Multimodal Analysis of Robust Changes in the South Asian Summer Monsoon under a warming climate

A Report

Submitted For The Degree Of

Master of Technology

by

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June 2024

Statement of Honesty

I, Kartik Soni, hereby declare that this research work titled "Multimodal Analysis of Robust Changes in the South Asian Summer Monsoon under a warming climate" is a product of my own independent scholarly efforts. All the information and data presented in this research are original and have been accurately collected, analyzed, and reported. Any sources, references, or materials from existing literature or other researchers have been properly acknowledged and cited following academic and ethical standards.

I understand and uphold the values of academic integrity and honesty, and I have taken great care to avoid plagiarism, falsification, or misrepresentation of data. This work has not been submitted previously for any degree or diploma at any other educational institution.

I am fully aware of the consequences of any breach of academic integrity policies. This research adheres to the highest academic honesty and ethical conduct standards.

Signed,

Kartik Soni

10/06/2024

Acknowledgements

First and foremost, I extend my deepest gratitude to my advisor, *Professor Govindasamy Bala*, for his unwavering support, insightful guidance, and inspiring mentorship throughout this research. His expertise and encouragement were instrumental in shaping the direction and quality of this work. I am particularly grateful for our stimulating discussions, which broadened my understanding of the Indian Summer Monsoon and its complexities. I also sincerely thank my co-supervisor, *Professor Ravi Nanjundiah*, for his feedback and insights. His expertise in numerical methods and his dedication to rigorous scientific inquiry have greatly enriched this research. A special acknowledgement goes to *Dr J. Srinivasan,* whose support and discussions broadened my perspective on how to look at the broader picture and also for his time to discuss all the opportunities across various topics as well.

I am deeply grateful to my labmates, *Harpreet, Mahendra, Ritesh, Jayakrishnan, and Sumit,* for their camaraderie, technical assistance, and hours of discussions. Their support and friendship have made my time in the lab both productive and enjoyable. I also thank all the other CAOS seniors for their willingness to share their knowledge and experience.

I want to acknowledge my friends, *Alok, Eleena, Gaurav, Jitendra, Kevin, Manya, Naveen, Sushant, Sushil*, for their encouragement, support, and countless moments of laughter and memories. Their friendship has been a strength and inspiration throughout my academic journey. Also, to Abhishek, Samudra, Shankar, and Shubhrangshu for all their help and memories together.

I am also indebted to the faculty of CAOS, including Prof. Jai Sukhatme for his enlightening lectures on atmospheric dynamics, Prof. Vinay for deepening my understanding of oceanography, Bhat sir for his emphasis on observational data, Prof. Bala for his comprehensive knowledge of climate systems, Ravi and Ashwin sir for their expertise in numerical methods, Arindham sir for his insights into thermodynamics, and JS for his expertise in satellite meteorology. Their passion for teaching and research has been truly inspiring.

I extend my heartfelt thanks to my parents and family friends, Karnik and Rohit, for their unwavering love, support, and encouragement throughout my academic journey.

I would also like to acknowledge the CAOS staff, including Raju, Suman, and Shivaji, for their efforts in ensuring the smooth functioning of the department and their assistance with various logistical matters. Finally, I am deeply grateful to the Indian Institute of Science for providing me with a world-class education, cutting-edge research facilities, and a vibrant intellectual community. This institution has fostered my growth as a researcher and provided me with invaluable opportunities to learn and collaborate with some of the brightest minds in the field.

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Abstract

The South Asian Summer Monsoon (SASM) is a vital climatic phenomenon influencing the socio-economic fabric of South Asia, particularly in agriculture, water resources, and energy production. This study investigates the response of the SASM to an abrupt quadrupling of atmospheric CO2 concentrations (abrupt-4xCO2) using multimodal data from CMIP6 climate models and ERA5 reanalysis data. The primary objective is to enhance the understanding of how increased atmospheric CO2 levels impact monsoon patterns, focusing on changes in precipitation, atmospheric circulation, and associated climatic variables.

Our analysis reveals that the SASM is projected to experience significant changes under the abrupt-4xCO2 scenario. Key findings include an overall increase in monsoon rainfall, a shift in the spatial distribution of precipitation, and alterations in large-scale atmospheric circulation patterns. Complex interactions between increased atmospheric moisture content, enhanced stability, and modifications in key circulation features such as the Walker circulation and the Somali Jet drive these changes.

The study provides robust insights into the future behaviour of the SASM, highlighting the need for improved predictive models and effective adaptation strategies. By integrating data from multiple climate models and observational sources, this research addresses gaps in our understanding of monsoon variability and response to extreme CO2 levels.

