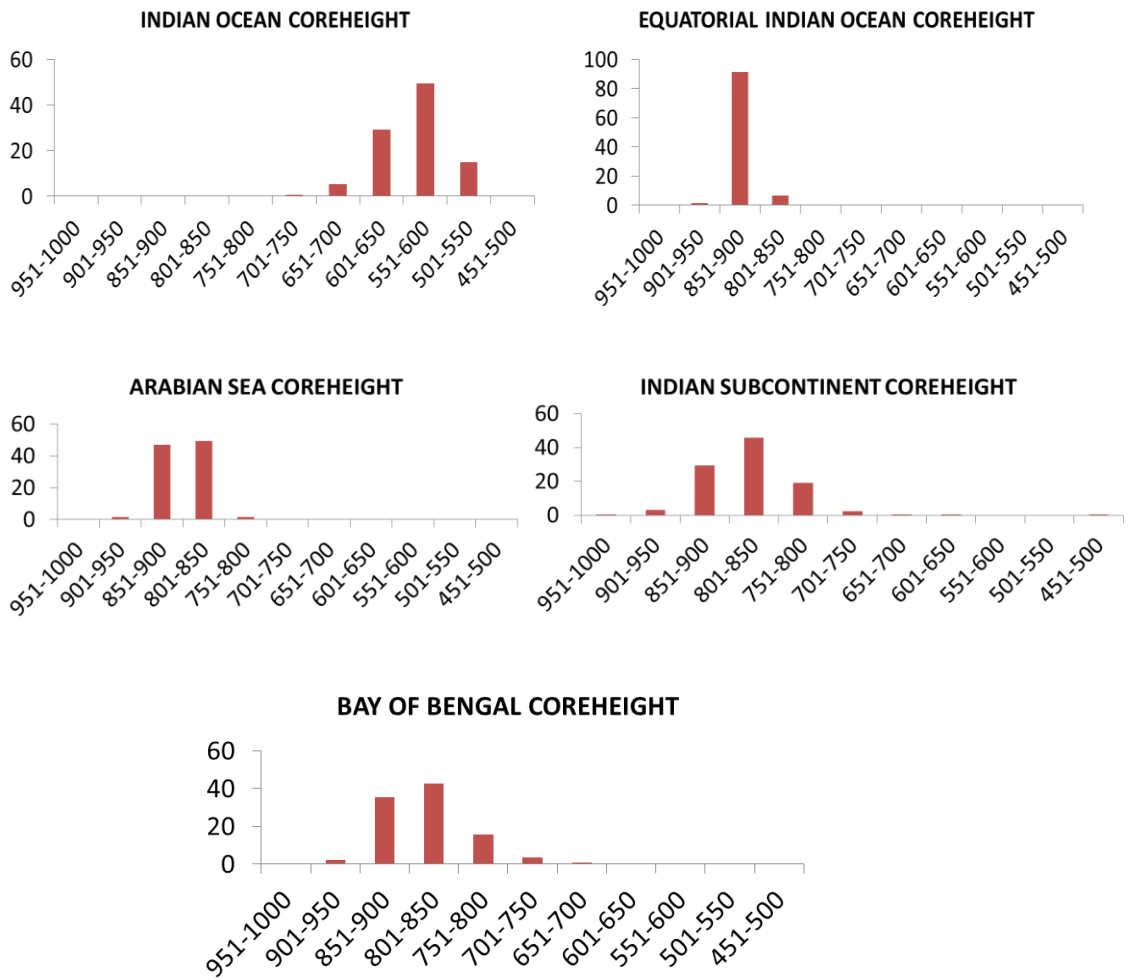


Fig. 8 Seasonal (JJA) Percentage of Core Height Occurrence

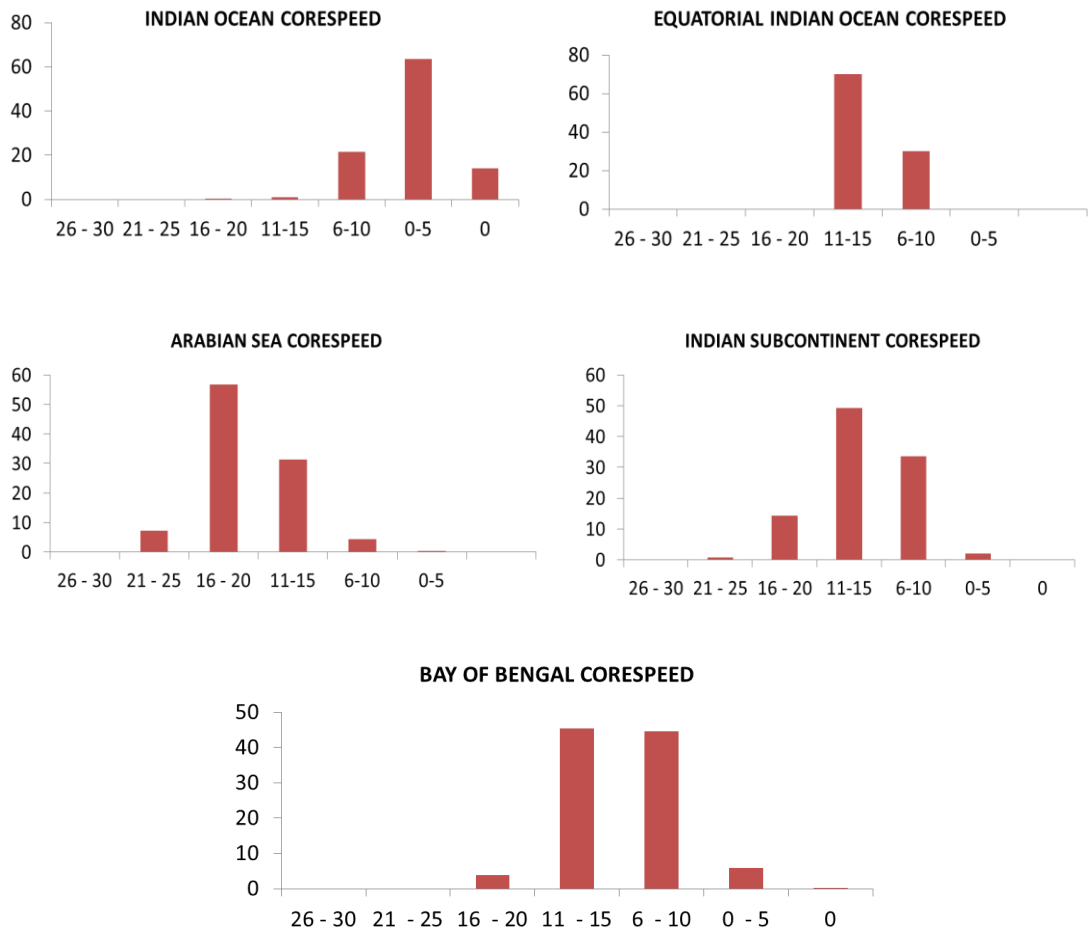


Fig. 9 Seasonal (JJA) Percentage of Core Speed Occurrence

Months	Mean		Standard deviation
	Mean	Standard deviation	
May	585.2053	41.15051	
June	581.2066	37.47685	
July	590.7568	36.96288	
Aug	594.3172	37.82864	
Sep	599.6164	40.65724	

Oct	610.4253	44.98381
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Table 1 Monthly variability of jet properties of Equatorial Indian Ocean

COREHEIGHT			CORESPEED	
Months	Mean	Standard deviation	Mean	Standard deviation
May	878.723	38.090	6.59219	2.042
June	874.330	18.091	10.034	1.129
July	869.691	16.806	10.963	0.9628
Aug	878.005	14.780	10.475	0.890
Sep	889.951	12.8375	9.0900	1.1852
Oct	849.124	69.2739	4.988	2.118

Table 2 Monthly variability of jet properties of Arabian Sea

COREHEIGHT	CORESPEED
------------	-----------

Months	Mean	Standard deviation	Mean	Standard deviation
May	860.420	65.004	5.4210	3.4974
June	859.368	24.037	14.773	3.646
July	843.176	20.694	17.241	2.4688
Aug	846.65	24.41	15.319	2.758
Sep	836.376	63.1788	9.747	3.557
Oct	797.427	88.150	3.44	3.846

Months	Mean	Standard deviation
May	860.4209	65.00424
June	859.3682	24.03771
July	843.176	20.69483
Aug	846.6573	24.41941
Sep	836.376	63.17887
Oct	797.4274	88.15095

Table 3 Monthly variability of jet properties of Indian Subcontinent

COREHEIGHT			CORESPEED	
Months	Mean	Standard deviation	Mean	Standard deviation
May	853.04	66.482	5.733	2.4947
June	833.160	41.663	10.981	3.277
July	829.574	35.320	12.356	3.3480
Aug	829.448	42.1895	10.935	3.4143
Sep	823.230	73.256	7.4459	3.5312
	COREHEIGHT		CORESPEED	
Oct	798.379	90.345	3.959	3.652
Months	Mean	Standard deviation	Mean	Standard deviation
May	812.489	69.3448	6.1599	3.180

Table 4 Monthly variability of jet properties of Bay of Bengal

June	830.280	40.908	9.8244	3.032
July	828.944	42.0340	9.9132	3.159
Aug	838.135	40.0946	9.8334	3.078
Sep	852.296	66.560	7.0482	3.491
Oct	812.482	89.0482	3.1436	3.9518

Months	Mean	Standard deviation
May	812.4891	69.34484
June	830.2802	40.9081
July	828.9442	42.03404
Aug	838.1356	40.09469
Sep	852.2966	66.56011
Oct	812.4824	89.04822

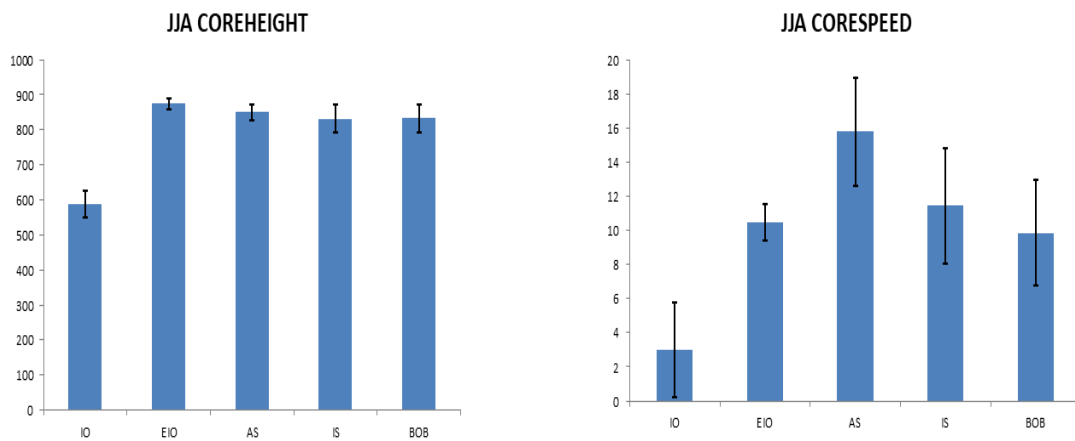


Fig. 10 Seasonal (JJA) mean standard deviation of jet properties in each region

It is very important to know the trend properties of the Jet characteristics over each region. For this linear trend analysis were applied to seasonal values of Jet core height and Jet core speed for each selected regions as depicted in (Fig.11) , (Fig.12). And the for both parameters and for each region we have plotted three trend lines for three periods. One is plotted for whole study period (1979-2022) and pre-20 (1979-2000) and post-20 (2001-2022). Trend analysis of core height Analysis on the IO region shows that all the trend lines indicates increasing nature of core height. The Jet core trend analysis gives some interesting results. Although the overall trend shows increasing, both the epochs shows contrast in their trends. Positive (negative) trend is visible in pre-20 (post-20) epoch. In case of EIO region, core height shows a considerable increasing trend in all the epochs considered. But the post epoch trend highlight more sharp trend as compared to pre-20 epochs. Trend characteristics are showing similar behavior as of IO region. Although the core height over AS region shows an increasing trend in whole range of years, the pre-20 and post-20 epochs are showing considerable differences. Post-20 epoch shows a decreasing trend in the core height. In case of sore speed both the epochs are showing positive trend which

indicates the unaltered increase of jet speed over Arabian sea. IS region trend characteristics also shows interesting result. In case of core height, although the trend shows an increasing trend in whole period of consideration, the different epochs displays quite different behavior in which recent epoch shows a strong increase in trend. Even though both epochs are showing contrasting nature in trend analysis of core speed, their magnitude is less over IS region. The trend analysis over the last region considered (BB region) is also carried out. The common trend exhibits an increase in core height . But the seperated epochs shows dissimilarities.It is seen that the rate of decrease is less in the recent epoch. Core speed shows a decreasing trend in all the epochs. But Sharper decrease is observed in the post-20 epoch. The Mann-Kendall test is performed over monthly trend lines for three time periods, and their significance is observed, as shown in the Table (6,7,8,9,10,11,12,13,14,15).

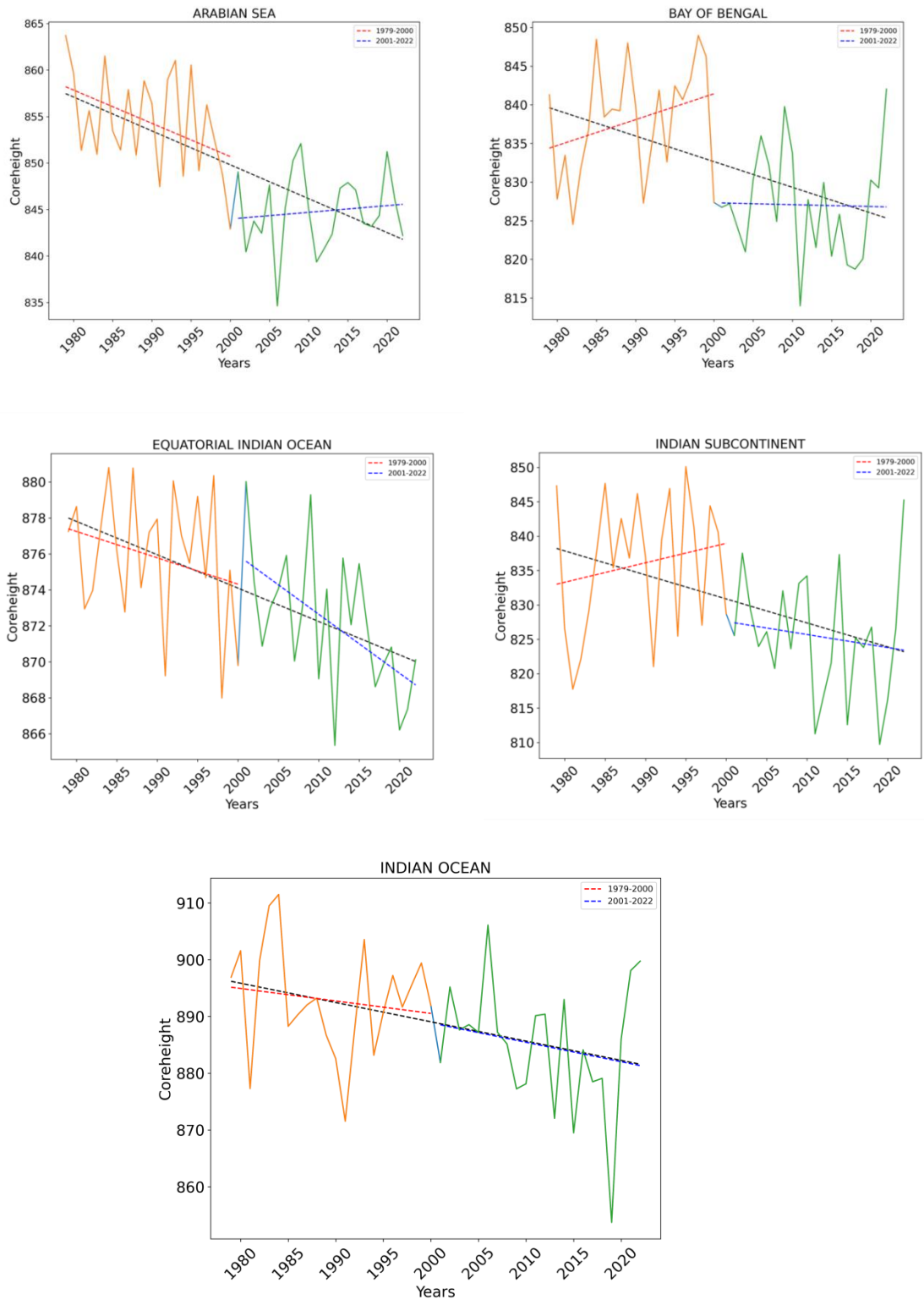


Fig. 11 Seasonal (JJA) trend of core height in each region

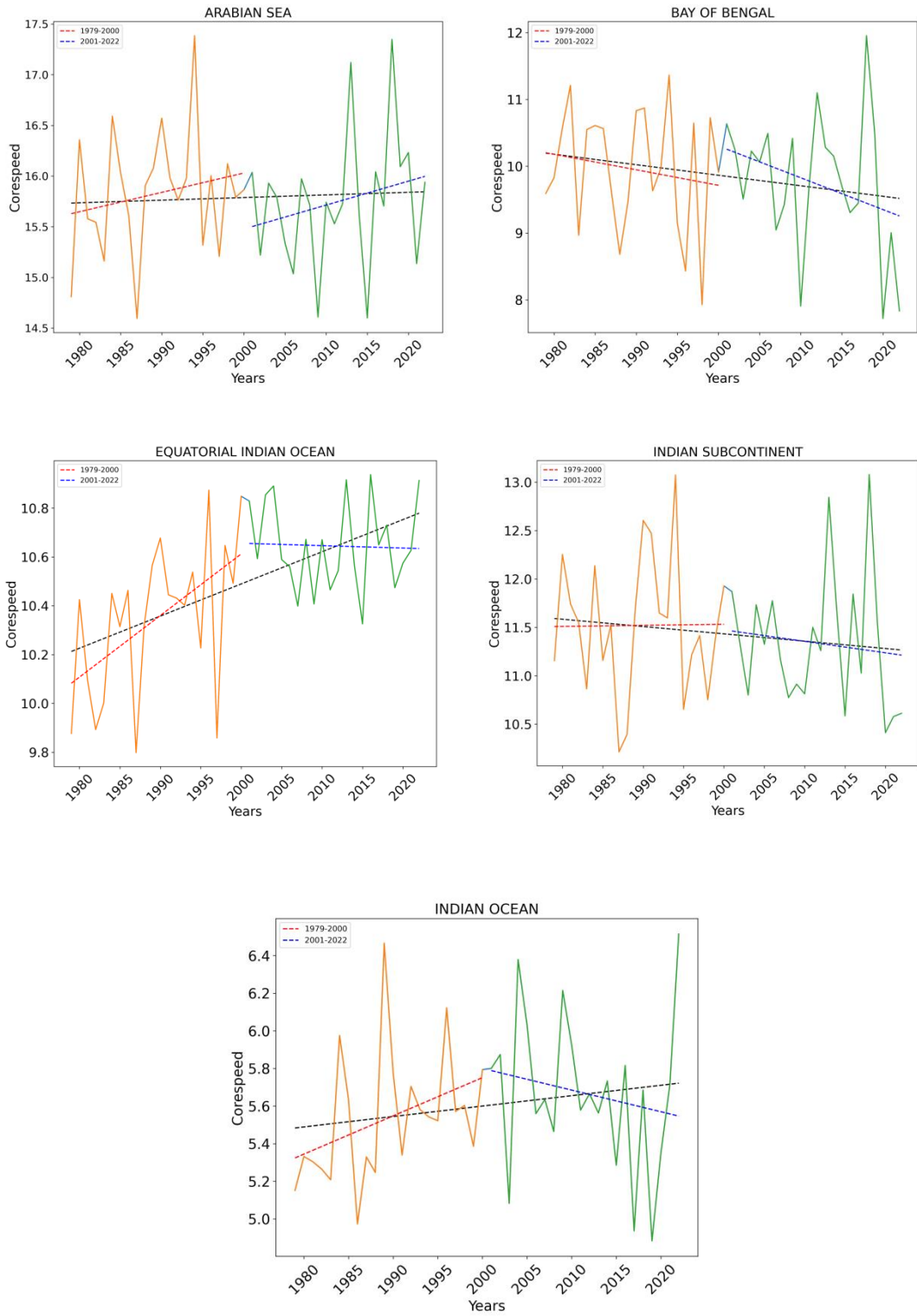


Fig. 12 Seasonal (JJA) trend of core speed in each region

Table 5 Mann-Kendall Test: Monthly Significance of Arabian Sea Core Height

ARABIAN SEA COREHEIGHT			
	Whole period	Pre 20	Post 20
May	-0.366	0.00402	-1.1222
June	-0.282**	-0.485	0.3762
July	-0.482***	-0.405	-0.430
Aug	-0.326	-0.186	0.280
Sep	-0.482	-4.981	0.276
Oct	-0.396	-3.002	0.373

Table 6 Mann-Kendall Test: Monthly Significance of Arabian Sea Core Speed

ARABIAN SEA CORESPEED			
	Whole period	Pre 20	Post 20
May	0.033	0.118	-0.031
June	-0.003	-0.024	-0.015
July	0.019	0.085*	0.030
Aug	0.040	0.175	0.060
Sep	0.040**	0.175*	0.060
Oct	0.021	0.265	0.013

Table 7 Mann-Kendall Test: Monthly Significance of Bay of Bengal Core height

BAY OF BENGAL COREHEIGHT			
	Whole period	Pre 20	Post 20
May	-0.721*	-0.117	-1.779
June	-0.104	0.896	-0.219
July	-0.637***	-0.385	-0.275
Aug	-0.246	0.512	0.415
Sep	-0.707***	-4.763	-0.247
Oct	0.315	-1.833	0.313

Table 8 Mann-Kendall Test: Monthly Significance of Bay of Bengal Core Speed

BAY OF BENGAL CORESPEED			
	Whole period	Pre 20	Post 20
May	0.020	0.075	-0.09*
June	-0.033	-0.069	-0.062
July	0.008	0.052	-0.034
Aug	-0.023	-0.053	-0.046
Sep	0.025	0.195	-0.014
Oct	0.007	0.189	0.019

Table 9 Mann-Kendall Test: Monthly Significance of Equatorial Indian Ocean Core Height

EQUATORIAL INDIAN OCEAN COREHEIGHT			
	Whole period	Pre 20	Post 20
May	0.099	0.300	-0.613
June	-0.212	-0.024	-0.346
July	-0.210***	-0.264	-0.468
Aug	-0.133**	-0.146	-0.168
Sep	-0.157***	-0.002	0.019
Oct	0.336	2.082	0.639

Table 10 Mann-Kendall Test: Monthly Significance of Equatorial Indian Ocean Core Speed

EQUATORIAL INDIAN OCEAN CORESPEED			
	Whole period	Pre 20	Post 20
May	0.036***	0.055	-0.012
June	0.0160**	0.021	-0.005
July	0.019***	0.036***	0.011
Aug	0.004	0.018	-0.008
Sep	0.021	0.035	0.009
Oct	0.012	0.074	0.005

Table 11 Mann-Kendall Test: Monthly Significance of Indian Subcontinent Core Height

INDIAN SUBCONTINENT COREHEIGHT			
	Whole period	Pre 20	Post 20
May	-0.500	-0.806	-1.77
June	-0.436***	0.196	-0.382
July	-0.420***	-0.140	-0.290
Aug	-0.192	0.790	0.097
Sep	-0.700***	-4.730**	0.103
Oct	-0.007	-2.728	-0.170

Table 12 Mann-Kendall Test: Monthly Significance of Indian Subcontinent Core Speed

INDIAN SUBCONTINENT CORESPEED			
	Whole period	Pre 20	Post 20
May	0.016	0.069	-0.052
June	-0.023	-0.032	-0.059
July	0.016	0.092	0.016
Aug	-0.016	-0.057	0.005
Sep	0.038**	0.202**	0.031
Oct	0.017	0.239	-0.002

Table 13 Mann-Kendall Test: Monthly Significance of Indian Ocean Core Height

INDIAN OCEAN COREHEIGHT			
	Whole period	Pre 20	Post 20
May	-0.374	-0.023	0.078
June	-0.144	0.057	-0.522
July	-0.413	-0.416	-0.242
Aug	-0.454	-0.290	-0.267
Sep	0.087	1.280	0.537
Oct	-0.634	-0.394	-0.339

Table 14 Mann-Kendall Test: Monthly Significance of Indian Ocean Core Speed

INDIAN OCEAN COREHEIGHT			
	Whole period	Pre 20	Post 20
May	0.005	0.031	0.011
June	0.0003	0.018	-0.017
July	0.004	0.021	-0.013
Aug	0.011	0.020	-0.004
Sep	0.009	0.015	-0.014
Oct	0.008	0.021	0.007

p-value less than 0.01 (1% significance level): '***'

p-value between 0.01 and 0.025 (1% to 2.5% significance level): '**'

p-value between 0.025 and 0.05 (2.5% to 5% significance level): '*'

Another interesting feature is the association among the jet parameters at different locations. This is investigated by using (Fig.13). Apart from the IO region all other regions show considerable relation between jet speed and jet core height. It is

seen that AS, IS and BB region shows good correlation with each other. So this study indicates that jet speed increase in jet height in these regions.