Keywords: South Asian Summer Monsoon (SASM), Climate Change, CMIP6 Models, ERA5, Monsoon Precipitation, Atmospheric Circulation, Climate Projections, CO2 Concentrations, Global Warming, Walker circulation, Climate Models

Chapter 1

Introduction

The South Asian Summer Monsoon (SASM) is an intricate climatic phenomenon that significantly influences the socio-economic landscape of South Asia. Characterized by its seasonal rainfall, the SASM plays a crucial role in agriculture, water resources, and energy production, making it a lifeline for over a billion people in the region. However, the increasing levels of atmospheric CO2 and the resulting global warming pose significant uncertainties regarding the future behaviour of the SASM ([1]). This research aims to address these uncertainties by comprehensively analysing the SASM's response to increased atmospheric CO2 concentrations using multimodal data from the latest climate models and observational reanalysis data.

Climate models have projected a range of changes in monsoon patterns due to global warming, but these projections are often marked by significant variability and uncertainty. The central problem addressed in this research is the need for a clearer understanding of how the SASM will respond to substantial increases in atmospheric CO2 levels. This understanding is vital because the monsoon directly affects agriculture, water availability, and energy production, all of which are critical to the livelihoods and economic stability of South Asia. Accurately predicting these changes is essential for developing effective adaptation and mitigation strategies to combat the adverse effects of climate change.

To tackle this complex problem, this study employs a comprehensive approach using data from the CMIP6 climate models and the ERA5 reanalysis data. By analyzing various climatic variables such as sea surface temperature (SST), vertical velocity, zonal winds, and precipitation anomalies, we aim to identify consistent patterns and robust changes across different models. This multimodal analysis enhances the reliability of our projections by integrating findings from multiple sources, thereby providing a more accurate picture of the future SASM under increased CO2 concentrations.

The primary purpose of this document is to present a detailed analysis of the SASM under an abrupt quadrupling of CO2 concentrations (abrupt-4xCO2 scenario) compared to pre-industrial control simulations (piControl). This research seeks to elucidate the key drivers of monsoon variability and their projected changes, providing valuable insights that can inform both scientific understanding and practical decision-making related to climate adaptation in South Asia.

The study of the SASM has evolved significantly over the years, with early research focusing on observational data to understand its seasonal and interannual variability. The introduction of climate models has allowed for more detailed investigations into the monsoon's physical processes. Previous studies have indicated that global warming could increase monsoon rainfall due to higher moisture availability in the atmosphere. However, these findings often come with large uncertainties, particularly regarding the spatial distribution of rainfall changes and the underlying mechanisms.

For instance, Li et al. ([5]2017) projected changes in SASM precipitation using CMIP5 models, highlighting the potential for increased rainfall but with significant model-to-model variability (Li et al., [5]2017). Similarly, Menon et al. ([6]2013) observed a consistent increase in Indian monsoon rainfall and its variability across CMIP5 models, but the mechanisms driving these changes remain unclear (Menon et al., 2013[6]). More recent studies using CMIP6 models, such as those by Li et al. ([4]2021), have continued to explore these uncertainties, emphasizing the need for a more integrated approach to understanding the monsoon response to global warming (Li et al., [4]2021).

The SASM is influenced by a range of climatic factors, including the Indian Ocean Dipole (IOD), El Niño-Southern Oscillation (ENSO), and the Madden-Julian Oscillation (MJO). These factors interact complexly to modulate the monsoon's intensity and variability. For example, the IOD can enhance or suppress monsoon rainfall depending on its phase, while ENSO events can lead to droughts or floods in the region (Vinayachandran et al., [12]2009; Yao et al., [13]2016).

Research has also identified the significant role of atmospheric circulation patterns in driving monsoon variability. The Clausius-Clapeyron relationship suggests that warmer air can hold more moisture, leading to increased precipitation. However, this is countered by increased atmospheric stability and suppressed convection, which can weaken the monsoon (Krishnamurthy & Ajayamohan, [3]2010). Large-scale circulation changes, such as the weakening of the Walker circulation and the Somali Jet, are also crucial in modulating the monsoon response (Sandeep et al., [9]2018).

Along with these insights, there remains a gap in understanding the integrated response of the SASM to abrupt and extreme changes in CO2 concentrations. This research aims to fill this gap by providing a multimodal perspective integrating findings from multiple climate models and observational data sources.

Understanding the robust features of the SASM response to global warming is crucial for several reasons. Firstly, it can help improve the predictability of seasonal monsoon rainfall, which is essential for the region's agricultural planning and food security. Secondly, insights into monsoon intensity and variability changes can aid in designing better water management and disaster mitigation strategies, particularly in floods and droughts. Lastly, this research contributes to the broader field of climate science by enhancing our understanding of the complex interactions between various climatic processes under extreme warming scenarios.

For example, the intensification of very wet monsoon seasons in India under global warming has been highlighted by Katzenberger et al. ([2]2022), who noted the significant socio-economic impacts of such changes (Katzenberger et al., [2]2022). Similarly, Roxy et al. ([8]2017) reported a threefold increase in widespread extreme rain events over central India, underscoring the urgent need for improved predictive models and adaptation strategies (Roxy et al., [8]2017).

Despite these advances, the robustness of these projected changes and the underlying mechanisms remain active research areas. Many studies have relied on limited model ensembles or focused on specific aspects of the monsoon system, leaving open questions about the generalizability of their findings. Additionally, model biases, such as the persistent dry bias over land and wet bias over the ocean, introduce uncertainties in simulations of present-day and future climates. This document is organized into the following chapters:

Data and Methods: This chapter outlines the data sources used in the study, including CMIP6 model data and ERA5 reanalysis data. It also details the experimental design, methodologies for data processing, regridding, and analysis techniques employed.

Results: This chapter presents the findings from the multimodal analysis, focusing on changes in monsoon circulation, precipitation patterns, and associated climatic variables under the abrupt-4xCO2 scenario compared to the piControl simulation. It discusses these results in a global context, highlighting the key mechanisms driving the observed changes.

Discussion and conclusion: This chapter provides a comprehensive discussion of the results, proposing mechanisms for the observed changes in the SASM and addressing the uncertainties and limitations of the study. It also suggests future research directions to build on these findings. The final chapter summarizes the key findings, emphasizing the robust features of the SASM's response to global warming and discussing their implications for regional climate projections and policy-making.

Chapter 2

Data and Methods

2.1 Data Sources

2.1.1 CMIP6 Model Data

We utilize output from the Coupled Model Intercomparison Project Phase 6 (CMIP6) model ensemble to investigate the robust features and uncertainties in the response of the Indian summer monsoon to increased CO2. The CMIP6 dataset is obtained from the CMIP6 database website (https://esgf-node.llnl.gov/search/cmip6). The CMIP6 data encompass various variables relevant to the monsoon system, including:

- Precipitation
- Zonal and Meridional Winds
- Vertical Velocity
- Air Temperature
- Sea Surface Temperature (SST)
- Specific Humidity
- Total Cloud Fraction
- Sea level pressure

This study analyzes output from 25 CMIP6 models, selected based on data availability for the piControl and abrupt-4xCO2 experiments for the period 1850-2000. Where available, a single ensemble member (r1i1p1f1) is used for each model. A table listing (Table: 5.1) the models and their institutions is provided.

2.1.2 ERA5 Reanalysis Data

Evaluating CMIP6 models against observational data is crucial for assessing their ability to simulate the Earth's climate system accurately. In this study, we used the ERA5 reanalysis dataset, a high-quality global atmospheric dataset that assimilates a wealth of observational data, as a benchmark for evaluating the performance of CMIP6 historical models in simulating the Indian summer monsoon (SASM). This evaluation focuses on the historical period from 1990-2010.

2.2 Experiments and Periods

2.2.1 CMIP6 Experiments

The study focuses on these CMIP6 experiments:

- **piControl**: Pre-industrial control simulation representing a climate state unaffected by recent anthropogenic forcings. The last 50 years are selected to encompass natural variability.

- **abrupt-4xCO2**: Simulation with an abrupt quadrupling of atmospheric CO2 concentration, used to investigate the climate system's response to strong radiative forcing. The final 20 years are analyzed as this period likely represents the equilibrated climate response to the abrupt CO2 change.
- **Historical**: This experiment simulates the climate system's response to observed changes in forcings (e.g., greenhouse gases, aerosols, land use) from the pre-industrial era to the recent past (1990-2010). We use this experiment to evaluate the models' ability to reproduce the observed characteristics of the ISM during this period.

Changes in South Asian monsoon rainfall under the abrupt-4xCO2 scenario will be analyzed relative to the base climate of the piControl experiment.

2.3 Model Evaluation and Historical Simulations

Evaluating CMIP6 models against observational data from ERA5 reanalysis involves assessing their performance in simulating key features and variability of the monsoon system. We evaluate the performance of the selected CMIP6 models by comparing their historical simulations (1990-2010) with ERA5 data.

2.4 Data Processing and Regridding

To ensure consistency across models, all atmospheric fields are regridded to the coarsest resolution of 64x128 (longitude x latitude). Additionally, ocean fields, which are four-dimensional (time, longitude, latitude, depth), are regridded to a 1-degree by 1-degree lat-lon grid using bilinear interpolation with Climate Data Operators (CDO). This is achieved using the following command line operation:

```
cdo remapbil,r360x180 infile.nc outfile.nc
```

For some models, the native grid for ocean fields is a tri-polar grid, which is resampled to the standard lat-lon grid to facilitate comparison across models. This regridding approach allows us to analyze the data from different models on a common grid, ensuring a consistent framework for our analysis and facilitating the identification of robust features and uncertainties in the monsoon response to increased CO2.

2.5 Analysis Methods

2.5.1 Time Series Analysis

Time series plots for area-averaged monsoon rainfall (JJAS) will illustrate the evolution of change in the abrupt-4xCO2 scenario relative to the variability seen in the piControl baseline.

2.5.2 Multi-Model Mean and Spread

To visualize projected ensemble mean change, spatial maps will show the difference in JJAS precipitation rates between the piControl and abrupt-4xCO2 scenarios.