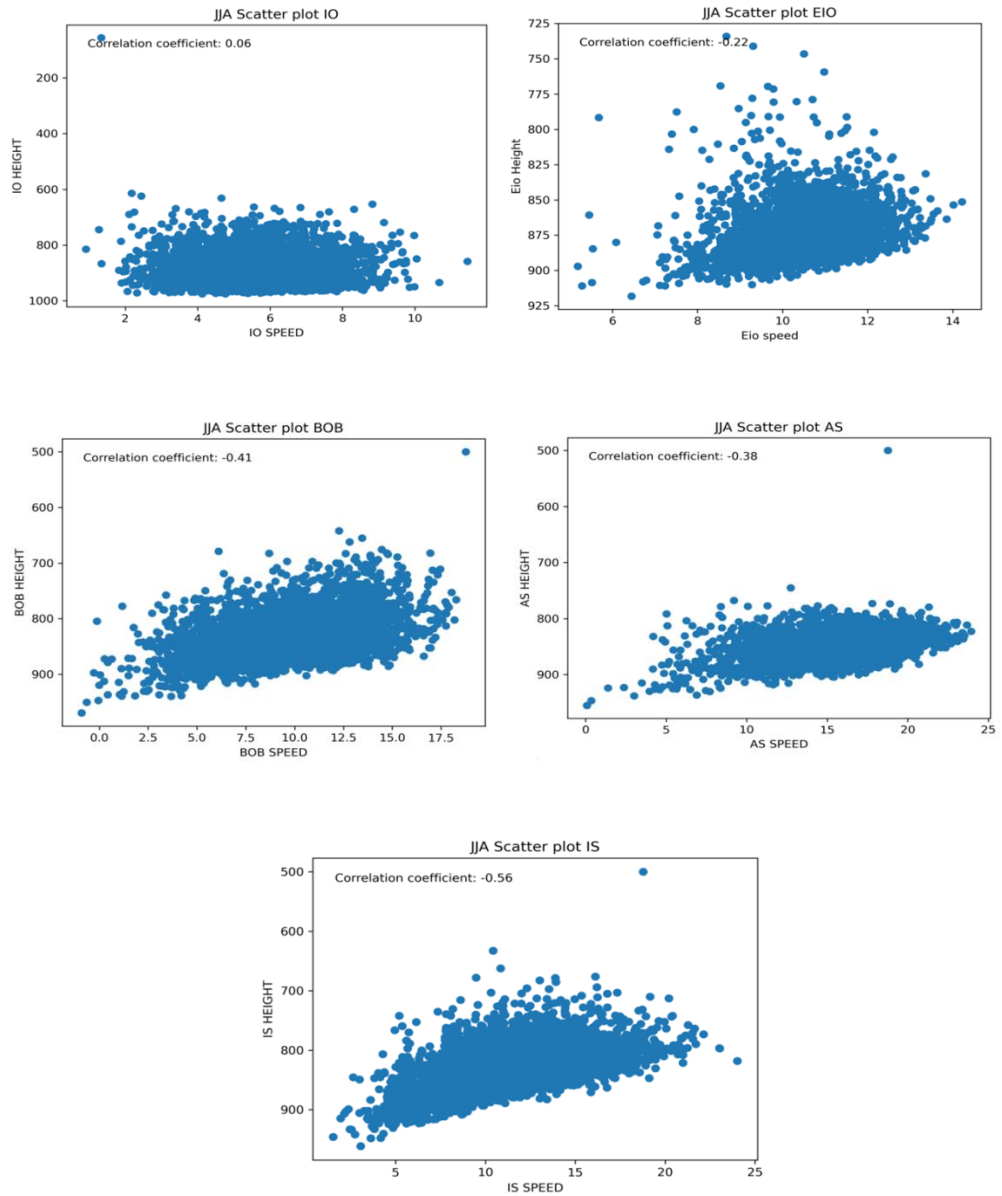


Fig. 13 Fig. 13 Relation between the jet properties in each region during the months of June - August

4.3 STRUCTURAL VARIABILITY DURING EXCESS AND DEFICIT MONSOON YEARS

Years with excess or deficit rainfall can indeed have a significant influence on atmospheric dynamics. In both the Arabian Sea and the Bay of Bengal regions, the relationship between rainfall patterns and atmospheric dynamics is evident. During years with deficit rainfall, the lower-level jet (LLJ) exhibits a higher median core height, while strong rainfall years show a broader range of core height values, signifying increased variability in LLJ core height depicted in the (Fig. 14a) Arabian Sea , (Fig. 14b) Bay of Bengal. These observations underline the impact of regional rainfall conditions on LLJ core height and variability, providing valuable insights into the intricate interactions between atmospheric dynamics and local climate phenomena.

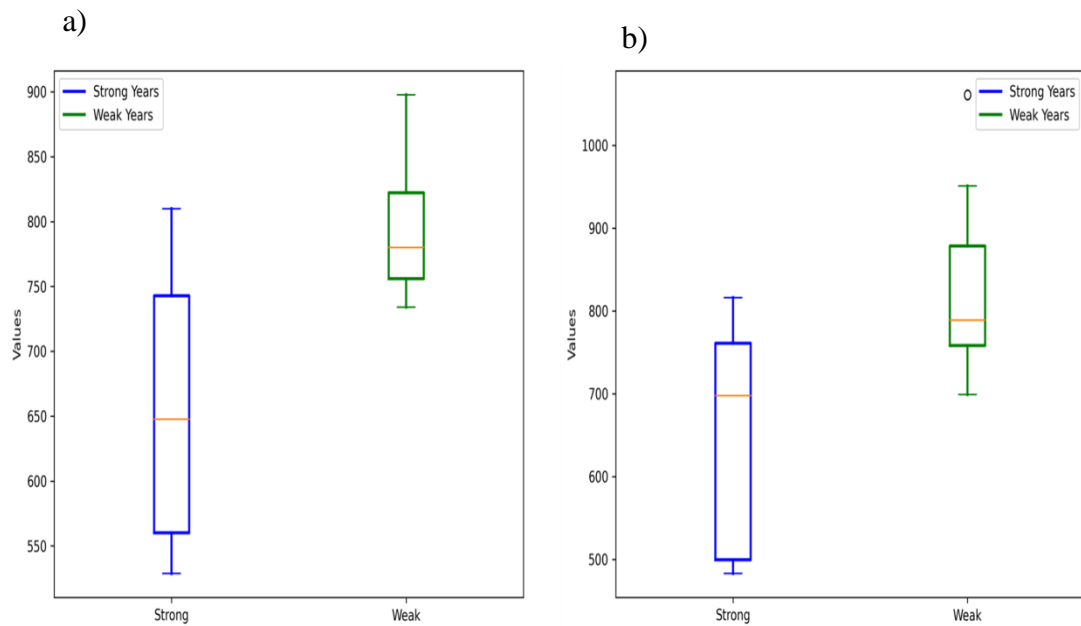


Fig. 14 Whisker plot of strong and weak rainfall years with coreheight in (a) Arabian Sea (b) Bay of Bengal

4.4 STRUCTURAL VARIABILITY DURING DIFFERENT OCEAN – ATMOSPHERE INTERACTION PROCESS

Examining the fluctuations in IOD, SIOD, and ENSO in relation to jet properties is imperative, as ocean-atmosphere interactions significantly influence the

structural variability of numerous atmospheric phenomena. The IOD (Indian Ocean Dipole), SIOD (Subtropical Indian Ocean Dipole), and ENSO (El Niño-Southern Oscillation) indices are calculated using the methodology outlined in the research. Subsequently, these index values are utilized to identify positive and negative years for IOD, SIOD, and ENSO, which are depicted in the (Fig.15a) IOD, (Fig.15b) SIOD, (Fig.15c) ENSO. Following the identification of positive and negative years for IOD, SIOD, and ENSO, a comparison is made with the jet properties of Arabian sea, as illustrated in the (Fig.16) Coreheight , (Fig.17) Corespeed. In IOD, it's observed that during IOD-positive years, the average core height is greater compared to IOD-negative years. This suggests that the height of the low-level jet (LLJ) tends to be higher in IOD-positive years. Furthermore, the range of values during IOD-positive years is wider than that during IOD-negative years, indicating a greater variability in LLJ core height in IOD-positive years. Similar observations hold true for ENSO as well. In the context of the SIOD, it's important to note that the median core height is elevated during SIOD-negative years. In contrast, during SIOD-positive years, there is a wider spectrum of core height values, indicating greater fluctuations in the lower-level jet (LLJ) core altitude. A similar pattern of variation is observed in core speed as well. Therefore, the most significant variations in core height and core speed are observed during both SIOD-positive and SIOD-negative years.

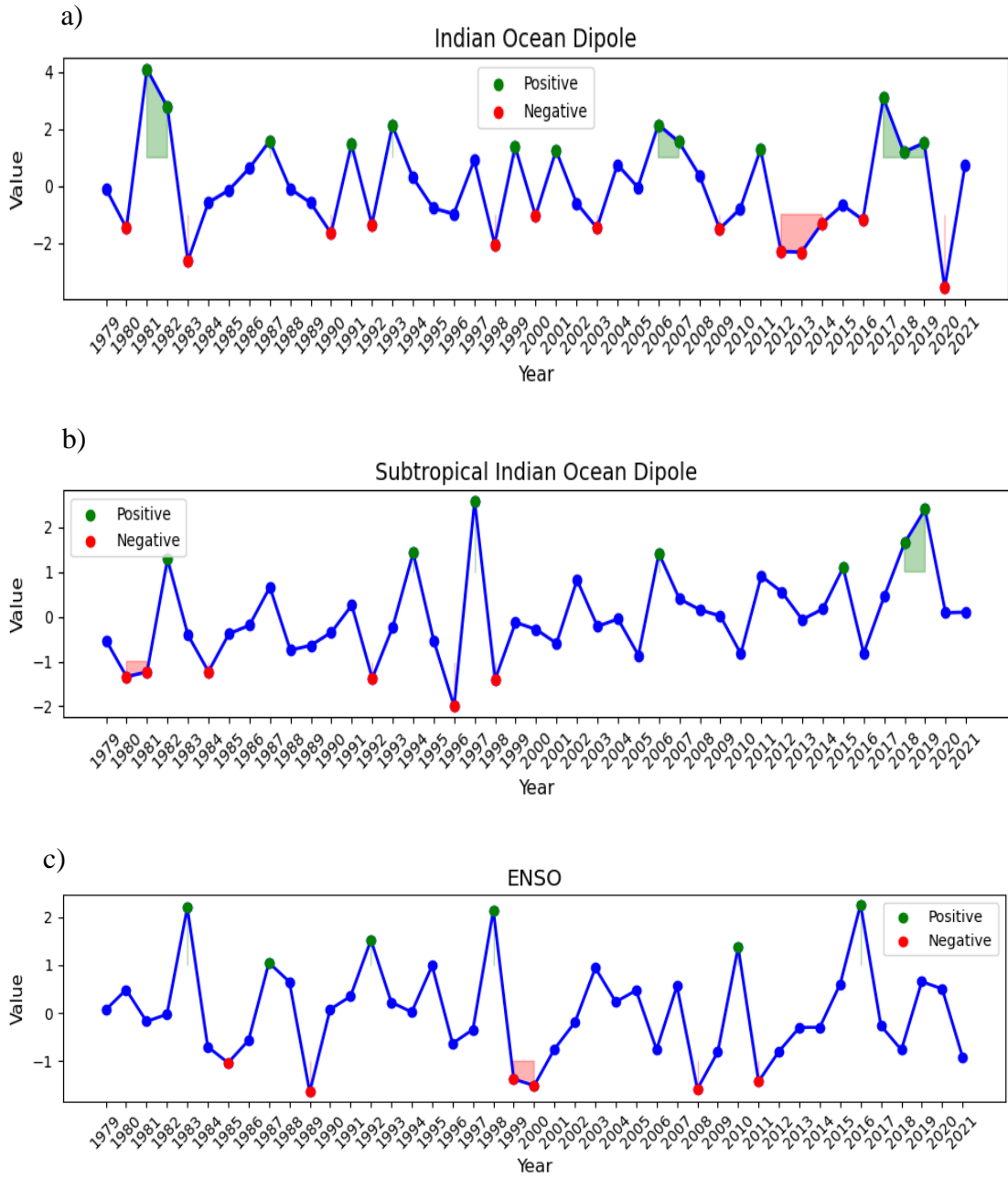


Fig. 15 Graph represents positive and negative years of Ocean-Atmospheric interaction processes (a) IOD, (b) SIOD, (c) ENSO

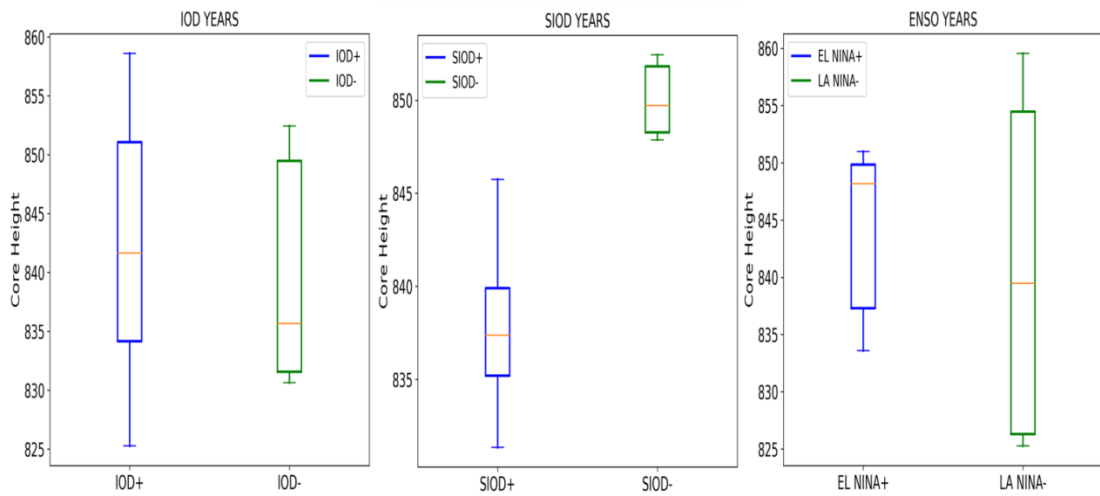


Fig. 16 Whisker plot of positive and negative years of IOD, ENSO, and SIOD with core height of Arabian sea

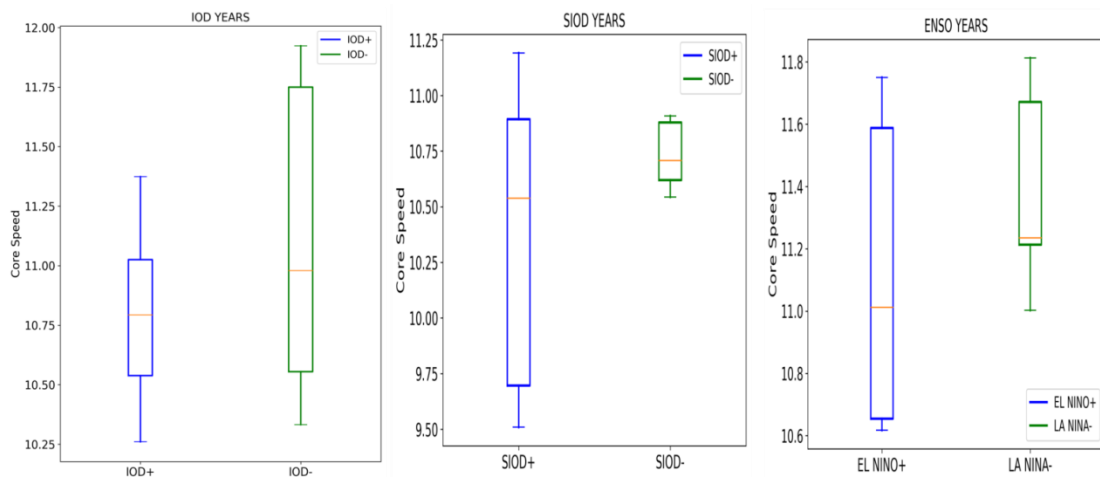


Fig. 17 Whisker plot of positive and negative years of IOD, ENSO, and SIOD with core speed of Arabian sea

4.5 RELATION BETWEEN UPWELLING PROCESS OVER INDIAN AND JET PROPERTIES

It is established that the upwelling systems are very prominent over different parts of Indian Ocean during south-west monsoon season. Three upwelling regions were selected for studying the coherence of upwelling systems and jet properties. They are Somali, Oman and South eastern Upwelling regions. The further details on the calculation is described in the methodology section. The upwelling index

calculated for the regions of Oman, Somalia, and the southeastern Arabian Sea is depicted in the (Fig. 18). The jet properties over IO, EIO and AS region were correlated with the upwelling indices of these regions as shown in (Fig.19) It is seen that Oman and SEAS upwelling regions were not showing much connection with the Jet properties of the selected regions. The main relation is seen between jet speed over the EIO and AS regions and upwelling of the Somalia region. Jet core height is not showing a significant relation with Somalian upwelling system. The Jet speed over EIO region shows a good negative correlation with upwelling index over Somalian region from 6 days' lead to more than 10 days lag. Maximum correlation is occurring at the 0 lag. The results give an exciting clue that Jet speed is influencing the upwelling 6 days prior and on the other way these upwelling is influencing the Jet speed even after 10 days.

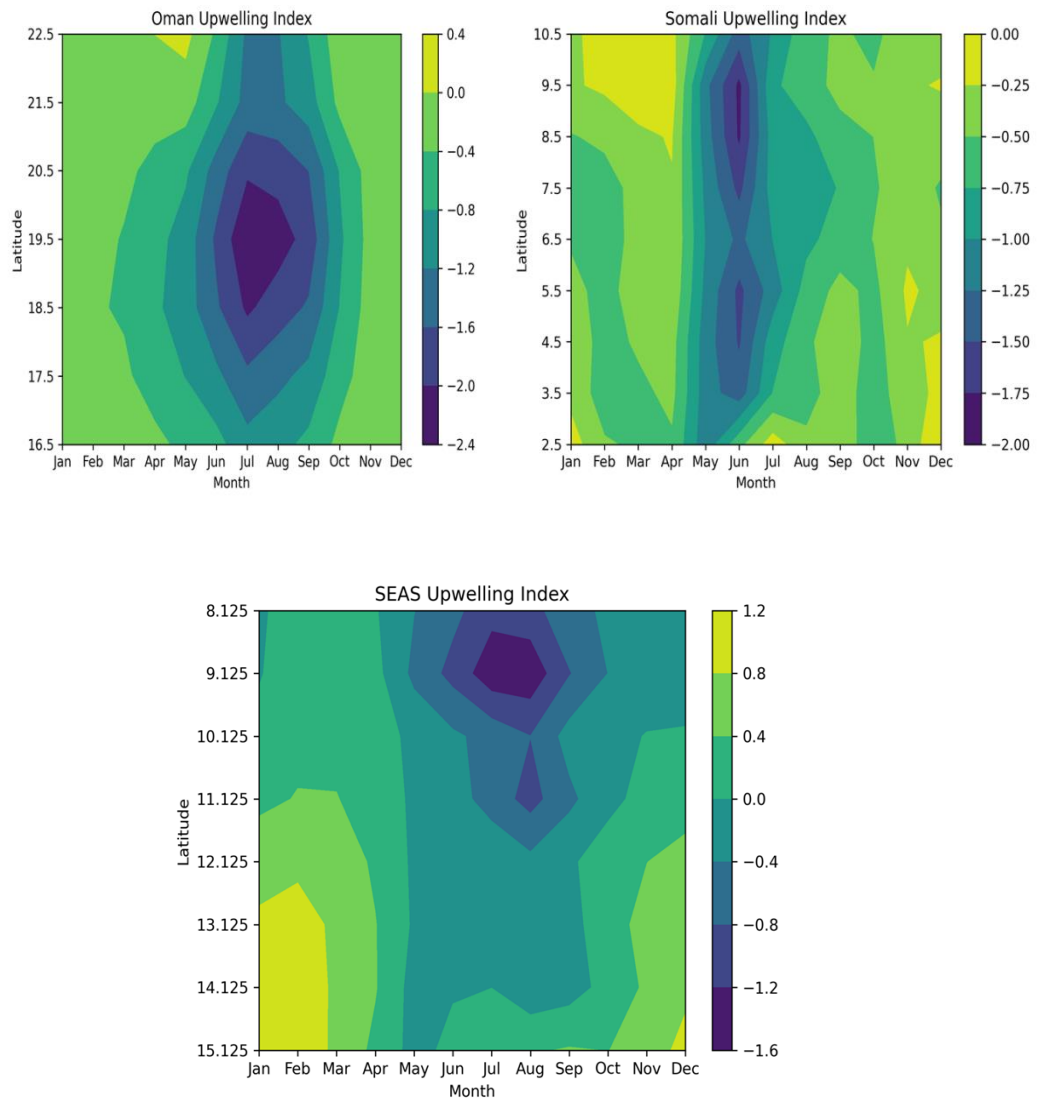


Fig. 18 Upwelling Index of regions Oman, Somalia, South Eastern Arabian Sea

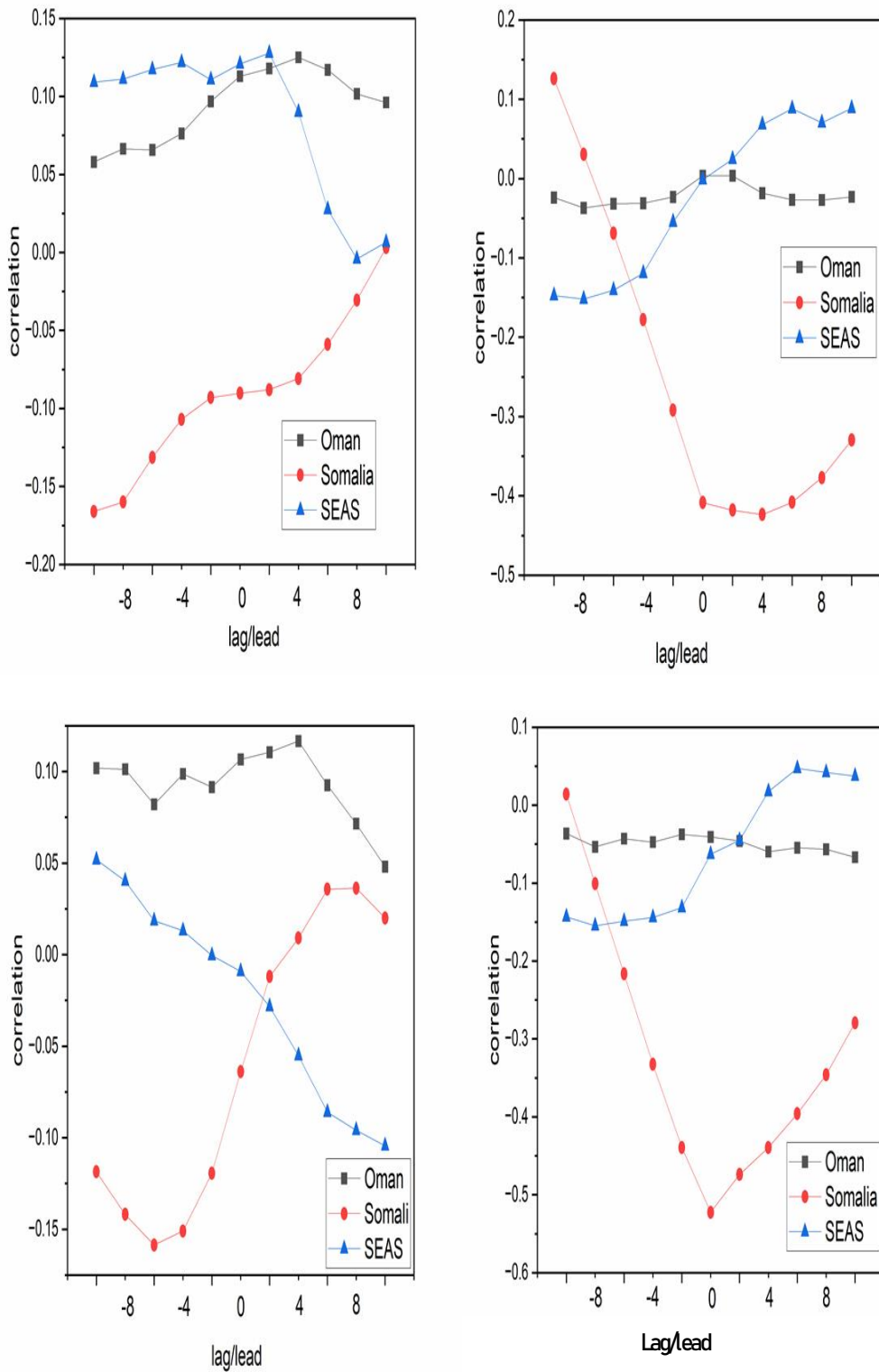


Fig. 19 Correlation of Jet Properties with regions Arabian Sea and Equatorial Indian Ocean with a 10-Day Lag and Lead

4.6 RELATION BETWEEN ARABIAN SEA MINI WARM POOL AND JET PROPERTIES

Arabian sea mini warm pool (ASWP) systems are very prominent system that exist just before the onset of Indian summer monsoon. In order to see the interaction of ASWP with jet properties, lead lag correlation analysis is carried out and presented in (Fig.20). It is seen that AS properties are having good influence on the ASWP. It is interesting to see that maximum association is seen during -5 to 0 lag period in case of jet speed and -10 to -5 days for the core height. This implies that Jet core is capable of influencing the ASWP during the month of May.

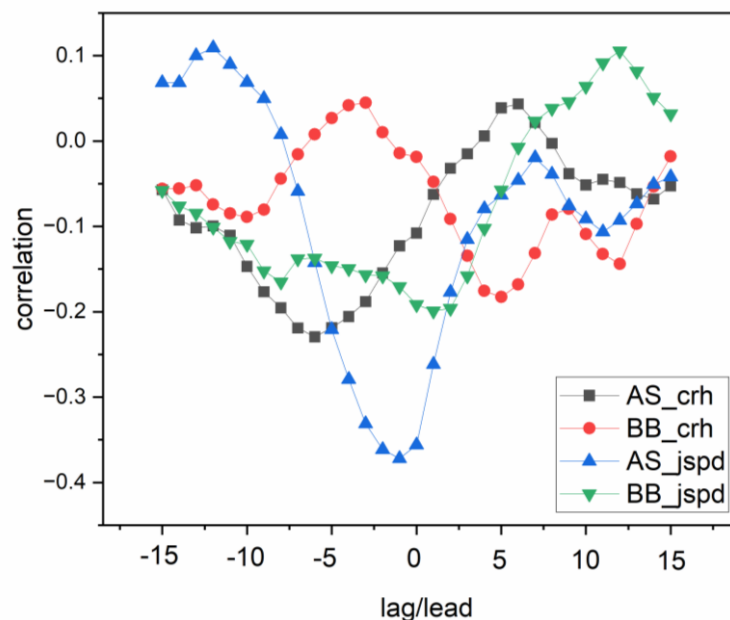
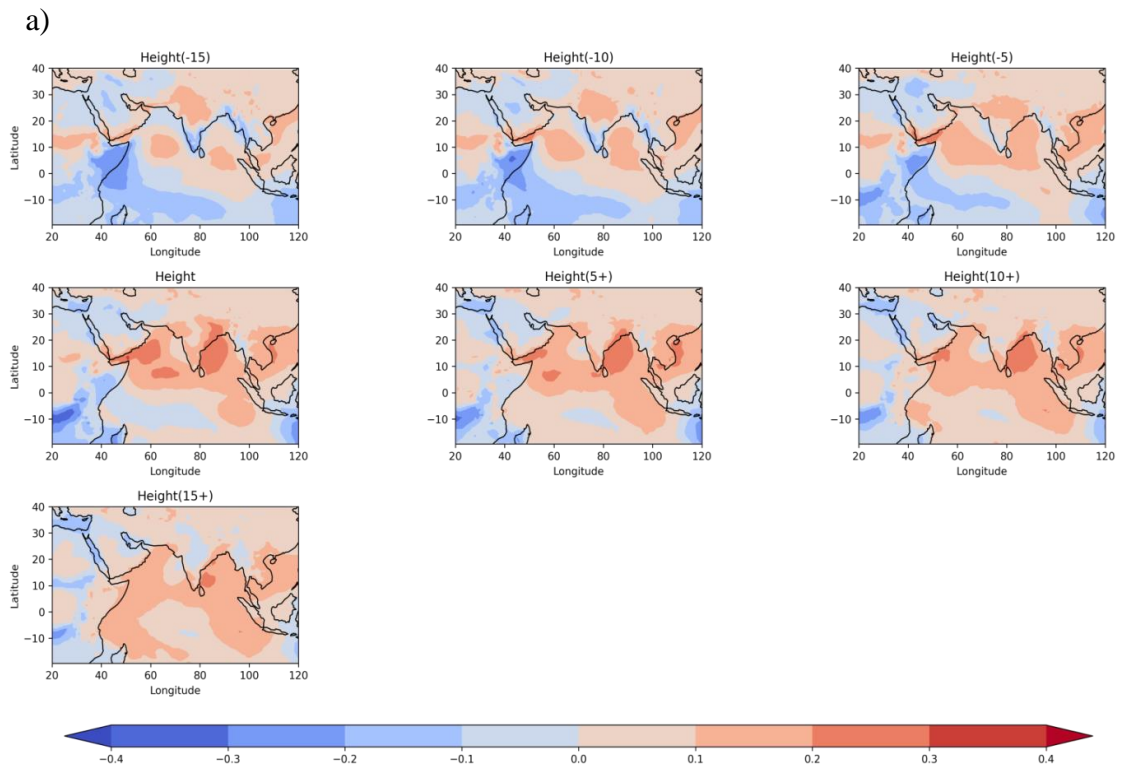


Fig. 20 Correlation of Jet Properties with Arabian Sea mini warm pool with a 15-Day Lag and Lead of Arabian sea and Bay of bengal

4.7 ASSOCIATION OF MLLJ PROPERTIES WITH CONVECTIVE CLOUDS AND PRECIPITATION

Study on the dynamical factors that influence the convection –cloud-precipitation interaction mechanism is very sparse. Especially during the monsoon time, the influence of MLLJ on these interaction processes is not yet studied. So in this analysis we are taking this initiative to explore these interaction processes in a deeper manner. (Fig.21, Fig.22) displays the lead/lag analysis of MLLJ properties

with CAPE which is correlated spatially. Firstly, the MLLJ properties over AS region is correlated Spatially with CAPE. It is evident from the figure that in case of core height, positive correlation occurs over northern Indian Ocean region and negative correlation in southern Indian sub-continent during the lag period (Jet core height is leading the cape). But as the lag reduces and the lead proceeds, this positive correlation becomes stronger and spreads to entire tropical Indian region. The correlation is more visible in the lead/lag range of 10 days. It is to be noted that since core height is prescribing in vertical pressure coordinate and it is opposite to the normal height coordinate, the positive correlation actually denotes that core height decreases as the CAPE values are increasing. This results are quite interesting. The detailed mechanism has to be investigated in detailed manner. In case of jet speed, the positive correlation is seen on the routes of MLLJ. This becomes stronger when cape leads the jet speed. The MLLJ properties over Indian sub-continent also displays the similar behavior as that of AS region.



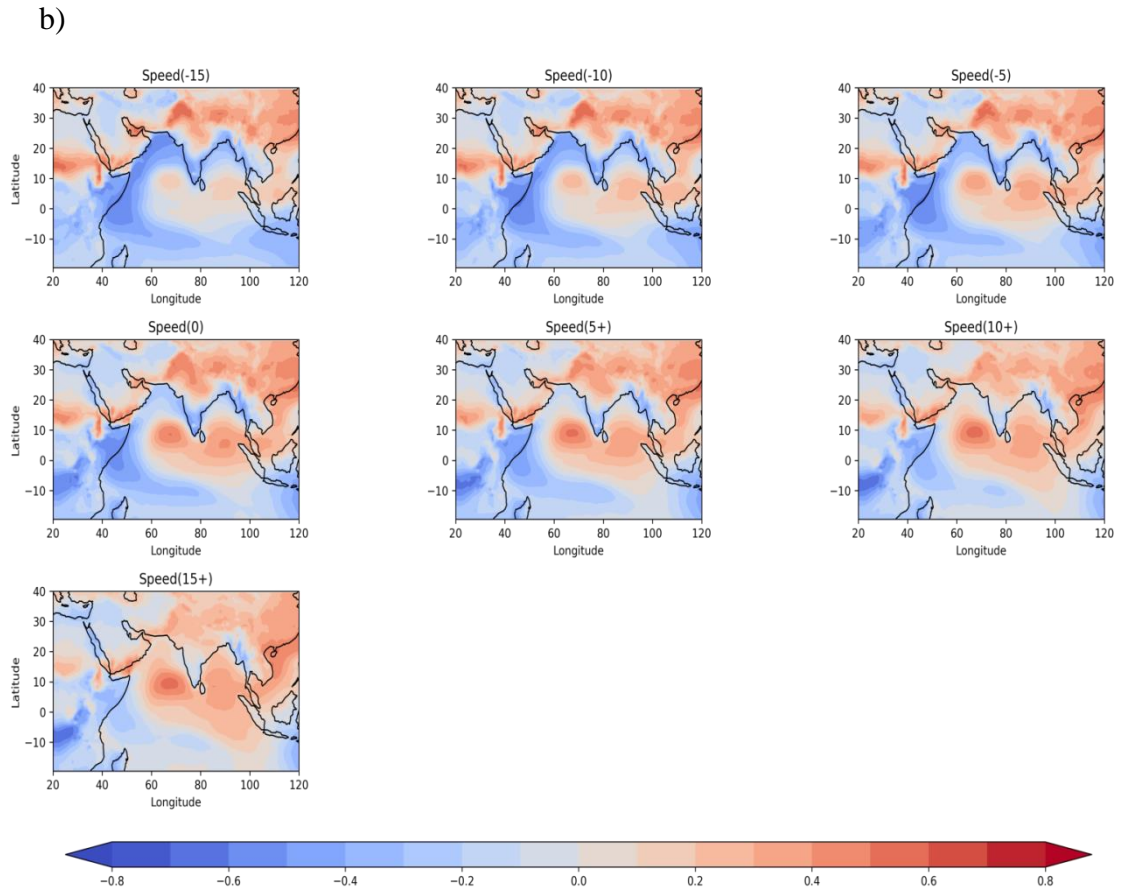
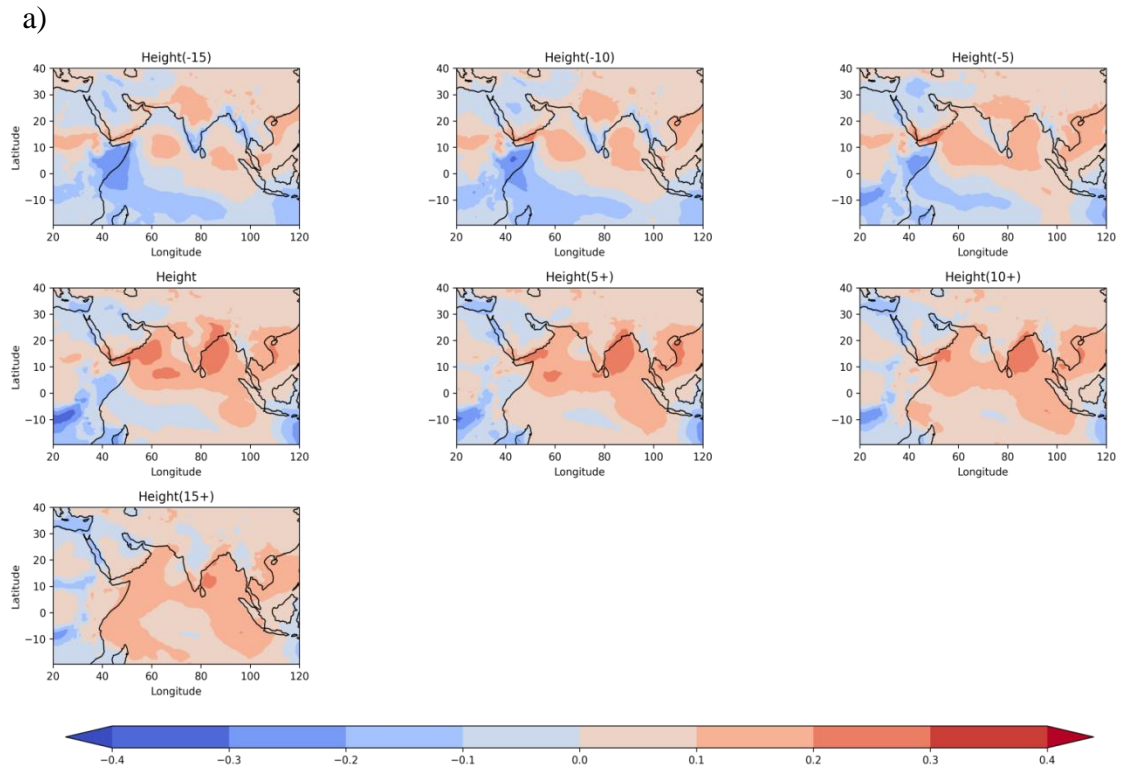


Fig. 21 Spatial correlation of CAPE in Arabian Sea with jet properties (a) Coreheight, (b) Corespeed



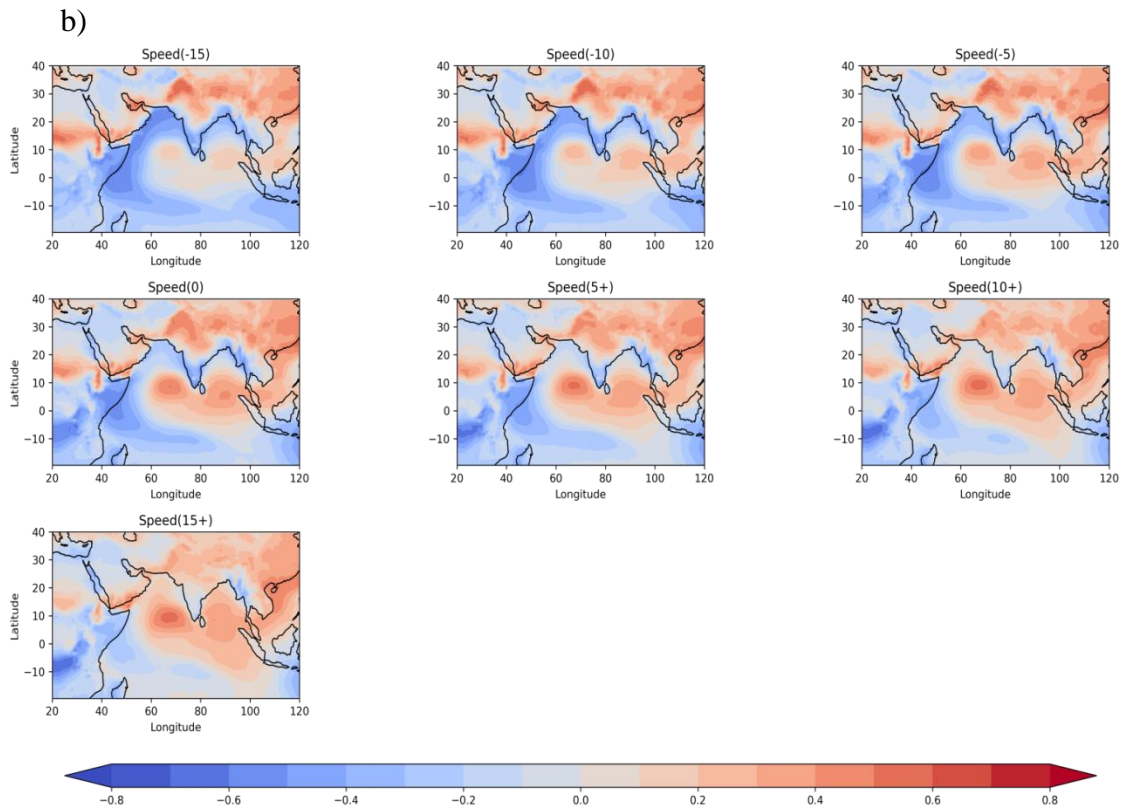
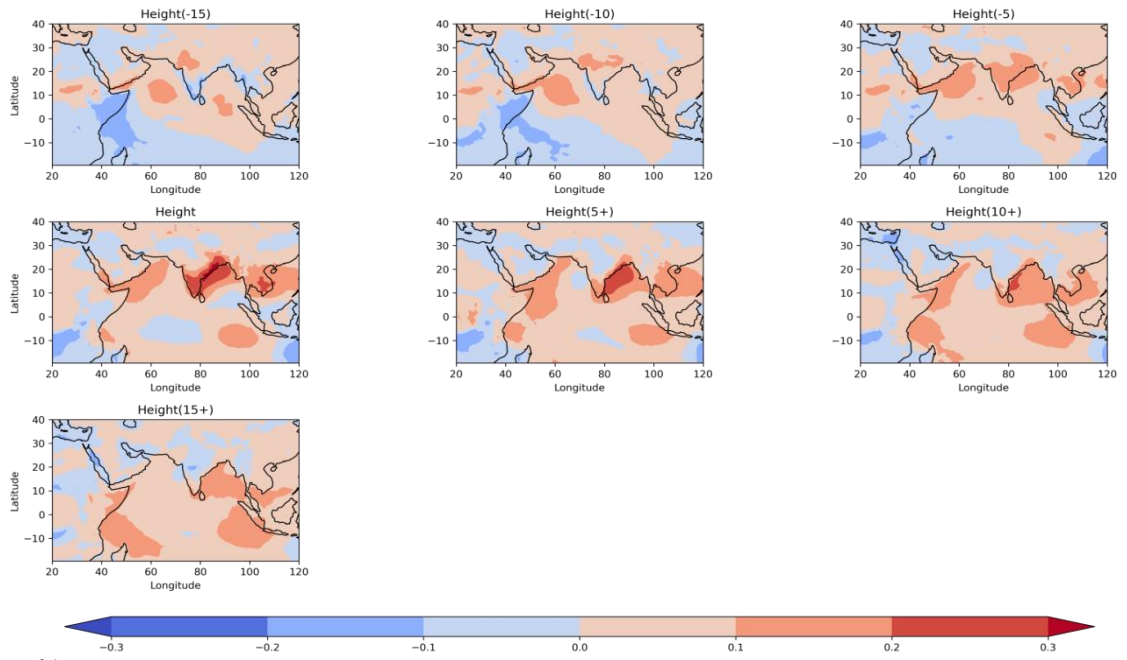