Chapter 3

Results

3.1 Evaluation of CMIP6 Models

Comparison of the multi-model mean (MMM) of CMIP6 historical simulations with ERA5 reanalysis data reveals that the models generally capture the broad spatial patterns of precipitation over the Indian subcontinent and surrounding oceans during the summer monsoon season (JJAS) (Fig: 5.1). However, systematic biases are evident(Fig: 5.2).

Dry Bias over Land: The CMIP6 models consistently underestimate precipitation over the Indian landmass, with a pronounced dry bias in the Western Ghats and the foothills of the Himalayas. Several factors could contribute to this dry bias, including difficulties in accurately representing complex land-surface processes in the models, such as evapotranspiration and soil moisture. Additionally, the coarse resolution of some models might not adequately capture the orographic effects that influence precipitation patterns in these mountainous regions.

Wet Bias over Ocean: Unlike the dry bias over land, the CMIP6 models tend to overestimate precipitation over the equatorial Indian Ocean. This wet bias could be attributed to biases in the representation of ocean-atmosphere interactions, particularly in the simulation of SSTs and the associated evaporation rates. Moreover, the parameterization of convective processes in the models might be another contributing factor.

The CMIP6 MMM generally reproduces the observed spatial pattern of SST, with a warm pool in the western Pacific and eastern Indian Ocean and colder waters in the eastern Pacific (Fig: 5.3). However, the models have a systematic cold bias (Fig: 5.4), with SSTs generally being underestimated, particularly in the warm pool regions. This cold bias could be due to several factors, including errors in the representation of ocean mixing processes, cloud cover, and the feedback between the ocean and atmosphere.

The underestimation of SST in the warm pool is particularly important, as this region is crucial in driving the monsoon circulation. Warmer SSTs in this region enhance evaporation and moisture transport, which are essential for the development and intensification of the monsoon. Therefore, the models' cold bias could lead to a weaker simulated monsoon circulation and reduced precipitation over the Indian subcontinent.

3.2 Changes in summer mean monsoon circulation

The projected change in mean June-July-August-September (JJAS) precipitation over the Indian region (5-35°N, 65-100°E) varies considerably across the CMIP6 models (Fig: 5.5). While most models simulate an increase in mean precipitation, the magnitude of this increase ranges from less than 10% to over 65%. This widespread highlights the inherent uncertainty in model projections. The multi-model mean (MMM) projects a 23% increase in mean JJAS precipitation over the Indian region under the 4xCO2 scenario. This suggests a general consensus among the models that the monsoon may intensify in a warmer climate in agreement with several earlier studies (Hu et al. 2000; Hsu et al. 2013; Rastogi et al. 2018; Sandeep et al. 2018; IPCC 2021).

The line graph in Figure (3.1) illustrates the monthly mean precipitation over the Indian region under the piControl and abrupt-4xCO2 scenarios. It reveals a distinct seasonal cycle, with a peak in precipitation during the summer monsoon season (June-September) and lower values during the rest of the year. Under the 4xCO2 scenario, the monsoon rainfall is projected to increase significantly, particularly during the peak months of July and August. This monsoon intensification is consistent with the overall increase in mean precipitation observed in the bar plot(5.5).

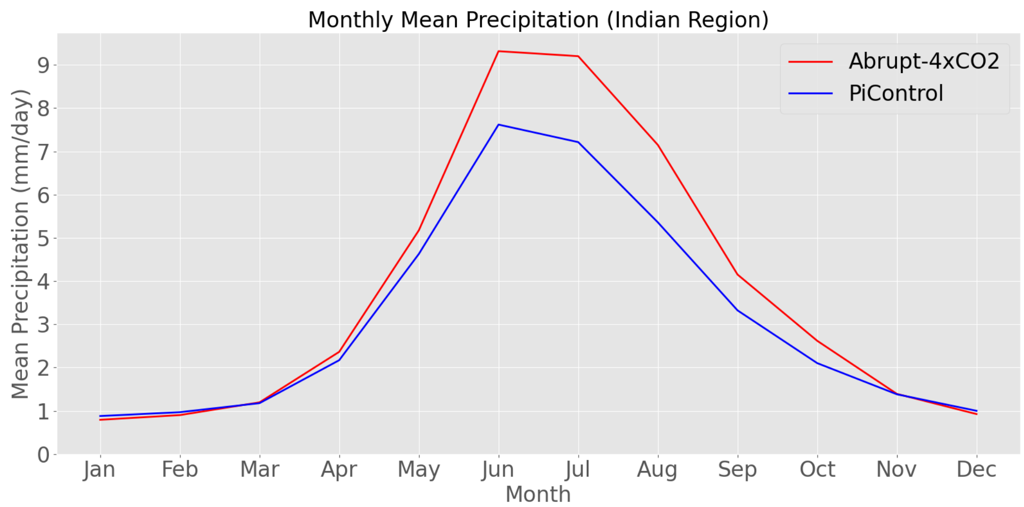


Figure 3.1: Monthly mean precipitation (mm/day) over the Indian region in the piControl simulation (blue line) and the abrupt-4xCO2 scenario (red line).