Fig. 22 Spatial correlation of CAPE in Indian Subcontinent with jet properties (a) Coreheight, (b) Corespeed

But the case is different with Bay of Bengal (Fig.23). They are having a strong negative correlation when LLJ height leads the cape and reverses its characteristics in the opposite manner especially over the Bay of Bengal region. The relation between the jet speed and cape is stronger during the lead/lag period of 5 days

a)



b)

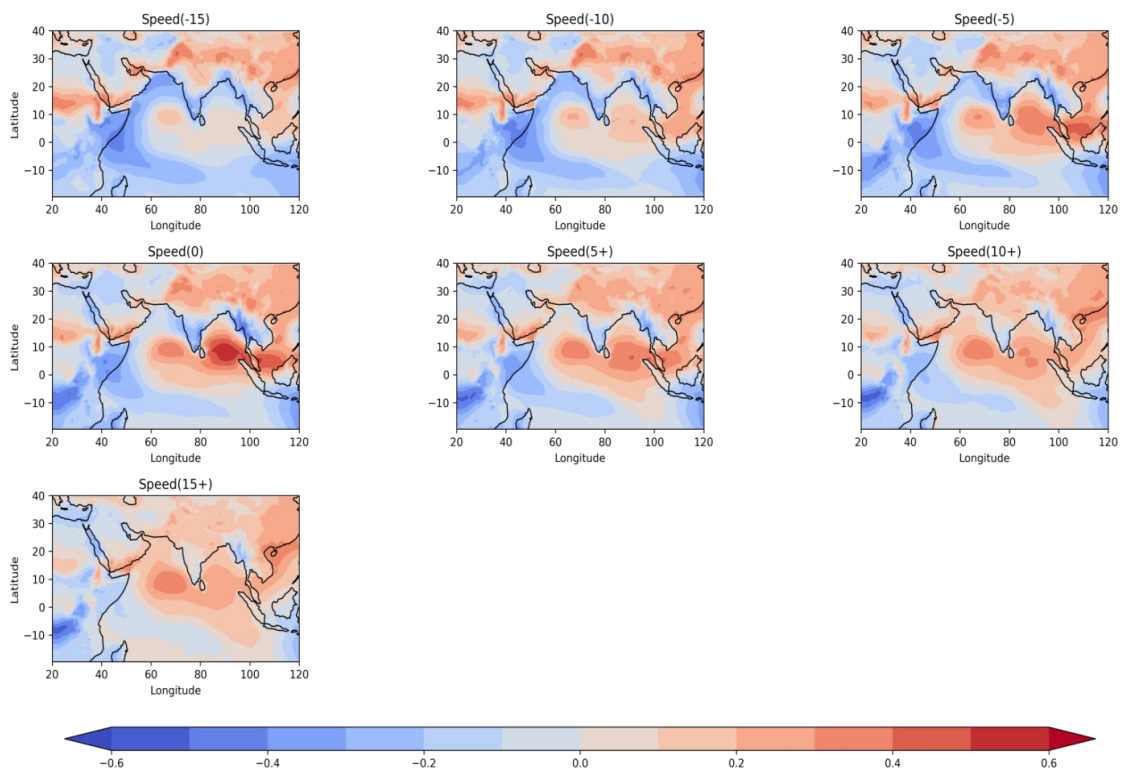
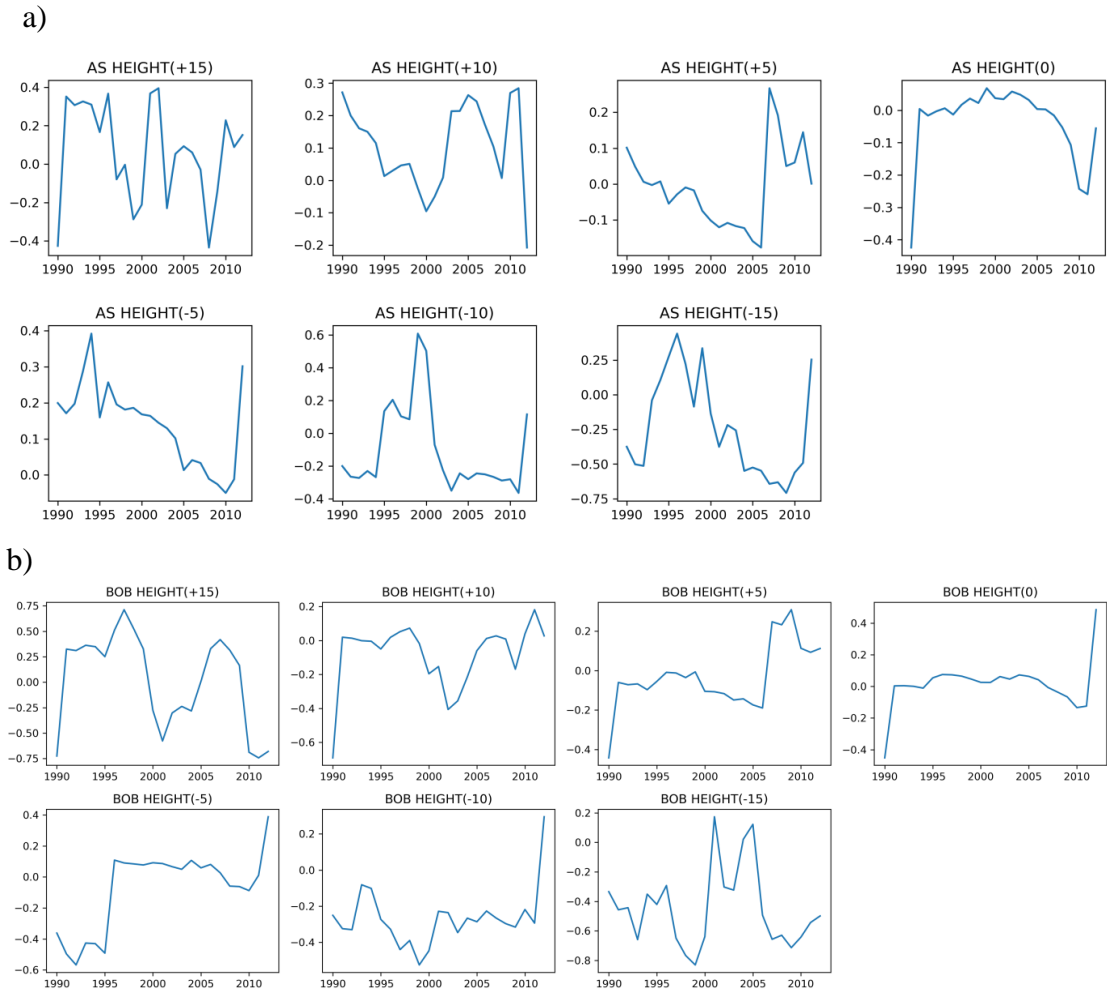


Fig. 23 Spatial correlation of CAPE in Bay of Bengal with jet properties (a) Coreheight, (b) Corespeed

To study the variations in CAPE with jet properties during pre 20 and post 20 periods, analyze sliding window correlations for specific regions depicted in (Fig.24, Fig.25)



c)

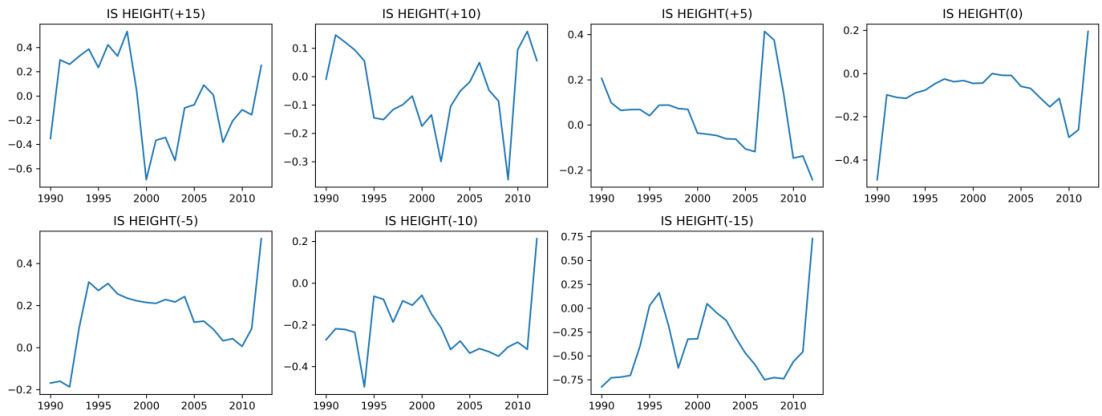
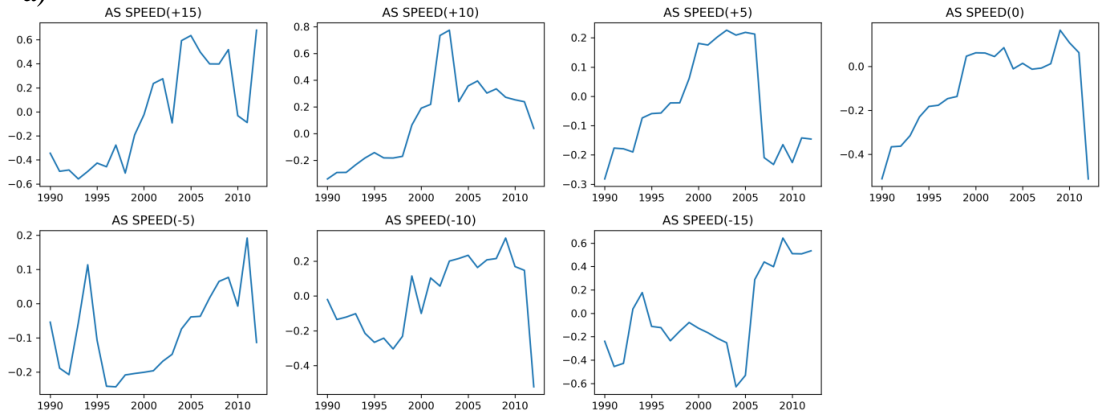
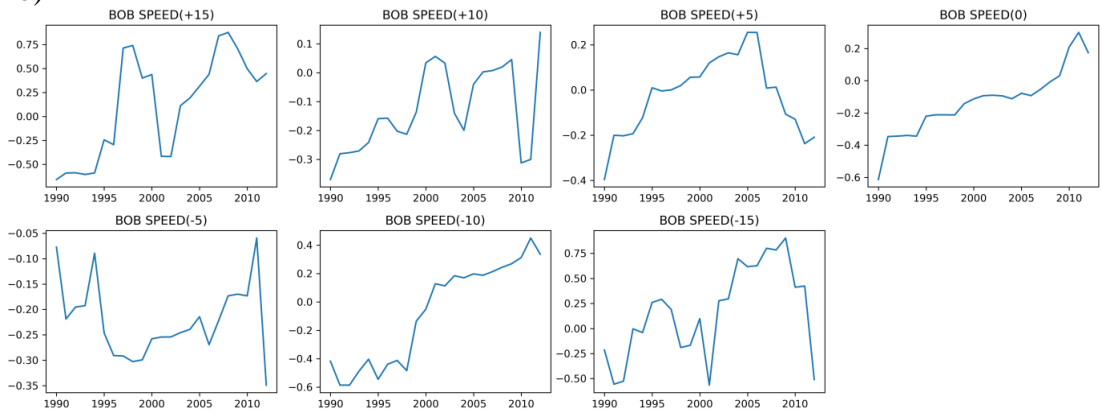


Fig. 24 Sliding window correlation of Core height with Regions (a) Arabian Sea, (b) Bay of Bengal, (c) Indian Subcontinent

a)



b)



c)

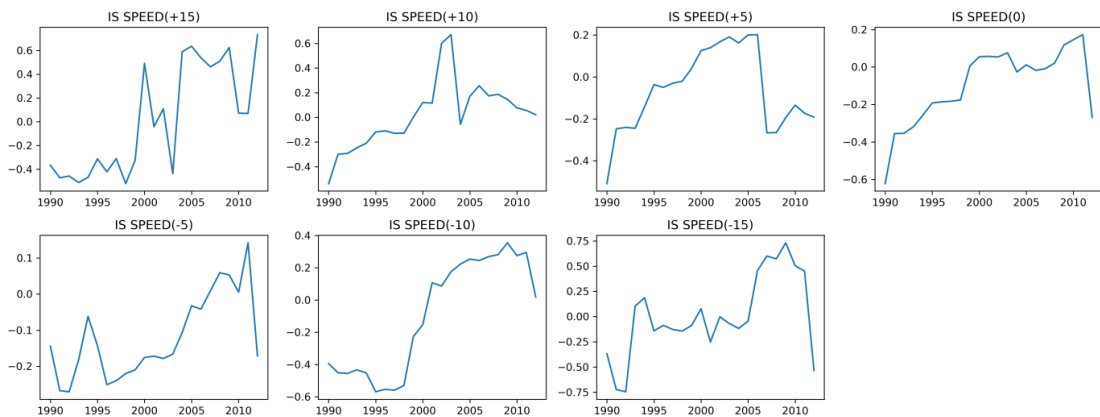


Fig. 25 Sliding window correlation of Core speed with Regions (a) Arabian Sea, (b) Bay of Bengal, (c) Indian Subcontinent

In order to have a deeper idea on the inter-dependence on MLLJ characteristics on the convection-cloud-precipitation interaction, we have done correlation analysis with convective precipitation as shown in (Fig.26, Fig.27, Fig.28) Core height over AS shows positive correlation especially in the western coast of Indian sub-continent and negative correlation lower eastern coast. As the lag reduces the positive correlation reduces and negative correlation becomes more and more visible. That implies that increase in core height can reduce the precipitation over the western coast, especially during the lead time of MLLJ. But the speed is positively correlated with CP especially over the western coast in almost all lead lag phases. Like mentioned in the case of cape here also IS region correlation shows almost similar behavior as of AS. But BB region is having differences. When the MLLJ core height leads, almost whole northern Indian Ocean region is exhibiting positive correlation indicating the inhibition of this in making the precipitation. but when the CP leads LLJ, the eastern coast shows a negative correlation implying the setting up of critical environment for the uplifting of the Jet core. Jet speed also shows good correlation in the northern bay especially in the 0 lag period.

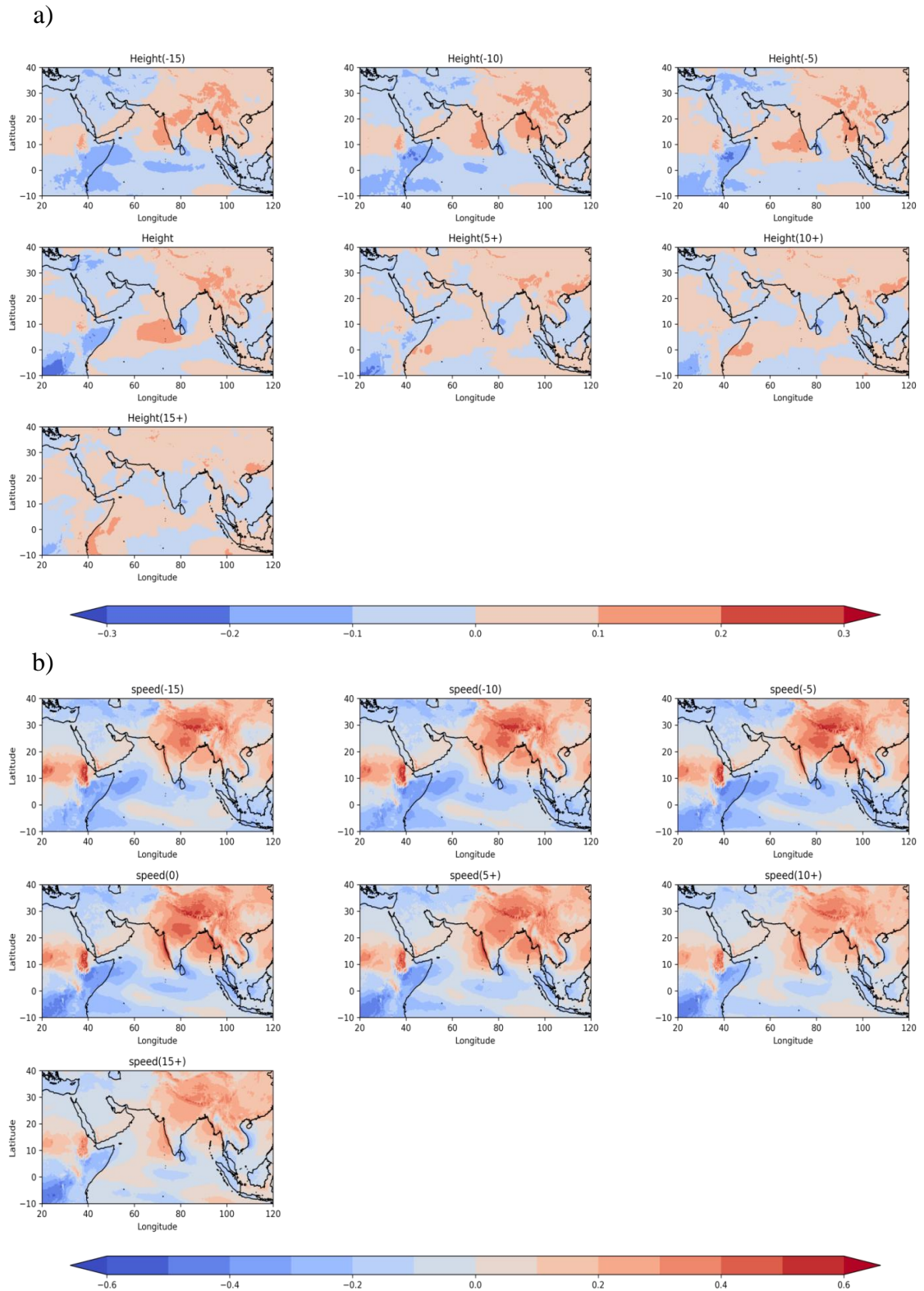


Fig. 26 Spatial correlation of convective precipitation in Arabian Sea with jet properties (a) Coreheight, (b) Corespeed

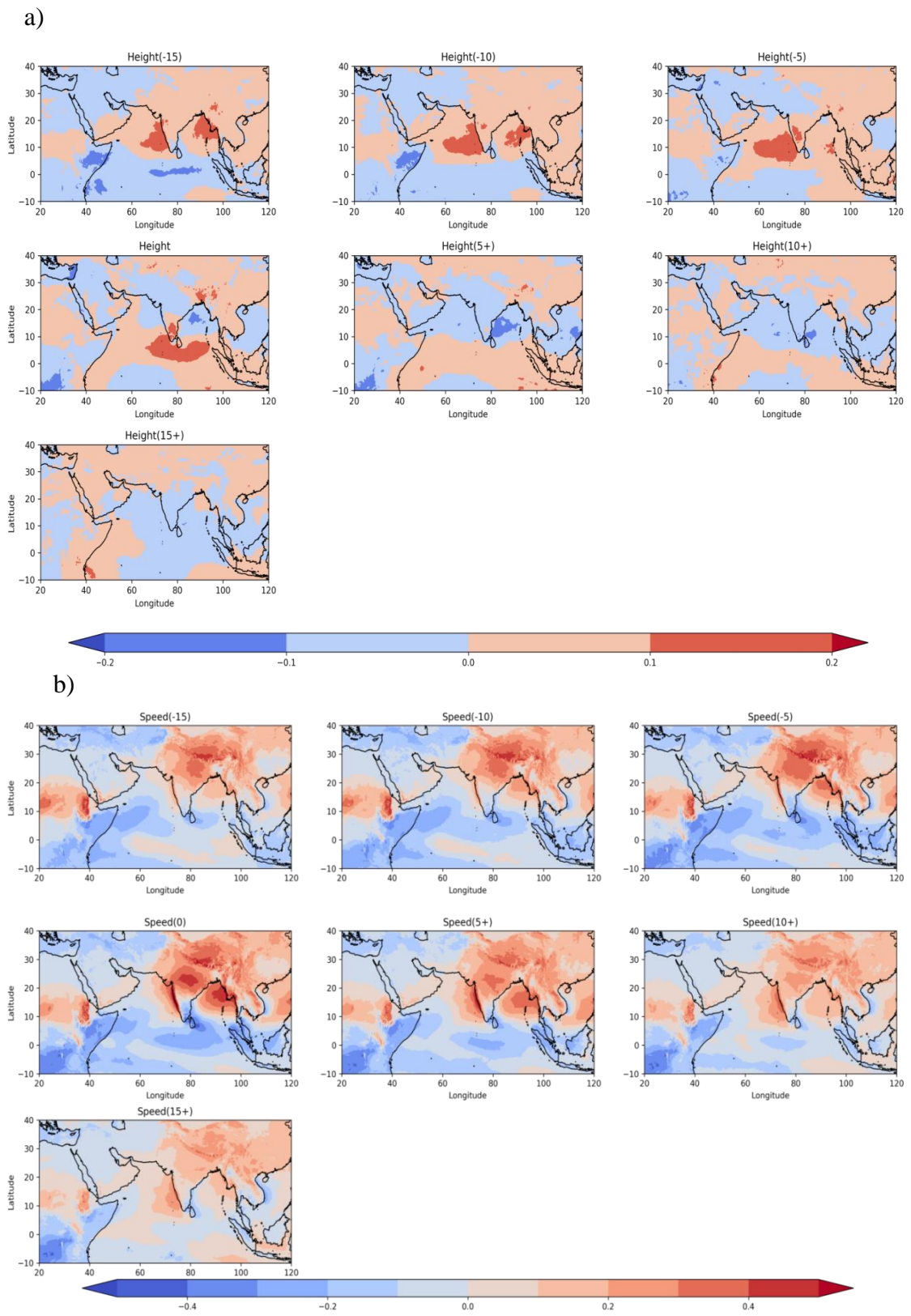


Fig. 27 Spatial correlation of convective precipitation in Indian Subcontinent with jet properties (a) Coreheight, (b) Corespeed

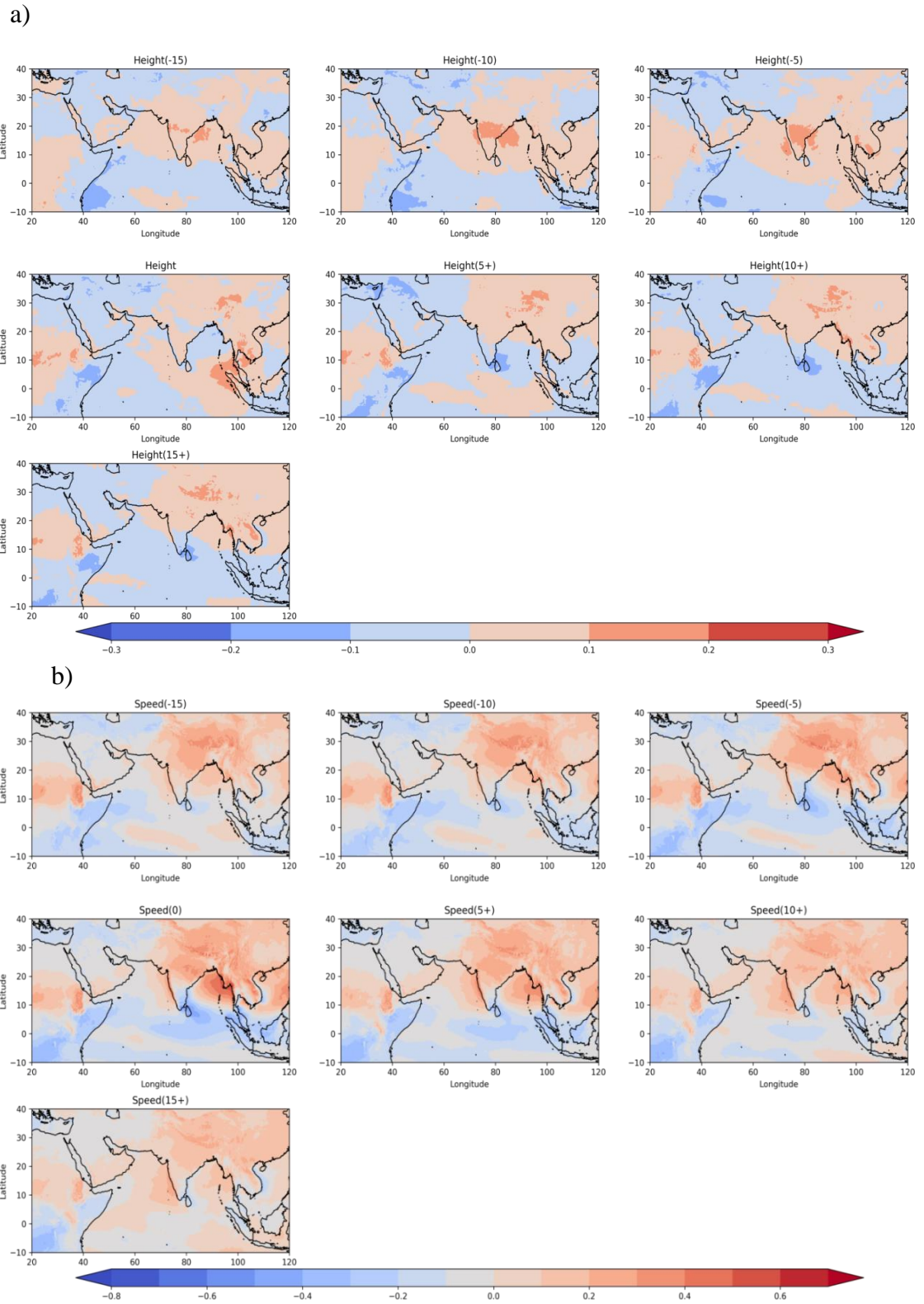


Fig. 28 Spatial correlation of convective precipitation in Bay of bengal with jet properties (a) Coreheight, (b) Corespeed

The moisture availability during the monsoon season is solely depending on the properties of MLLJ. In order to see this, the jet speed has done lag correlation with total precipitate water over the selected region and is represented in (Fig.29). It is seen that Jet speed over AS is well correlated with the moisture availability over this region especially in the lag range 14 to 0. This implies that the moisture availability over Arabian sea is solely depending on the strength of MLLJ during the south-west monsoon season. Similar analysis was conducted for BOB and IS regions. All the regions show maximum correlations when the lag decreases.

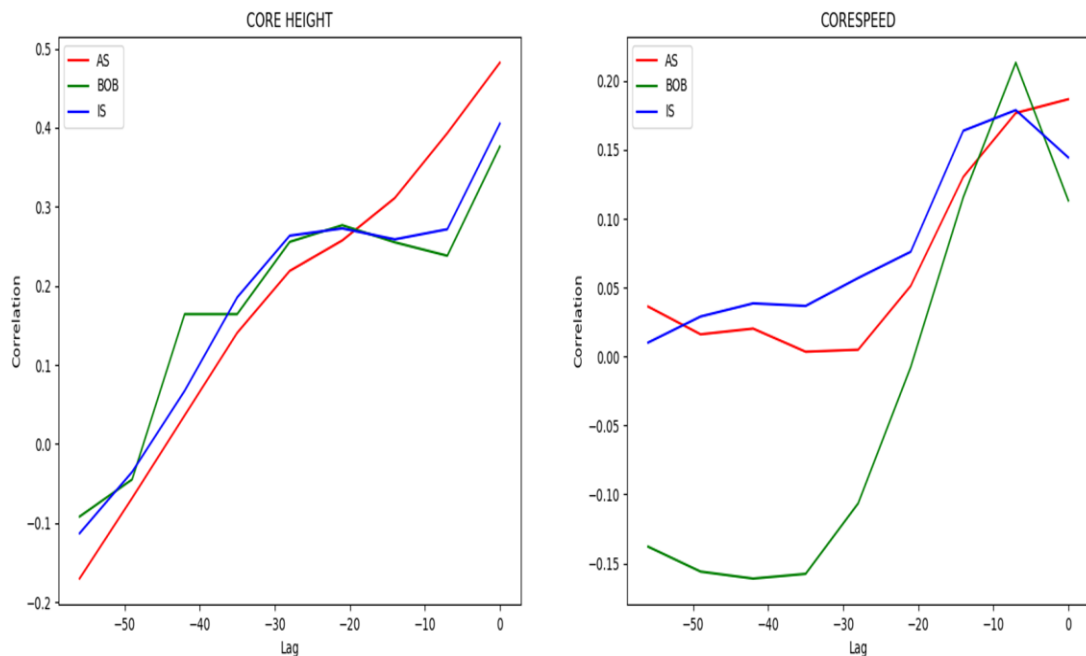
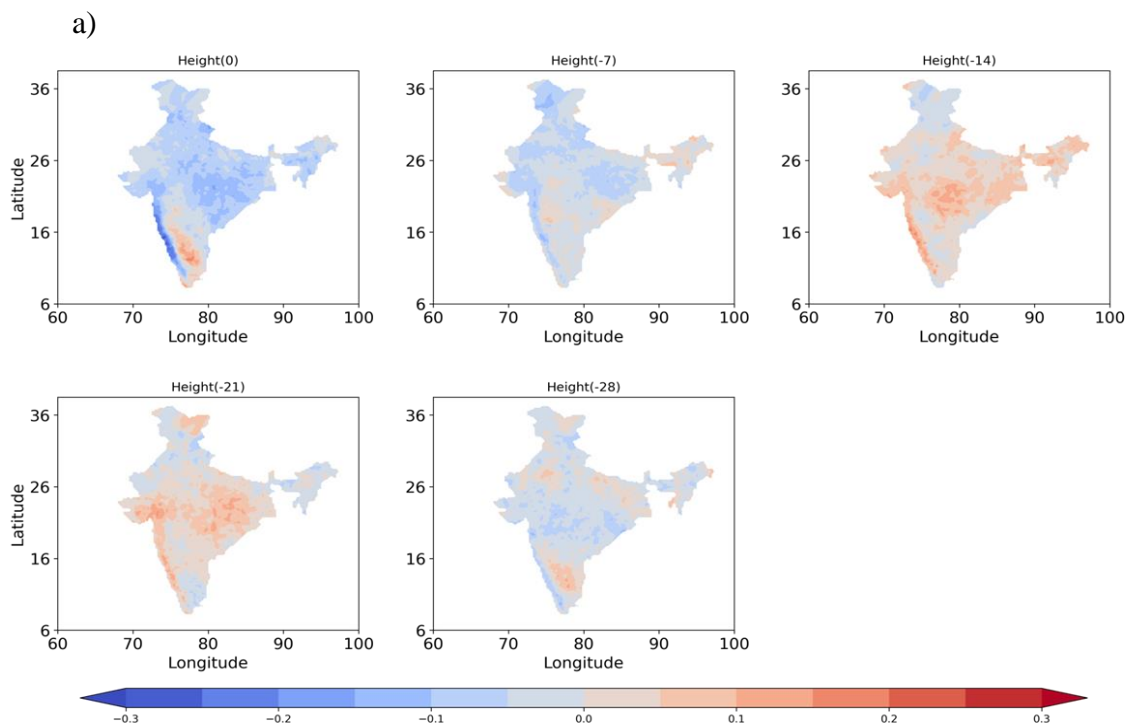


Fig. 29 Correlation of Jet Properties with moisture availability with a 52-Day Lag of Arabian sea, Bay of Bengal, Indian Subcontinent.

The MLLJ characteristics are having close association with Indian summer rainfall. So exploring their association is very much essential. Here an attempt is made to link the MLLJ properties with summer time precipitation over Indian region. The analysis is carried out with three regions. AS, BOB and IS region were lag correlated with ISMR. In order to have more clarity, this analysis is performed for June, July, August and September separately. They are shown in (Fig.30, Fig.31, Fig.32, Fig.33)The core height shows negative correlation with ISMR over western coast and central Indian region in June, July and August months especially in the

simultaneous cases. September shows different behavior. In case of speed, it is well correlated positively in July and August months with the western and central Indian rainfall. Jet core height over BOB shows stronger negative correlation with western and central Indian rainfall as compared to the AS properties. Except August all other three months shows good correlation between jet speed and monsoon rainfall over western and central India. Almost same relation is visible in case of Jet properties and ISMR association.



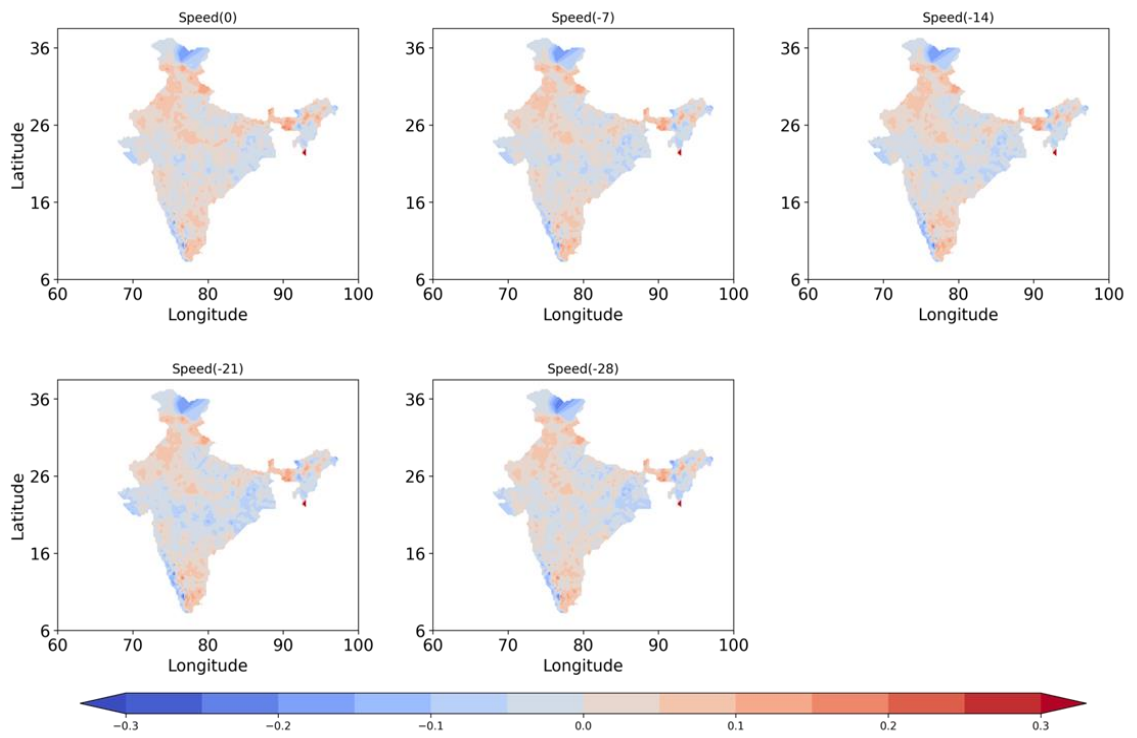
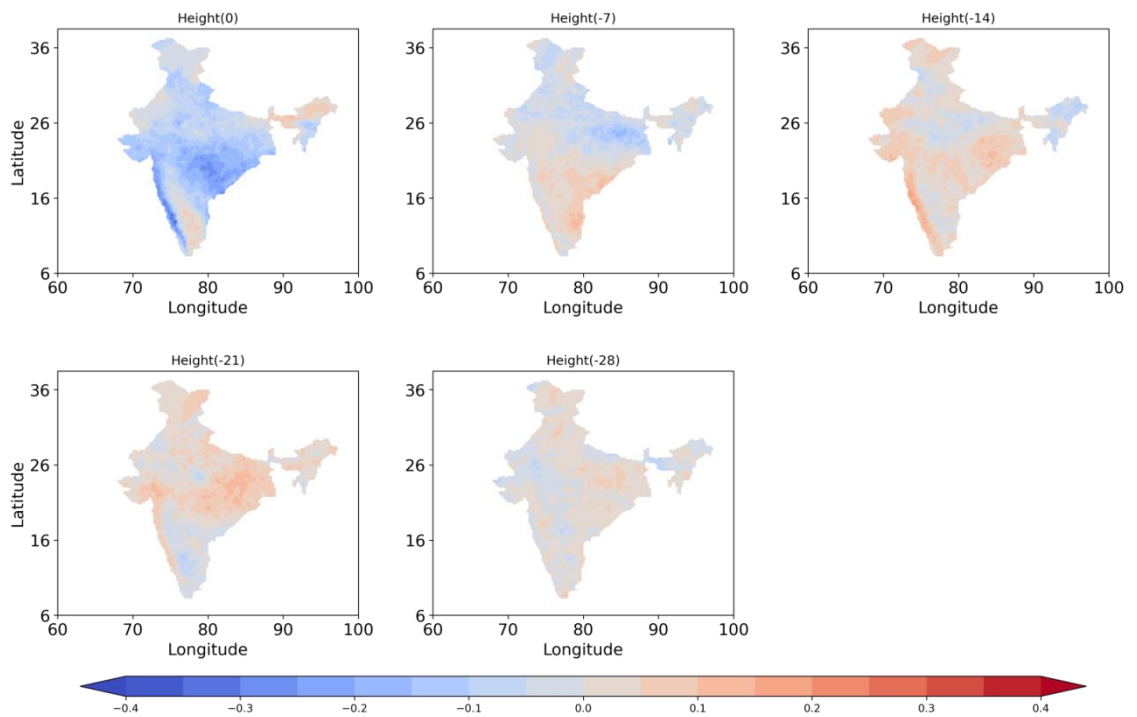


Fig. 30a Spatial correlation of rainfall with jet properties in June of Arabian Sea

b)



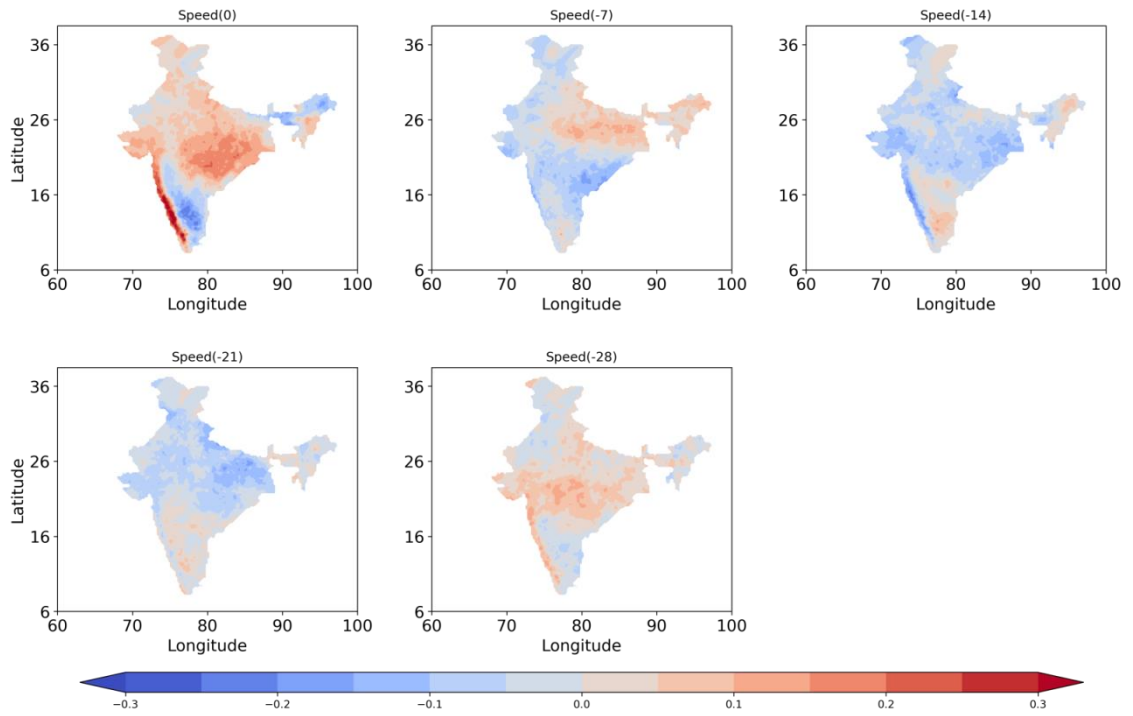
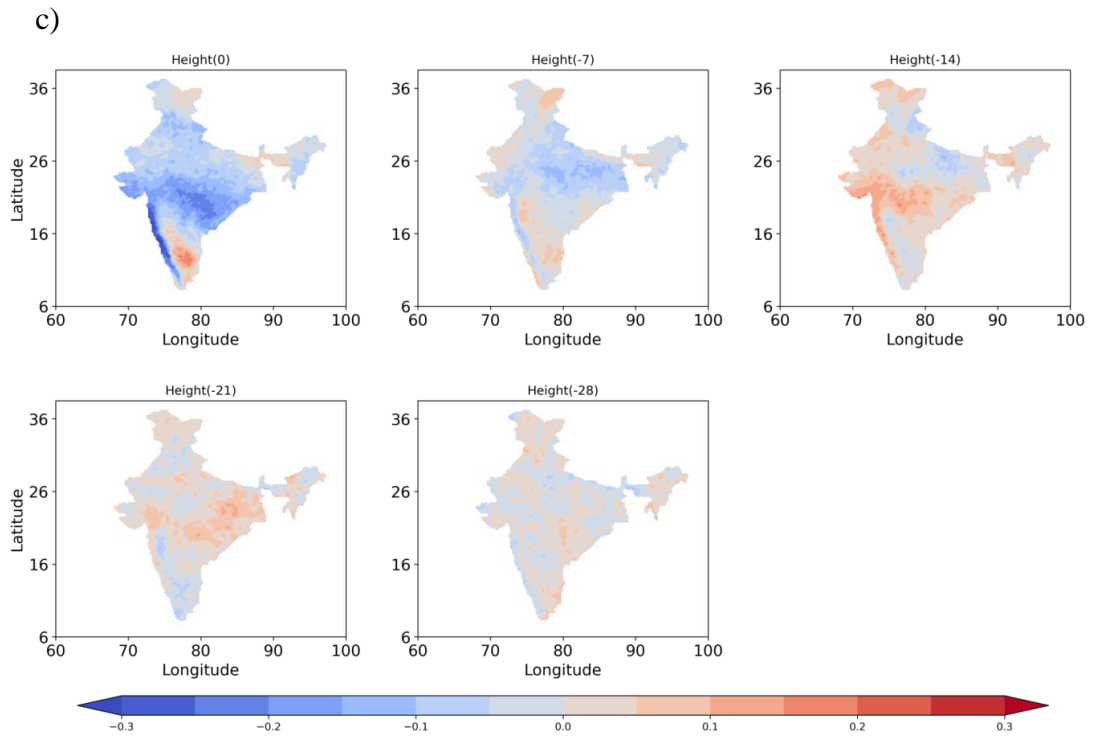


Fig. 31b Spatial correlation of rainfall with jet properties in June of Bay of Bengal