However, the line graph provides additional insights into the temporal evolution of these changes, suggesting that the increase in rainfall is not uniform throughout the monsoon season.

Monsoon strength could also be measured in terms of the mean kinetic energy of low-level jets, called the Somali jet, over the Arabian Sea (50°–65°E and 5°–15°N; Ajayamohan 2007). Under the abrupt-4xCO2 scenario (red line), the Somali Jet Index (SJI) is significantly weaker than in the pre-industrial control simulation (piControl, blue line), particularly during the peak monsoon months of June-September. This is consistent with earlier studies, which show a weakening of the Somali jet index by the end of the 21st century(Lin et al 2008). This weakening suggests a potential reduction in the cross-equatorial moisture transport. The study by Stowasser et al. (2009) also examines the response of

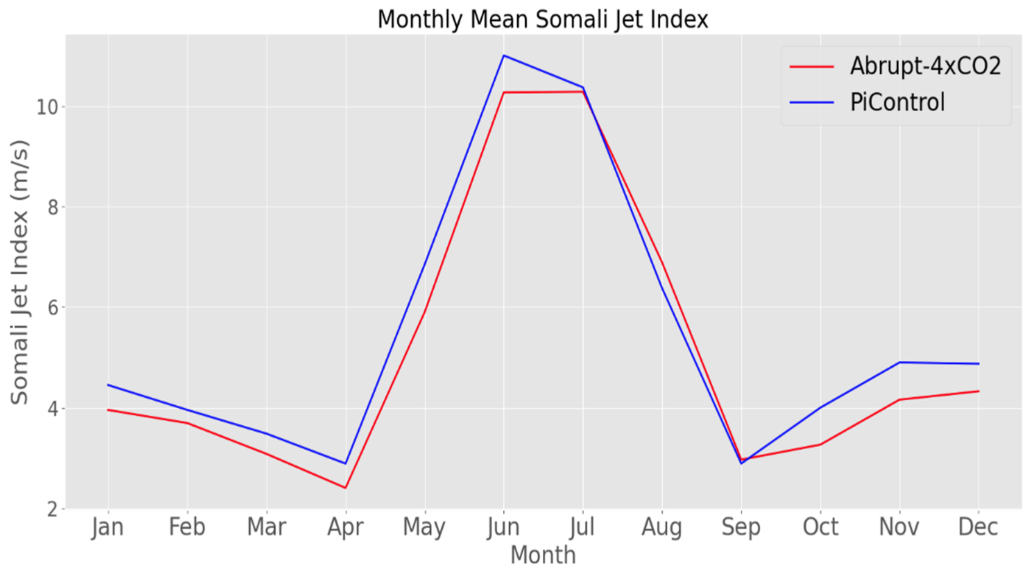


Figure 3.2: Climatological monthly mean kinetic energy of low-level Somali jet calculated at 850 hPa averaged over 50°–65°E and 5°–15°N (red box in Fig. 2a) in the piControl and abrupt-4xCO2 simulations

the South Asian summer monsoon to global warming. They also showed this, where they found that despite a weakened cross-equatorial flow, the time-mean precipitation over peninsular parts of India increases by about 10%–15% in a warmer climate.

The simulations' spatial distribution of mean summer JJAS precipitation exhibits substantial inter-model variability, particularly over the Indian subcontinent and the western Pacific (Fig: 5.6). However, a consistent feature across most models is the presence of a monsoon precipitation maximum over India and Southeast Asia, extending into the western Pacific warm pool. Increasing monsoon precipitation is prominent in peninsular India under a warming climate. There is a slight decrease in simulated precipitation in the northwest India. There is a significant increase in precipitation over most of the Indian subcontinent, particularly over the western coastal areas and the northeastern regions, where some area's precipitation anomaly exceeds 3 mm/day.

The ensembled mean precipitation anomaly (Fig: 3.3) reveals a robust contrasting dipole pattern of change in the warming scenario. The broad pattern of changes over the Indian Ocean is similar to those simulated by Stowasser et al. (2009) for quadrupling the carbon dioxide content in the atmosphere. The decrease in precipitation over the equatorial Indian Ocean extends westwards. This dipole pattern is consistent with previous studies and suggests a potential shift in the monsoon circulation under a warming climate.

The CMIP6 multi-model ensemble reveals a complex interplay between SST warming, enhanced atmospheric stability, suppressed vertical motion, and altered wind patterns in the Indian Ocean and surrounding regions under a quadrupled CO2 scenario.