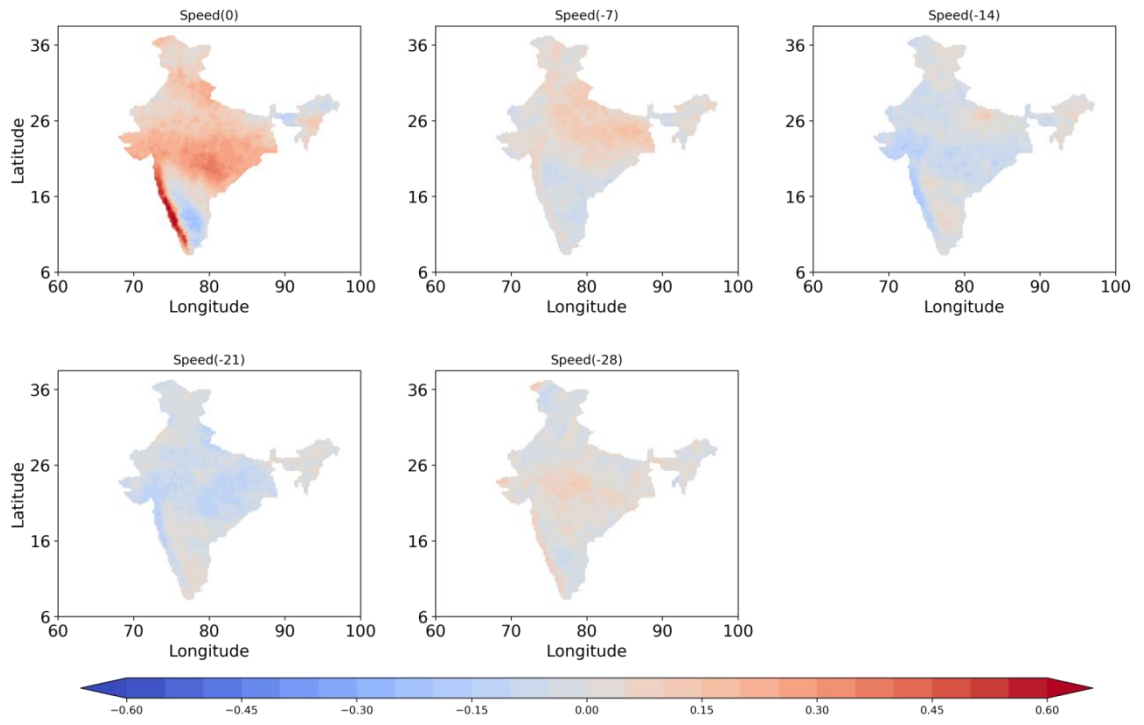
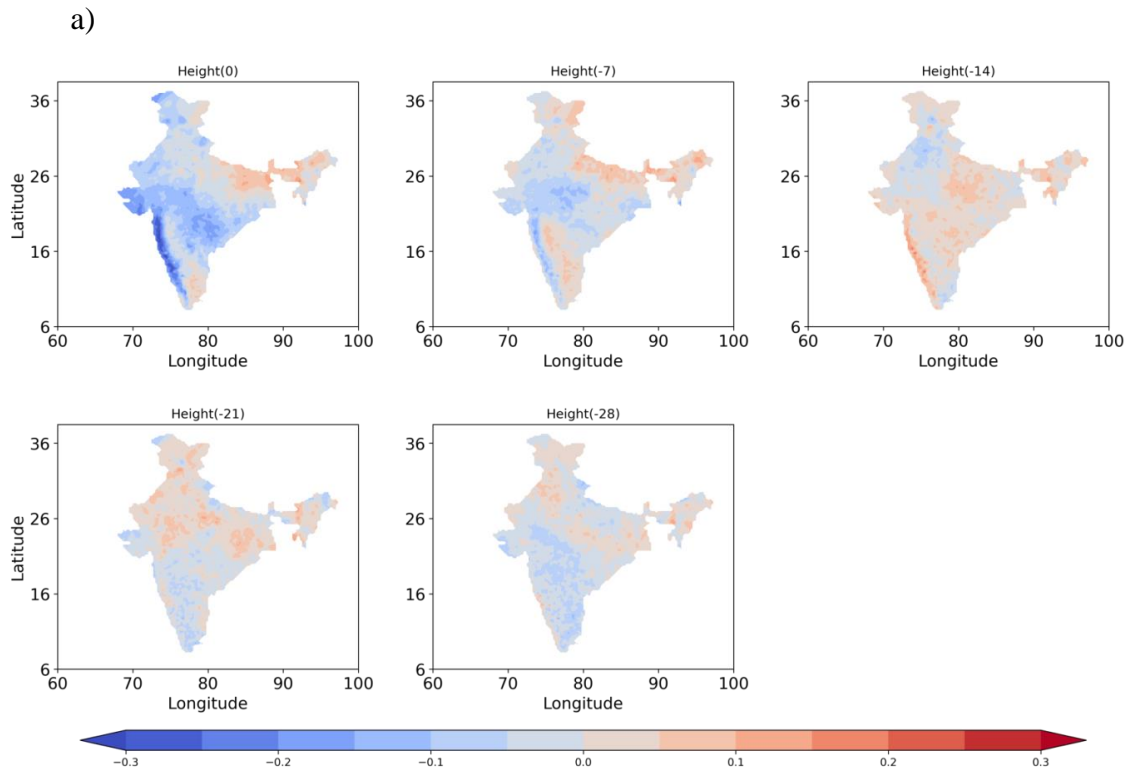


Fig. 32c Spatial correlation of rainfall with jet properties in June of Indian subcontinent



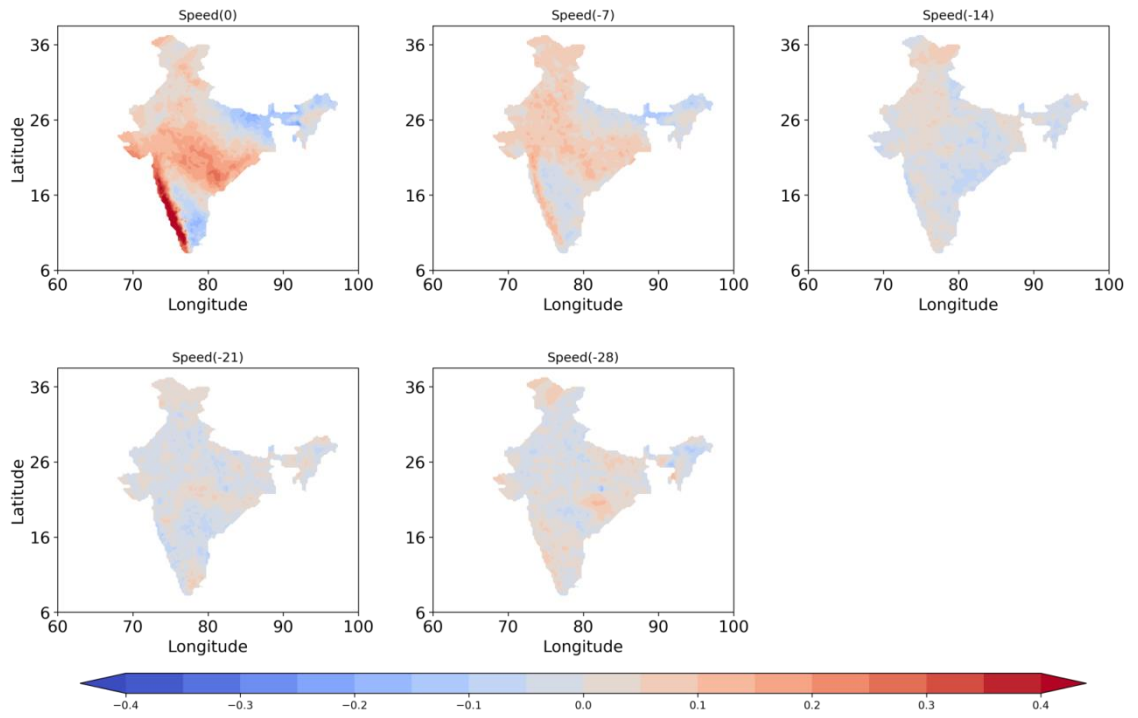
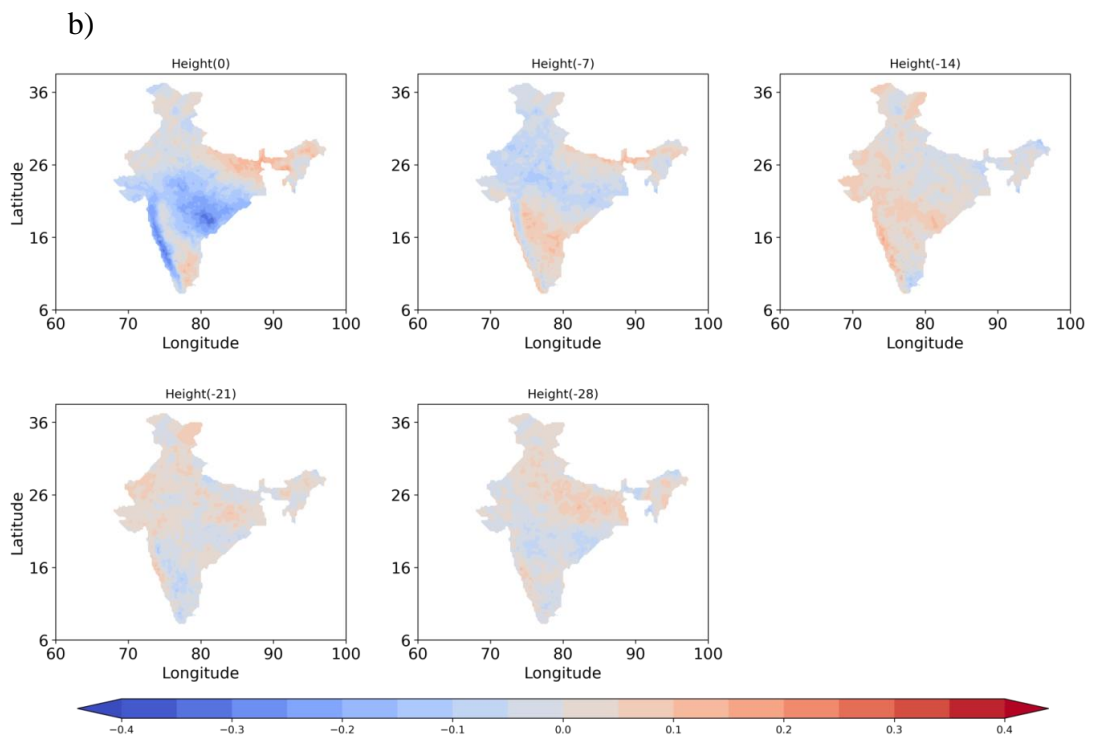


Fig. 33a Spatial correlation of rainfall with jet properties in July of Arabian Sea



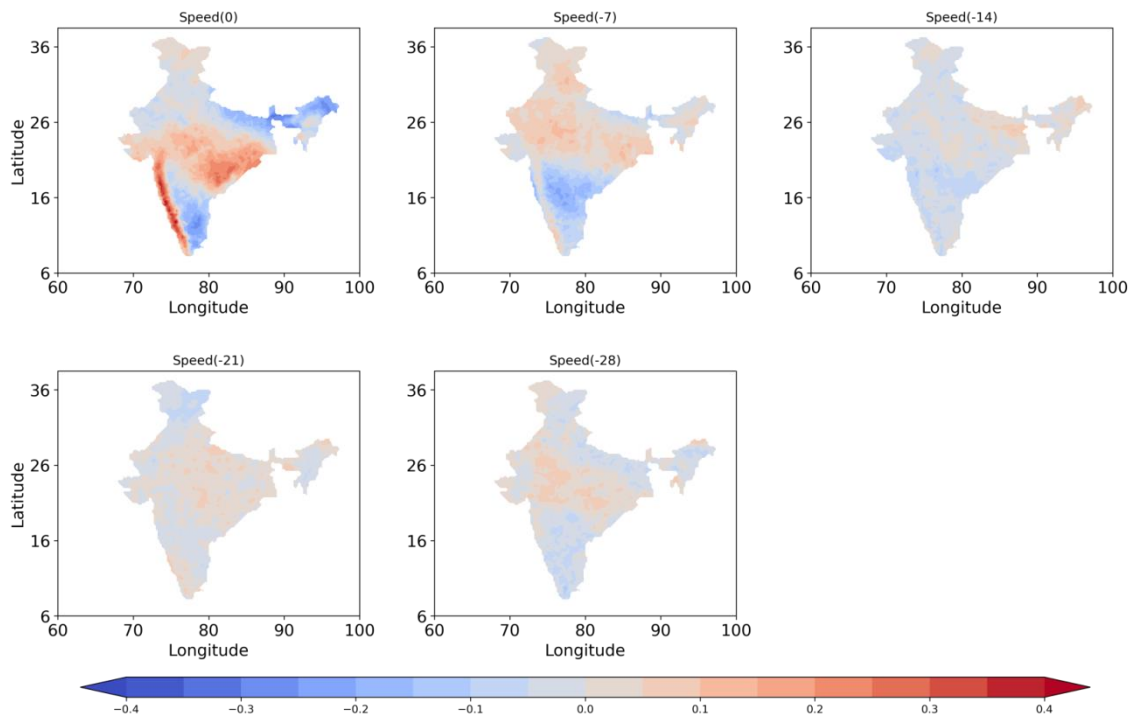
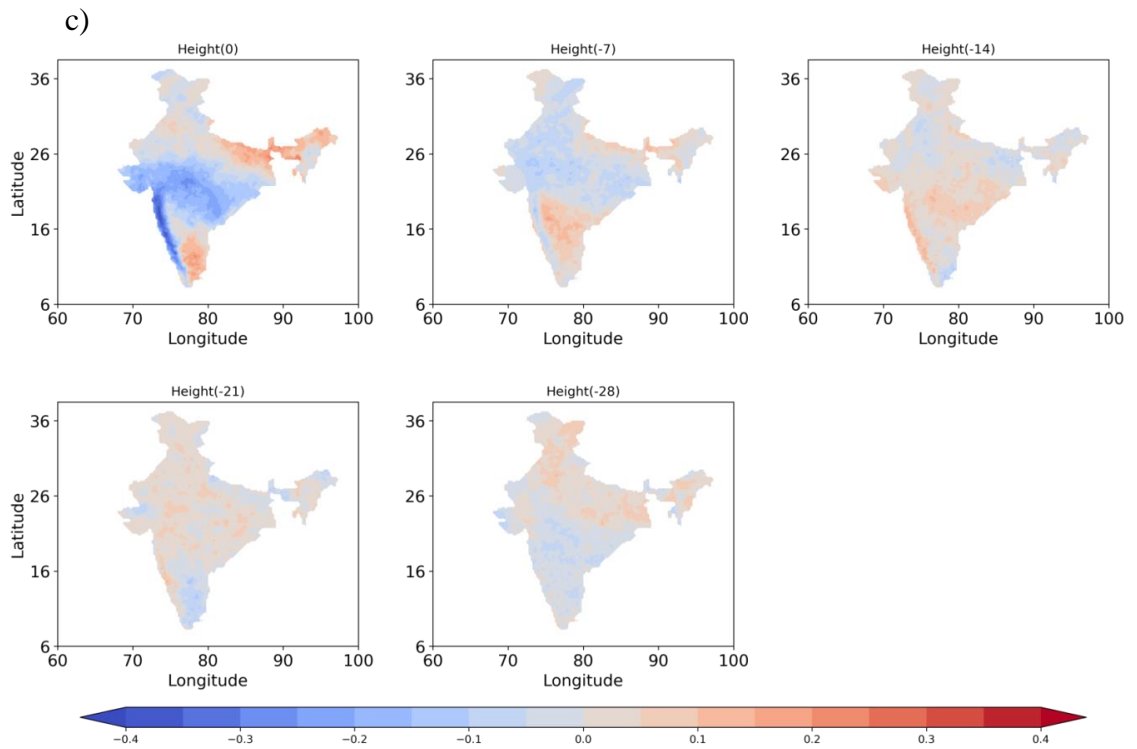


Fig. 34b Spatial correlation of rainfall with jet properties in July of Bay of bengal



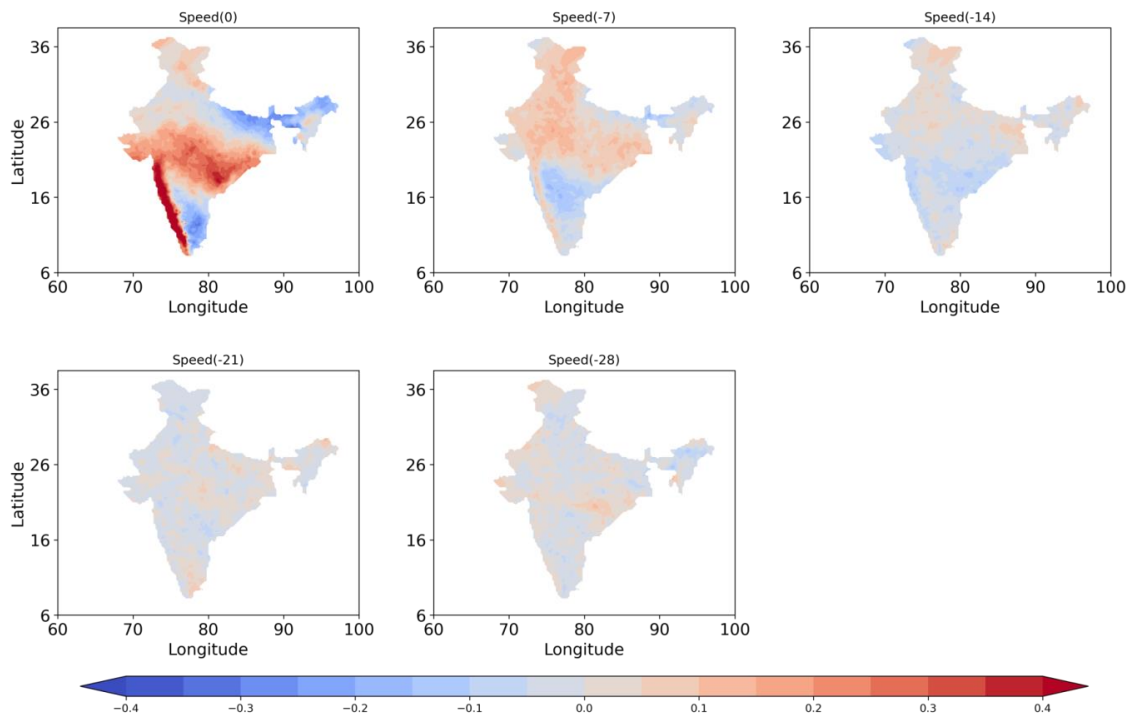
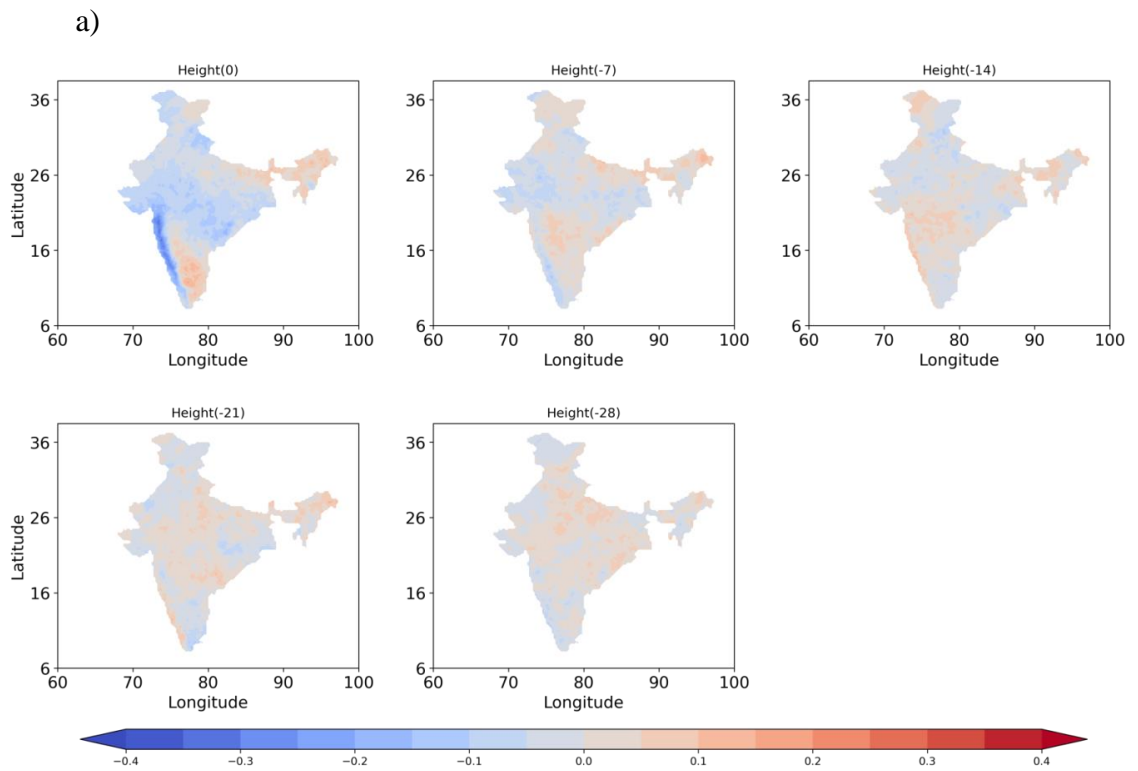


Fig. 35c Spatial correlation of rainfall with jet properties in July of Indian subcontinent