The SST plot (Fig: 3.4) reveals a widespread warming of the Indian Ocean, particularly pronounced in the western equatorial region, the Arabian Sea, and the Bay of Bengal. The warming extends into the western Pacific warm pool. The 4xCO2 simulation projects a reduction in precipitation over the equatorial Indian Ocean, mirroring the findings of Stowasser et al. (2009) for a scenario where they linked increased precipitation over India to heightened evaporation in the southern Arabian Sea caused by warmer sea surface temperatures and reduced Somali upwelling. This enhanced evaporation fuels increased

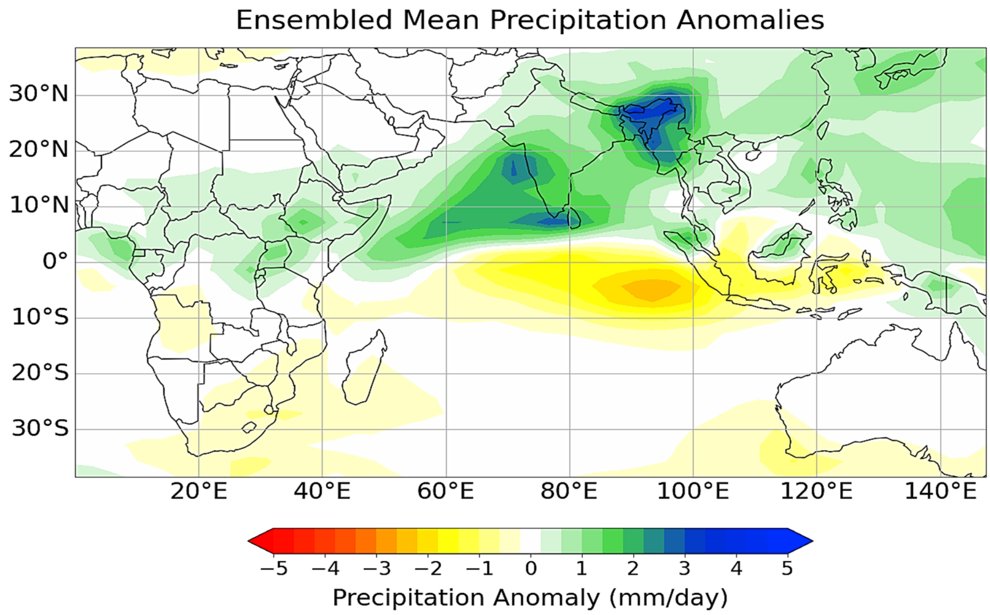


Figure 3.3: Ensembled mean JJAS rainfall Anomaly (mm/day) for the period last 20y under abrupt-4xCO2 scenario and for the period last 50y for piControl.

rainfall over peninsular India. The pattern resembles a positive Indian Ocean Dipole (IOD; Vinayachandran et al. 2009), with warmer-than-average SSTs in the western Indian Ocean and cooler-than-average SSTs in the eastern Indian Ocean. A similar pattern is observed in the Tresa et al. paper([11]), where an increase in SST is noted particularly towards the western Indian Ocean, linked with the westward expansion of the South Asian monsoon rainy zone. The Rajesh et al. paper (2023 [7]) also highlights this expansion, noting that increased evaporation over the Arabian Sea due to higher SSTs leads to more moisture and precipitation over peninsular India. Positive IOD events are often associated with increased rainfall in India. The warming of the Indian Ocean could intensify the land-sea thermal contrast, enhancing the monsoon circulation.

The difference in Temperature Anomalies (200 hPa - 850 hPa) plot (Fig: 3.5) shows a positive temperature anomaly difference, indicating greater warming at 200 hPa (upper troposphere) than at 850 hPa (lower troposphere). This implies a decreased environmental lapse rate, leading to increased atmospheric stability. The region between the equator and 20°N exhibits the most pronounced increase in stability, suggesting a potential suppression of convection (the process by which warm, moist air rises and forms clouds) in this crucial monsoon region. Increased stability could weaken the monsoon circulation by suppressing upward motion and cloud formation, potentially reducing overall rainfall. However, the increased moisture content in the lower troposphere (discussed next) could somewhat counteract this.

While looking at the plot (Fig: 5.7b) for vertical velocity omega reveals a large-scale pattern of suppressed upward motion (negative anomalies) over most of the Indian subcontinent, especially in the south. This indicates a weakening of the monsoon's deep convection and uplift, essential for rainfall generation. The positive anomalies (red colours) over the western Pacific and parts of the Indian Ocean suggest increased subsidence (downward motion), potentially related to the weakening of the Walker circulation.

The mean zonal wind plot(Fig: 3.7) shows a general weakening of the low-level westerlies (winds blowing from west to east) over the Arabian Sea and northern Indian Ocean. This is a key feature of the monsoon circulation that brings moisture to the subconti-

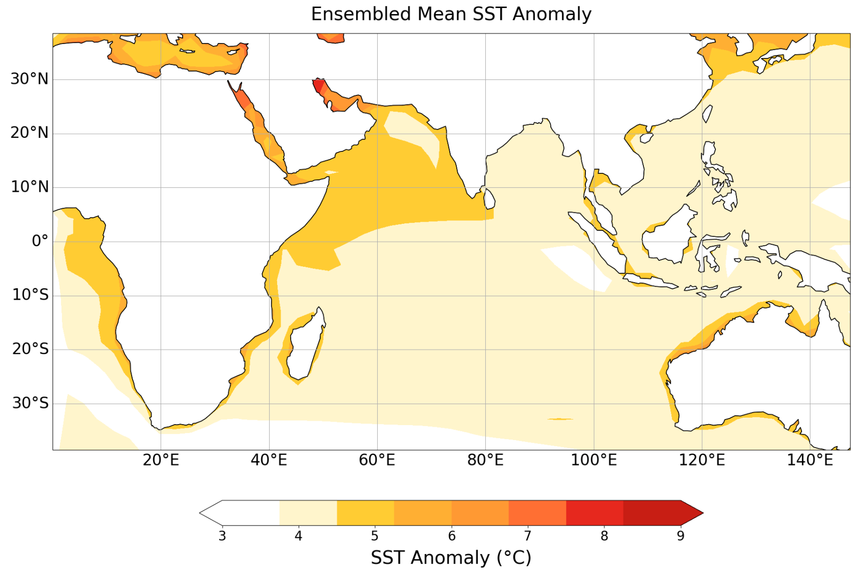


Figure 3.4: Ensembled mean SST anomalies (°C) for JJAS for the period last 20y under abrupt-4xCO2 scenario and the last 50y for piControl.

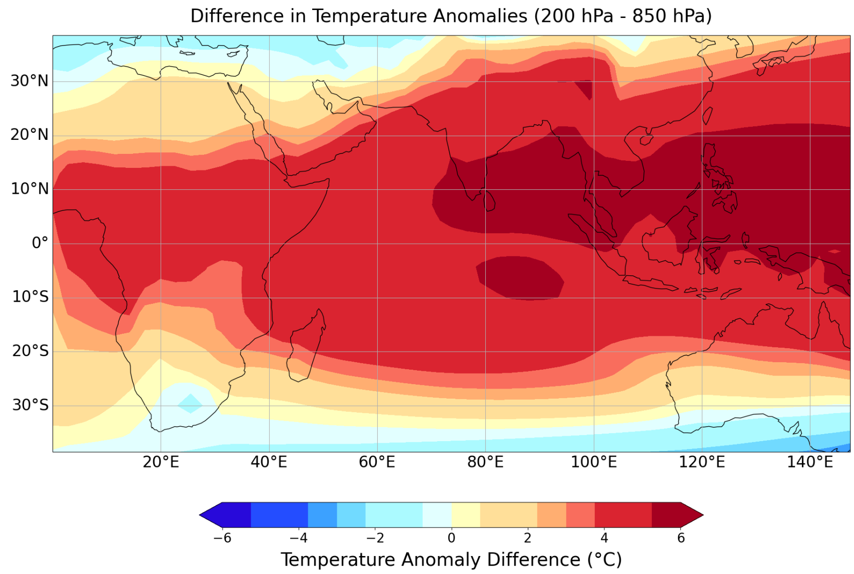
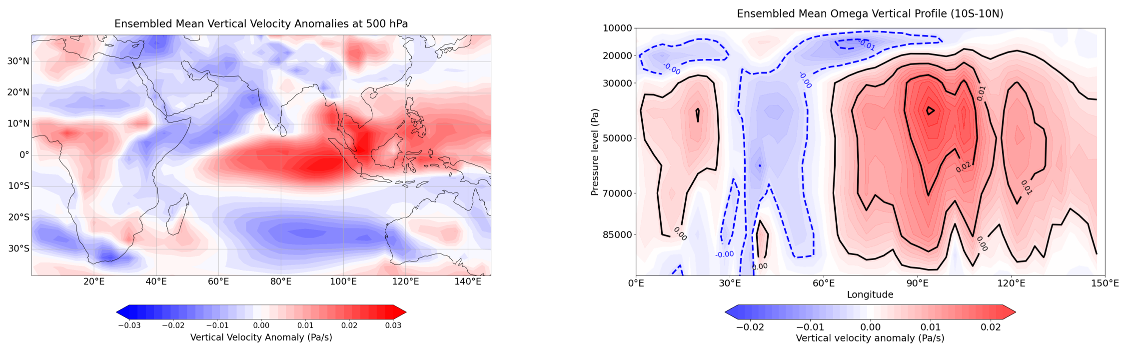


Figure 3.5: Difference in ensemble mean temperature anomalies (°C) between 200 hPa and 850 hPa for JJAS under the abrupt-4xCO2 scenario relative to the piControl simulation.

nent. Conversely, there are stronger easterlies (winds blowing from east to west) over the equatorial Indian Ocean, potentially disrupting the cross-equatorial moisture transport. Stowasser et al. (2009) also identified a circulation pattern resembling the monsoon break phase, with twin anticyclones flanking the equator, suppressing convection over the equatorial Indian Ocean (similar to Annamalai and Sperber, 2005). The formation of twin anticyclonic anomalies (Fig: 3.7) across the equator and a divergent wind pattern(Fig: 5.8) in meridional winds further support these changes.