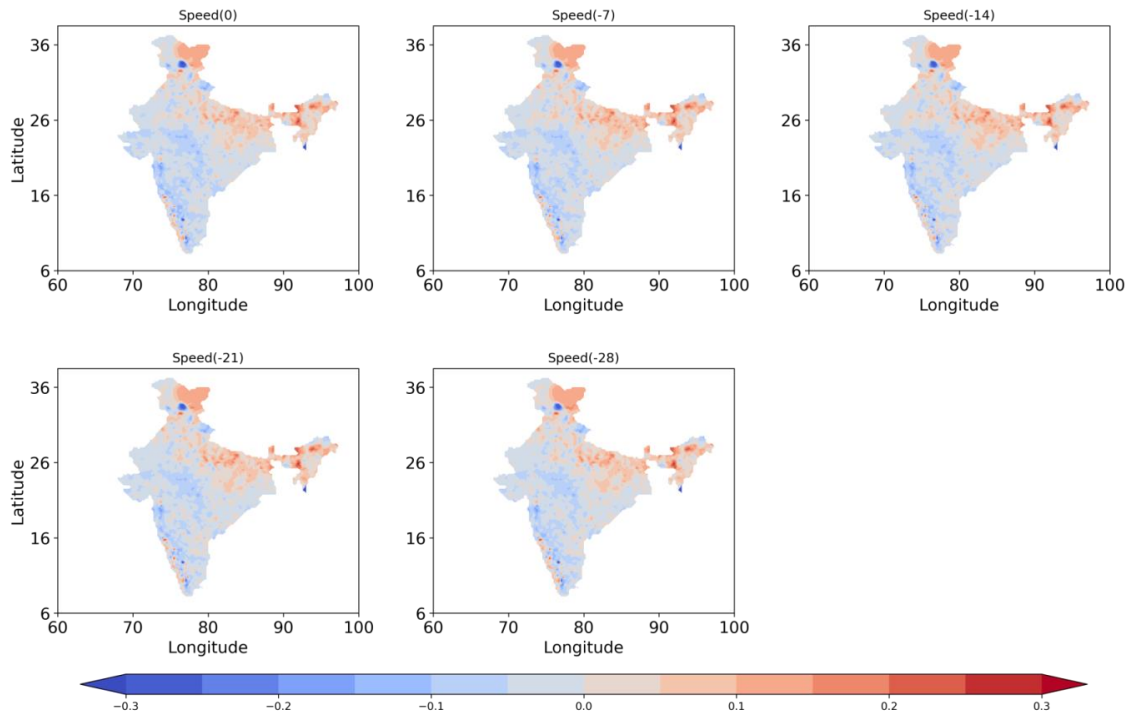
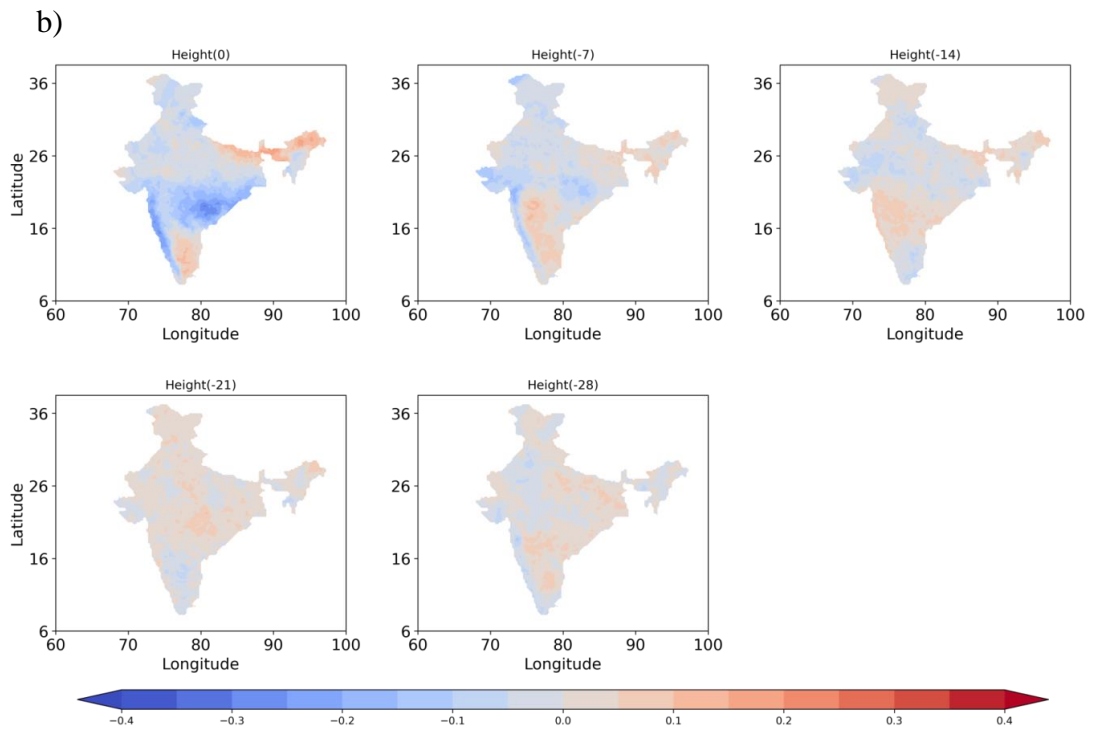


Fig. 36a Spatial correlation of rainfall with jet properties in August of Arabian Sea



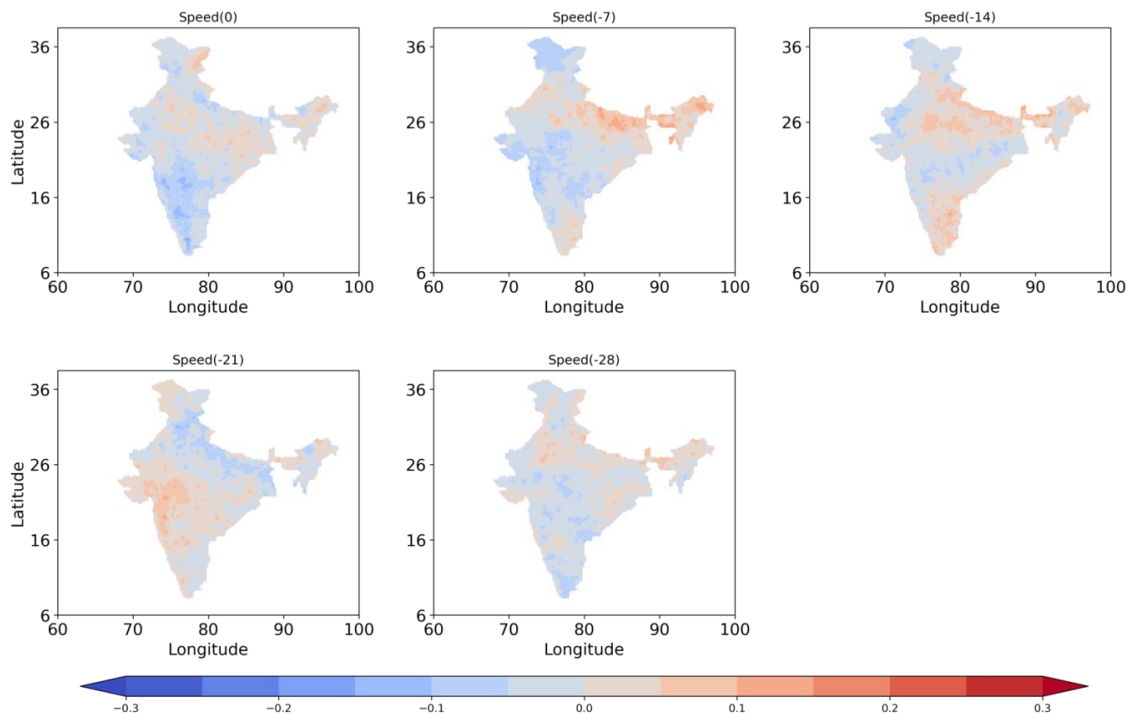
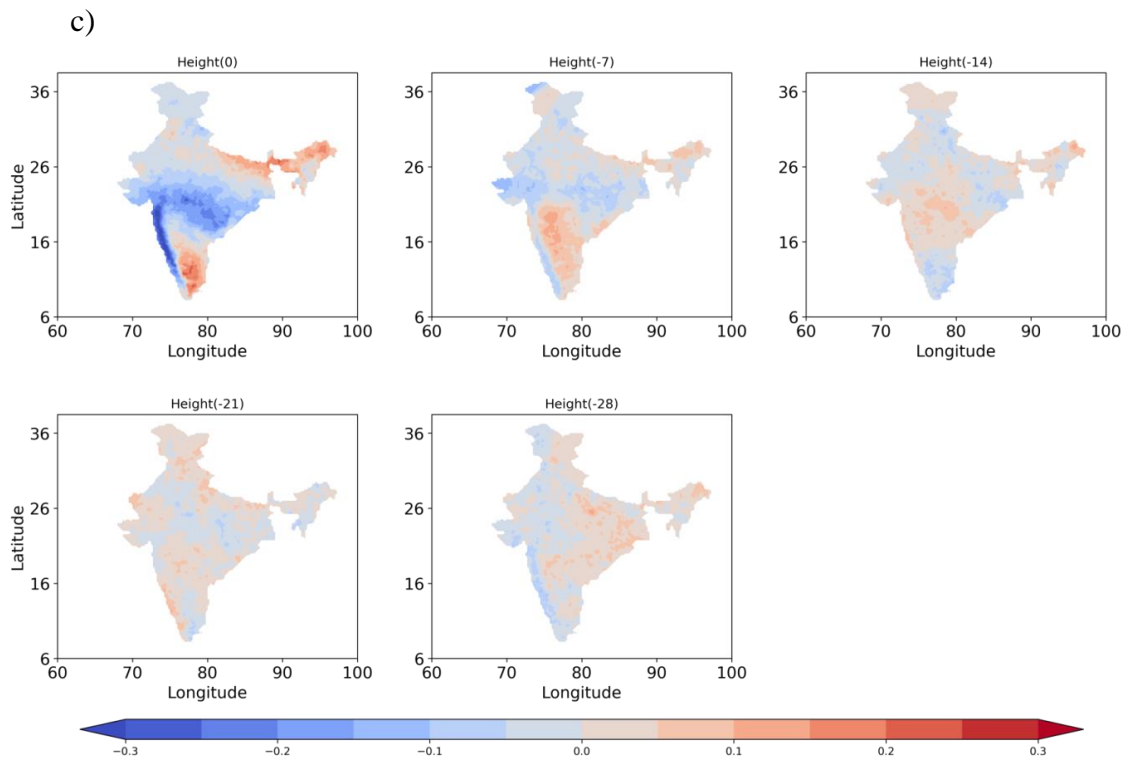


Fig. 37b Spatial correlation of rainfall with jet properties in August of Bay of bengal



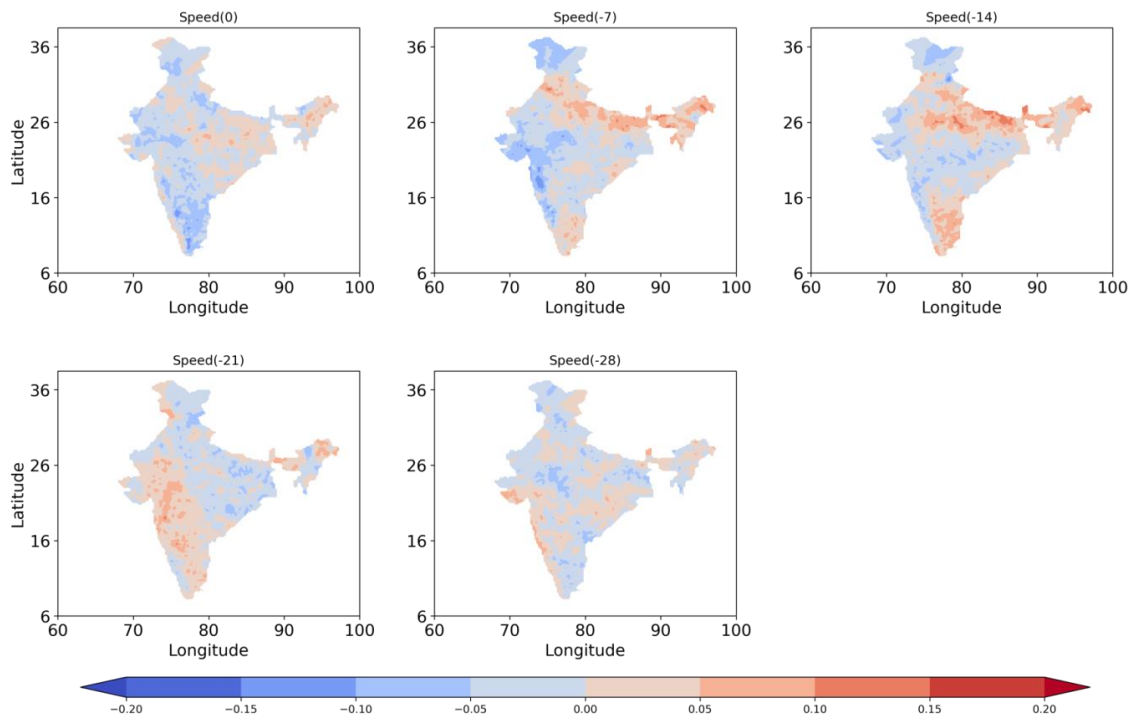
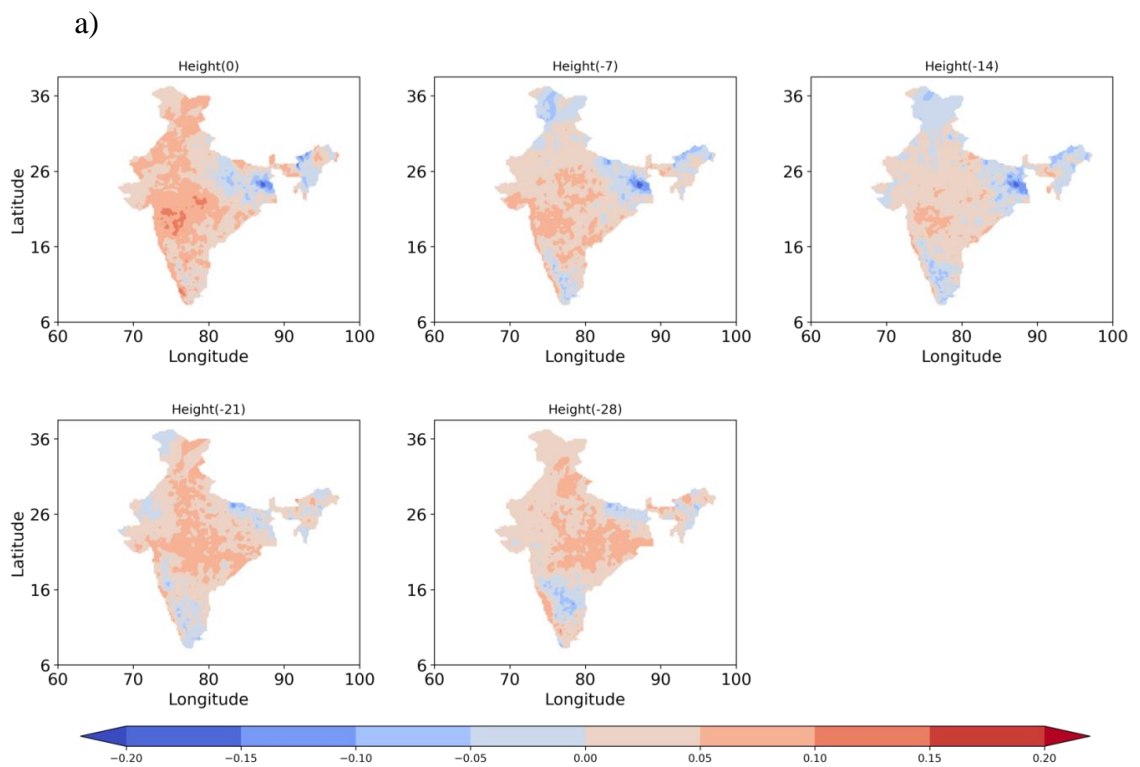


Fig. 38c Spatial correlation of rainfall with jet properties in August of Indian subcontinent



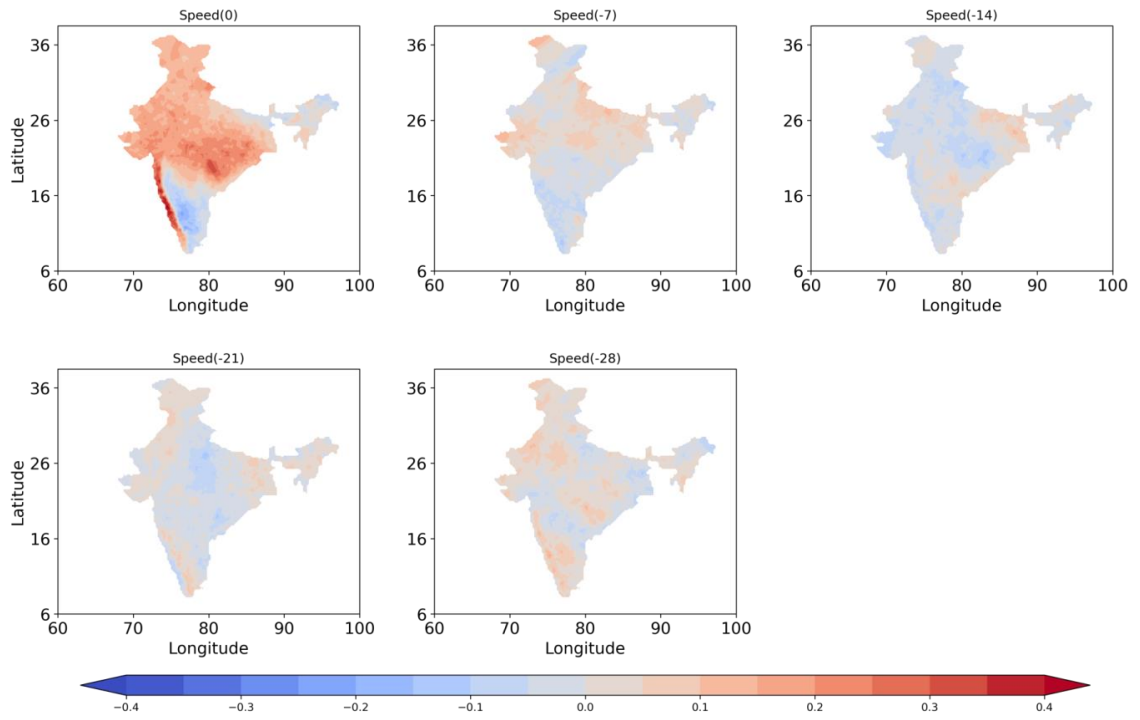
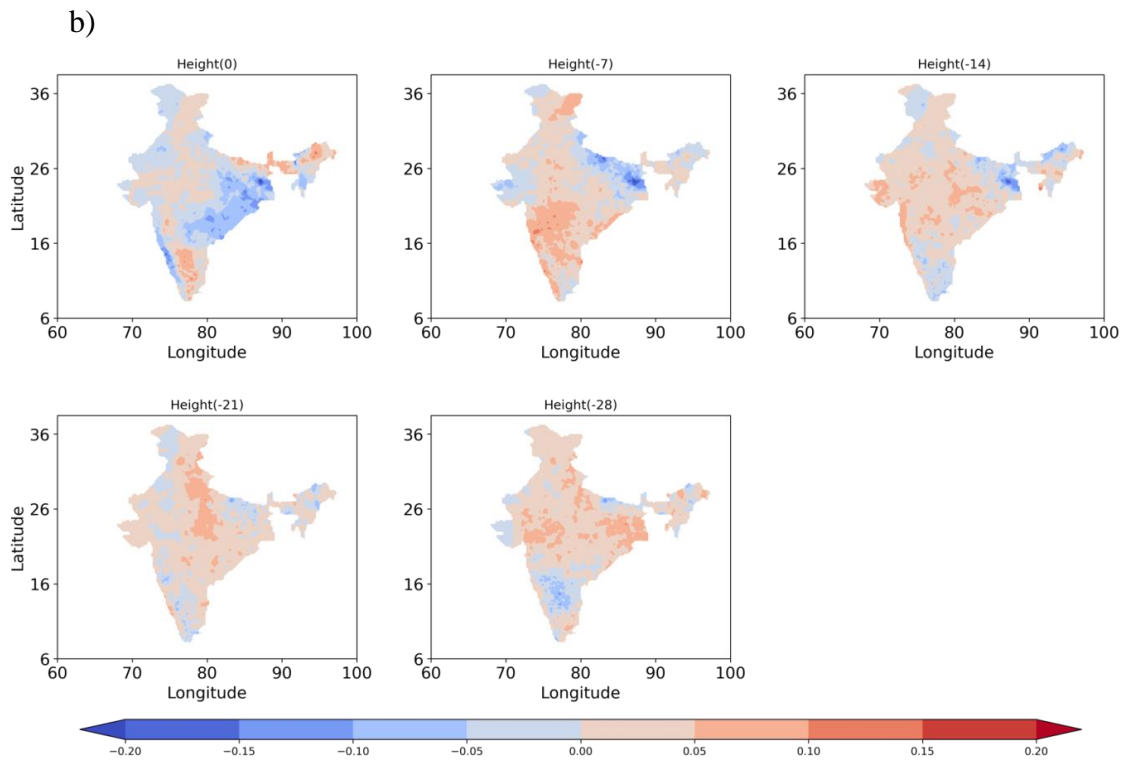


Fig. 39a Spatial correlation of rainfall with jet properties in September of Arabian Sea



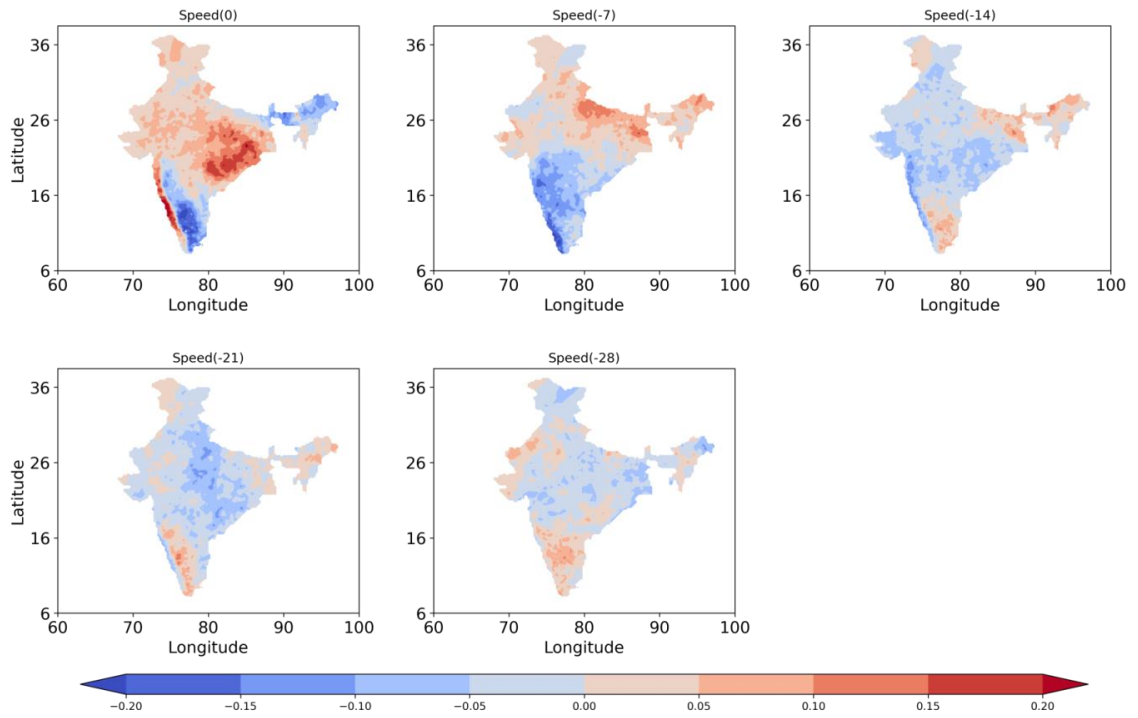
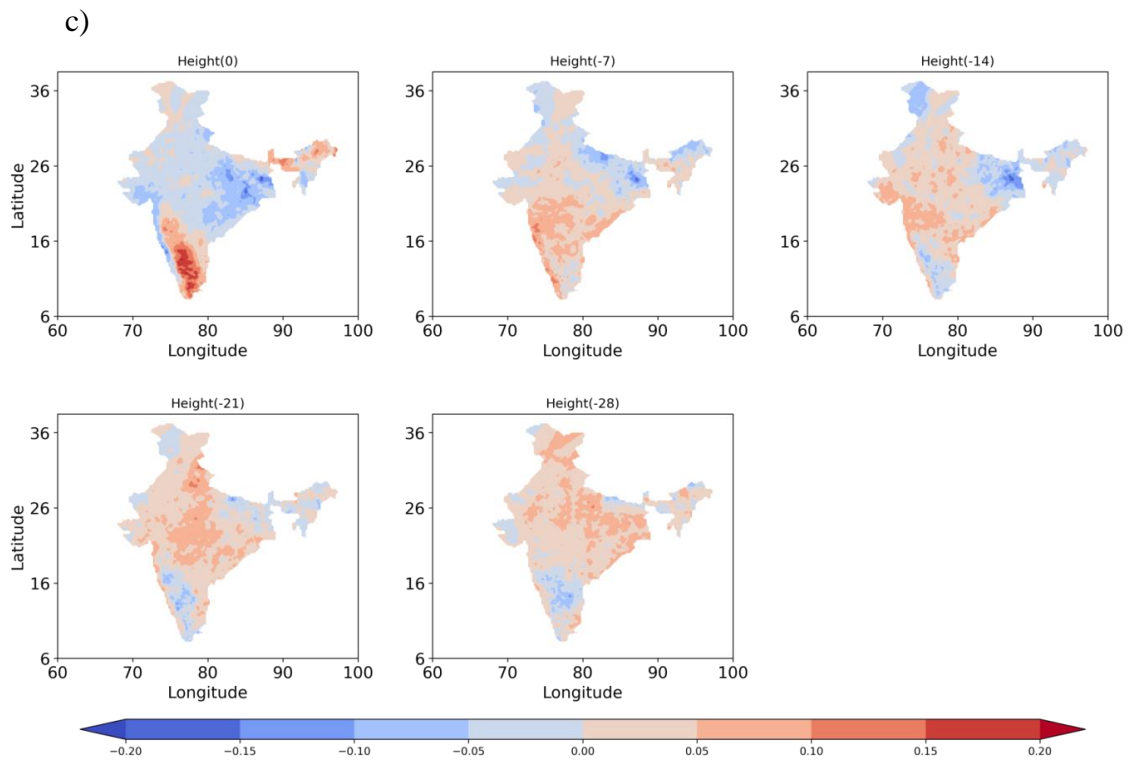


Fig. 40b Spatial correlation of rainfall with jet properties in September of Bay of bengal



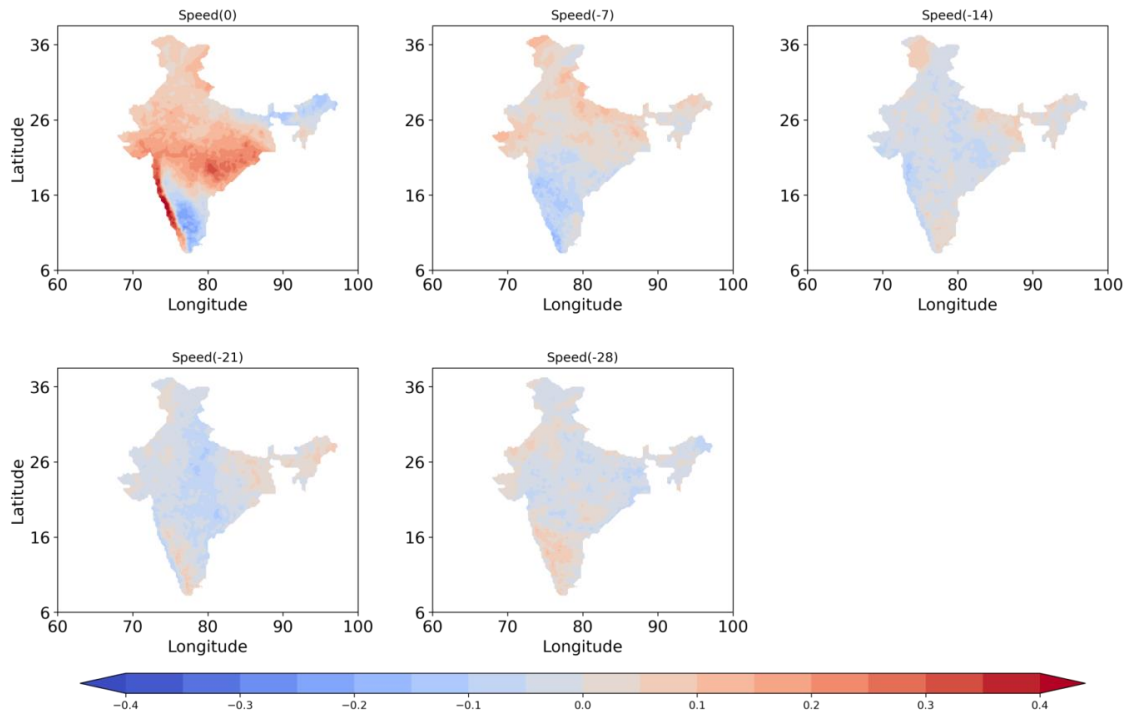


Fig. 41c Spatial correlation of rainfall with jet properties in September of Indian subcontinent

4.8 MLLJ VARIABILITY IN PRESENT AND FUTURE CLIMATE: IITM-ESM ANALYSIS

Using historical and projection data from IITM ESM, the occurrence of Jet properties during the season (June-August) in AS, BOB, and IS regions is analyzed and depicted in the (Fig.34, Fig.35) projection data and (Fig.36, Fig.37) is historical data.

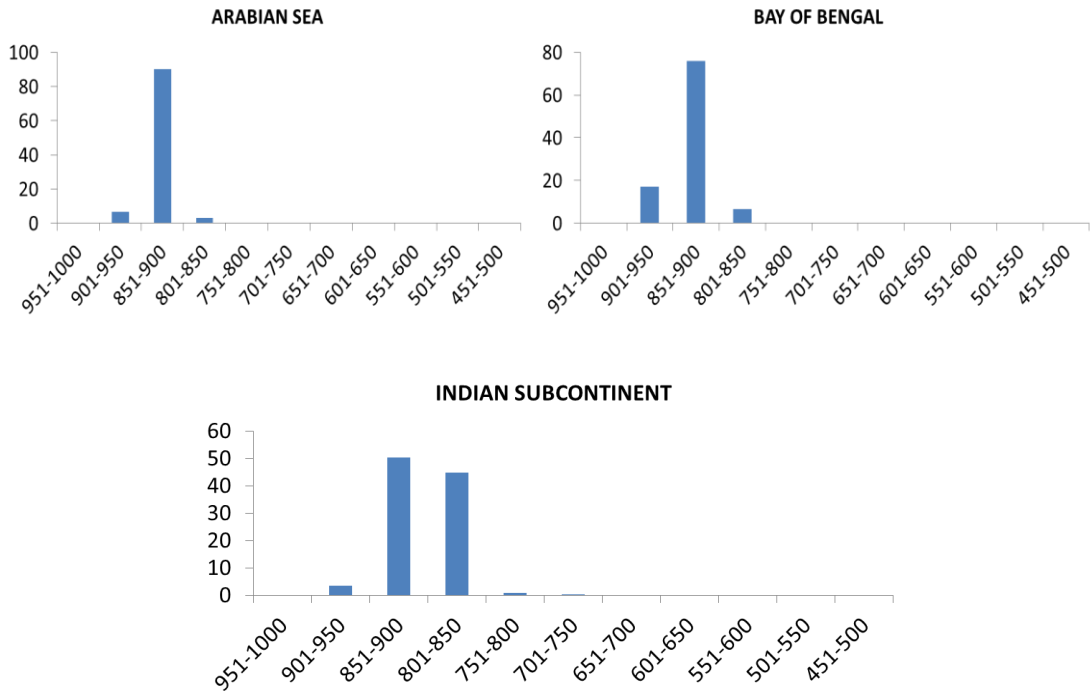


Fig. 42 Seasonal (JJA) Percentage of Core Height Occurrence in projection data in each region

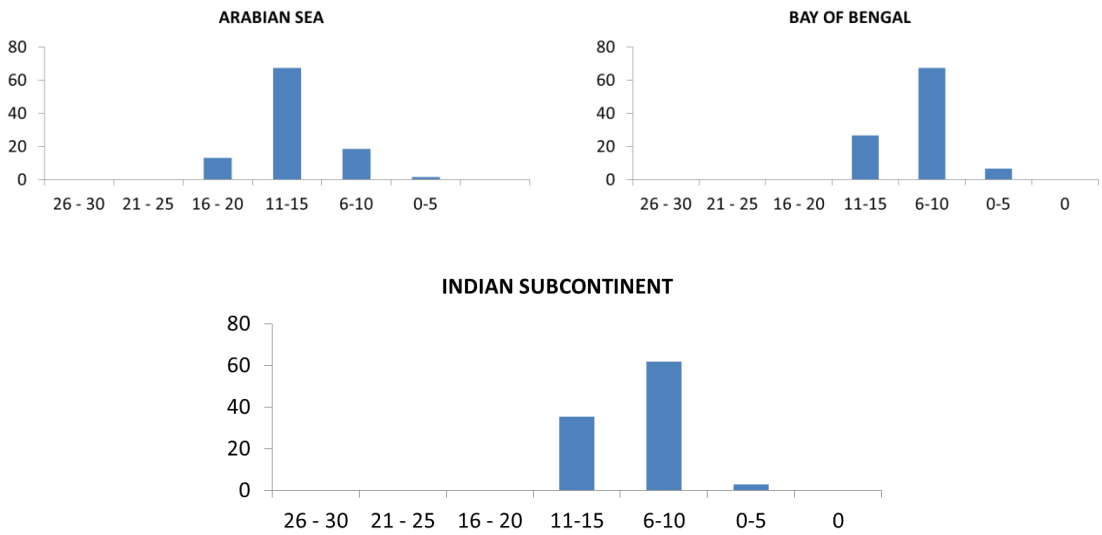


Fig. 43 Seasonal (JJA) Percentage of Core Speed Occurrence in projection data in each region

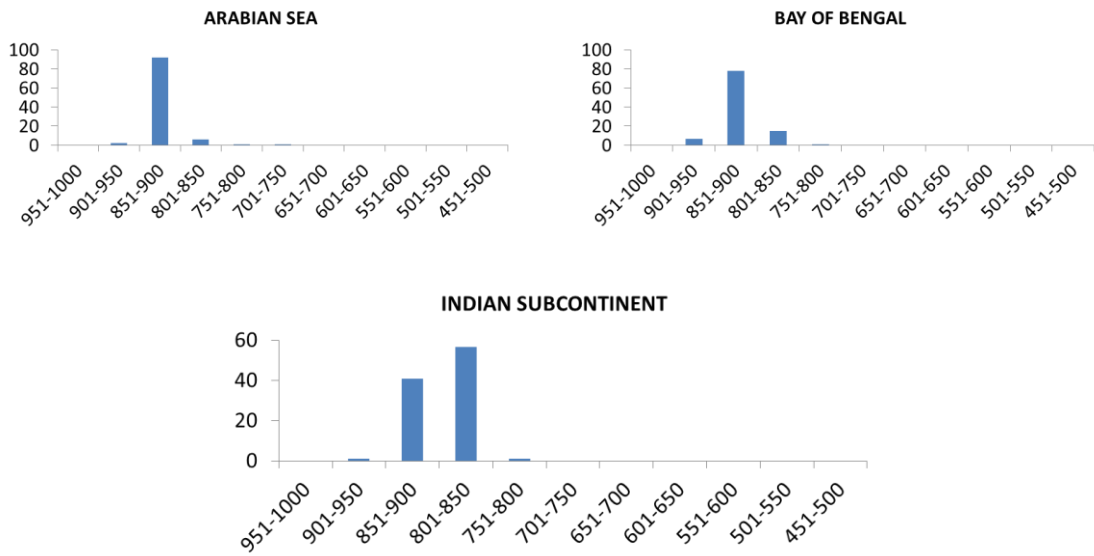


Fig. 44 Seasonal (JJA) Percentage of Core Height Occurrence in historical data in each region

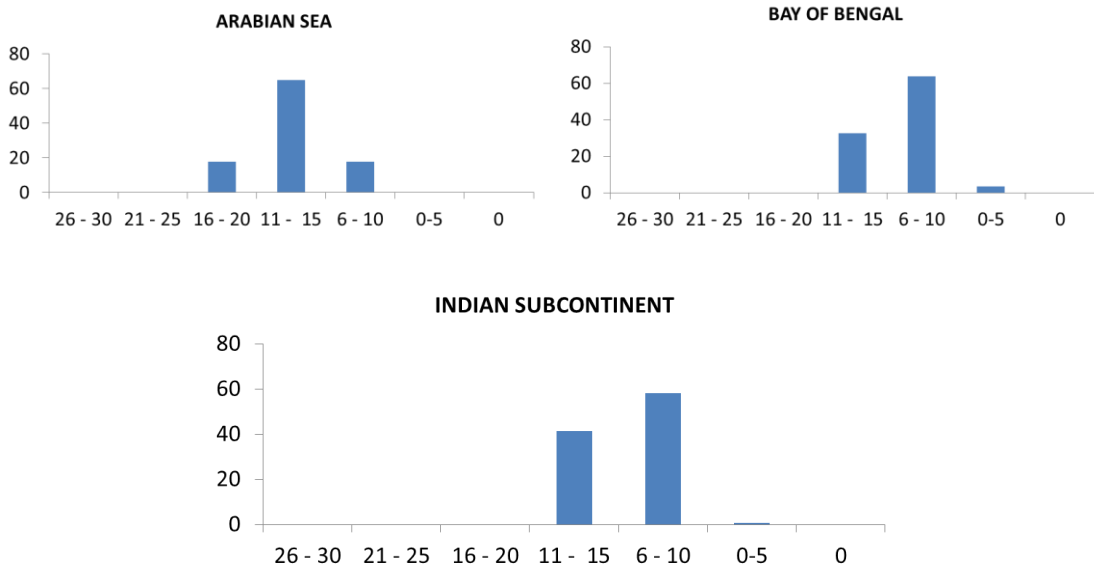


Fig. 45 Seasonal (JJA) Percentage of Core Speed Occurrence in projection data in each region

CHAPTER 5

SUMMARY

The Indian summer monsoon is an annual weather phenomenon that takes place over the Indian subcontinent from June to September. It is a crucial component of India's weather patterns, contributing to approximately 70-90% of the country's total annual precipitation. The Monsoon Low-Level Jet (MLLJ) is a crucial synoptic feature of the Indian summer monsoon, responsible for a significant portion of moisture transport to the Indian subcontinent.

The present study aims to elucidate various dimensions of Low-Level Jet (LLJ) characteristics, examining their variations across spatial and temporal scales. This research significantly advances our understanding of Indian Ocean processes, which have a substantial impact on LLJ dynamics. Moreover, it sheds light on the critical role that LLJ plays in triggering extreme precipitation events in the Indian subcontinent, particularly within the context of a warming climate. The study also delves into how LLJ influences processes related to convection, cloud formation, and precipitation mechanisms. Major results of this work are pointed below

In this study, the comparison of Monsoon Low Level Jet (MLLJ) parameters of ERA 5 data set with radiosonde data yield good results. The bias values are -40.53 hPa and -0.485 m/s respectively for core height and core speed. Spread values were tabulated as 90.58 and 11.08 respectively. The correlation values for core height and core speed were 0.54 and 0.85 respectively. This results indicates that both the data sets were showing good agreement, and RMSE which is 122.863 and 2.677 gives us the confidence to say that ERA 5 can be used for characrising the MLLJ features. So we analyzed reanalysis data of zonal wind in regions such as the Indian Ocean (IO), Arabian Sea (AS), Bay of Bengal (BOB), and meridional wind in the Equatorial Indian Ocean (EIO). We aimed to understand the transformation of the monsoon Low-Level Jet (LLJ) across the entire Indian Ocean region by calculating the core height and core speed of the LLJ. Subsequently, we examined the percentage of occurrence, trends, and mean standard deviation for these jet properties. The average

height of jet cores in various regions was determined to be 588.84 ± 37.81 , 874 ± 16.9 , 849.62 ± 24.11 , 830 ± 39.85 , and 832 ± 41.25 , and the mean jet speeds were found to be 2.96 ± 2.78 , 10.49 ± 1.07 , 15.79 ± 3.1 , 11.43 ± 3.4 , and 9.857 ± 3.09 , respectively. This implies that, on a seasonal basis, the Arabian Sea experiences the highest core speed, whereas the Equatorial Indian Ocean exhibits the maximum core height. This pattern is particularly noticeable in the northern hemisphere, where there is a positive correlation among the properties of the jet. Analyzing IOD, SIOD, and ENSO indexes reveals considerable variations in SIOD with jet properties. Notably, when analyzing trends for the periods before and after 2020, significant variations were observed across the specified regions. Jet core height in IO region increases, speed shifts to negative. AS region sees rise in height then decrease, speed increases. IS region has strong increase in height, speed trends differ in time periods but changes are small. BB region has increase in height and decrease in speed, with sharper decline in speed after 2020.

The study also observed upwelling indexes for the Somali, Oman, and southeastern Arabian Sea regions. It shows a strong interrelation between jet speed and Somali upwelling. The Equatorial Indian Ocean (EIO) jet speed and the Somalian upwelling index exhibit a significant negative correlation. This relationship holds strong within a time frame ranging from 6 days in advance to over 10 days later, with the strongest correlation observed at the 0 lag point. This suggests that jet speed influences upwelling up to 6 days prior, and conversely, upwelling impacts jet speed even beyond a 10-day delay. Before the Indian summer monsoon, the Arabian Sea Mini Warm Pool (ASWP) systems are significant. Analyzing their interaction with jet properties, a lead-lag correlation study was performed. The results show that jet properties have a notable influence on ASWP. The most pronounced impact occurs in the period of -5 to 0 days for jet speed and -10 to -5 days for core height, suggesting that the jet core can influence ASWP, particularly in May. In the investigation of cloud precipitation properties, data on CAPE (Convective Available Potential Energy), convective precipitation, and moisture availability were used. The association between CAPE and convective precipitation with core height reveals similarities in the AS and IS regions, the correlation is more visible in the lead/lag

range of 10 days. While the BB region exhibits notable differences. The relation between the jet speed and cape is stronger during the lead/lag period of 5 days. In convective precipitation analysis, MLLJ core height leading shows a positive correlation across the northern Indian Ocean, inhibiting precipitation. Conversely, CP leading LLJ results in a negative correlation along the eastern coast, promoting Jet core uplift and precipitation. Jet speed also correlates well in the northern Bay, especially at 0 lag. In moisture analysis, AS Jet speed correlates with Arabian Sea moisture availability at lags from 14 to 0. AS moisture depends on MLLJ strength during the southwest monsoon. Similar trends were found for BOB and IS regions with max correlations at decreasing lags. Additionally, lag relations between MLLJ height over AS, CAPE, and moisture availability suggest that lower-level core height can enhance convection through frictional convergence, with this effect diminishing at higher levels. Analyzing MLLJ characteristics with Indian Summer Monsoon Rainfall (ISMR) using IMD data reveals a negative correlation between Core Height and ISMR over the western coast and central Indian region in June, July, and August, particularly for simultaneous cases. However, September exhibits different behavior. In terms of Core Speed, except for August, a strong correlation is observed between jet speed and monsoon rainfall over western and central India in the other three months.

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**INFLUENCE OF INDIAN OCEAN ON STRUCTURE AND VARIABILITY OF
MONSOON LOW LEVEL JET IN THE PRESENT AND FUTURE CLIMATE
PERSPECTIVES**

by

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(2018 - 20 - 022)

THESIS

**Submitted in partial fulfilment of the
requirements for the degree of**

B.Sc. – M.Sc. (Integrated) Climate Change Adaptation

Faculty of Agriculture

Kerala Agricultural University



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2023

ABSTRACT

The Monsoon Low-Level Jet (MLLJ) is a crucial synoptic feature of the Indian summer monsoon, responsible for a significant portion of moisture transport to the Indian subcontinent. The present study focuses on analyzing the variability and vertical structure of the Monsoon Low-Level Jet (MLLJ) during the Southwest Monsoon season from 1979 to 2022. To conduct in-depth analysis, the total MLLJ path was divided into five regions: the Southern Indian Ocean, Equatorial Indian Ocean, Arabian Sea, Indian subcontinent, and the Bay of Bengal. The mean jet core height for these selected regions was found to be 588.84 ± 37.81 , 874 ± 16.9 , 849.62 ± 24.11 , 830 ± 39.85 , 832 ± 41.25 and mean jet speed were found to be 2.96 ± 2.78 , 10.49 ± 1.07 , 15.79 ± 3.1 , 11.43 ± 3.4 and 9.857 ± 3.09 respectively. Monthly variation in the jet properties were also analysed. To consider the impact of global warming on MLLJ characteristics, the analysis was conducted by dividing the study period into two epochs: pre-20 (1979 – 2000) and post-20 (2001 – 2022). The properties of the jet exhibit remarkable differences between these two epochs. Trend analysis also indicates a significant change between these epochs. Jet properties show robust interconnections with sub-seasonal ocean processes, including Somali, Oman, and South Eastern Arabian Sea upwellings in the Indian Ocean. The Arabian Sea Mini Warm Pool exhibits a significant correlation with jet properties, especially Arabian Sea core height. Extensive research was conducted to deeply investigate the pivotal influence of MLLJ characteristics on cloud and precipitation processes. The association of Convective Available Potential Energy (CAPE) and convective precipitation with core height exhibited similarities in the Arabian Sea (AS) and Indian subcontinent (IS) regions, while the Bay of Bengal (BB) region displayed notable differences. The Jet speed exhibits same pattern. In the study, MLLJ characteristics were examined in relation to ocean-atmospheric processes, including the IOD, ENSO, and SIOD indices, with a focus on notable variations in the SIOD index. The MLLJ characteristics also correlate with Indian summer rainfall, showing significant relationships. To assess future prospects, historical (1850-2014) and projection (2015-2096) data from IITM ESM were analyzed in conjunction with jet properties.