(a) Omega winds(vertical velocity) 500mbar

(b) Vertical profile of Omega

Figure 3.6: Ensemble mean (a) omega (vertical velocity) anomalies (mb/day) at 500 hPa, (b) vertical profile of the omega anomaly averaged for tropics (10N-10S) for JJAS under the abrupt-4xCO2 scenario relative to the piControl simulation. Positive values (red) indicate suppressed upward motion.

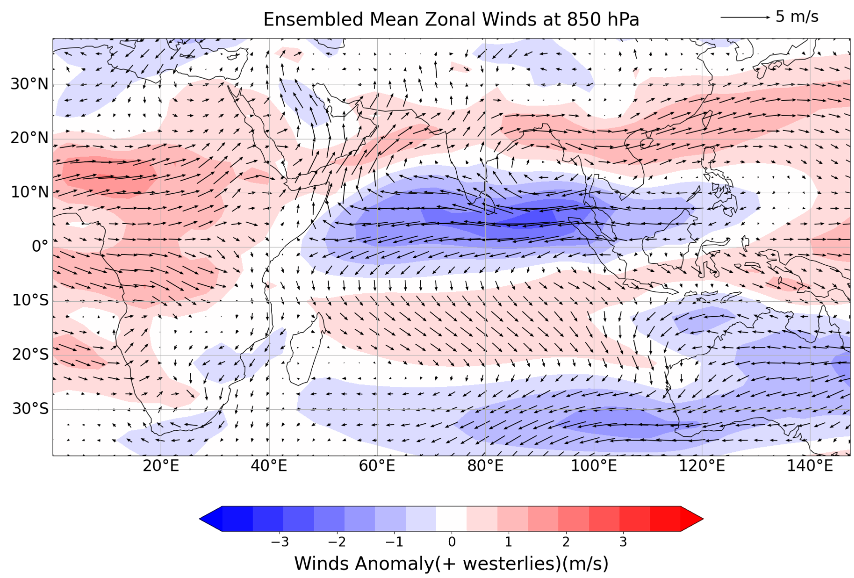
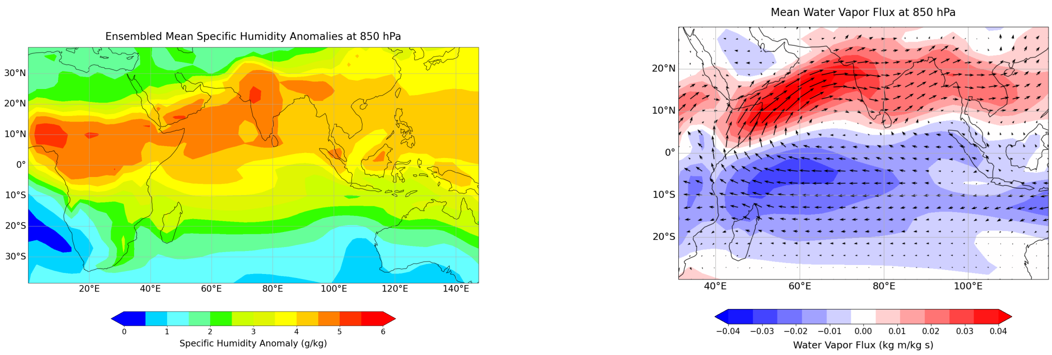


Figure 3.7: Ensemble mean Zonal winds anomalies(m/s) at 850 hPa for JJAS under the abrupt-4xCO2 scenario relative to the piControl simulation. Positive values (red) indicate westward motion

The anomalies in precipitation and circulation simulated by the CMIP6 MMM in this study align with findings from multiple sources, including multi-model averages from both CMIP5 (various model ensembles by Li et al., 2017; Menon et al., 2013; and Mohan and Bhaskaran, 2019) and CMIP6 (18 models by Chen et al., 2020). This convergence of evidence across different models and studies strengthens the confidence that these simulated anomalies are robust and likely to occur in a warming climate.

Under the 4xCO2 scenario, the specific humidity (moisture content) increases significantly over most of the Indian subcontinent and surrounding oceans (Fig: 3.8a). This increase is particularly pronounced over the Arabian Sea, a key moisture source region for the ISM. This finding aligns with Li et al. (2017), who attributed the increase in precipitation over India under a warming climate to an increase in moisture flux, primarily driven by the moisture component (specific humidity), while the dynamic component (vertical velocity) influenced the spatial distribution of the changes. Similarly, our analysis with CMIP6 models demonstrates a significant increase in water vapour flux at 850 hPa under the 4xCO2 scenario (Fig: 3.8b). As in the Tresa et al. (2023) study, the moisture component plays a major role in this increase, while the vertical velocity component shapes the spatial pattern (Fig: 3.9). The enhanced moisture flux, especially over the Bay of Bengal, is consistent with the increased monsoon precipitation over India (Fig: 3.3).



(a) Specific humidity (b) Horizontal Moisture flux

Figure 3.8: Mean specific humidity anomaly(kg/kg) at 850 hPa for JJAS under the abrupt-4xCO2 scenario relative to the piControl simulation. (b)Change in direction (vectors) and magnitude (shading) of the mean horizontal water vapour flux at the 850 hPa level

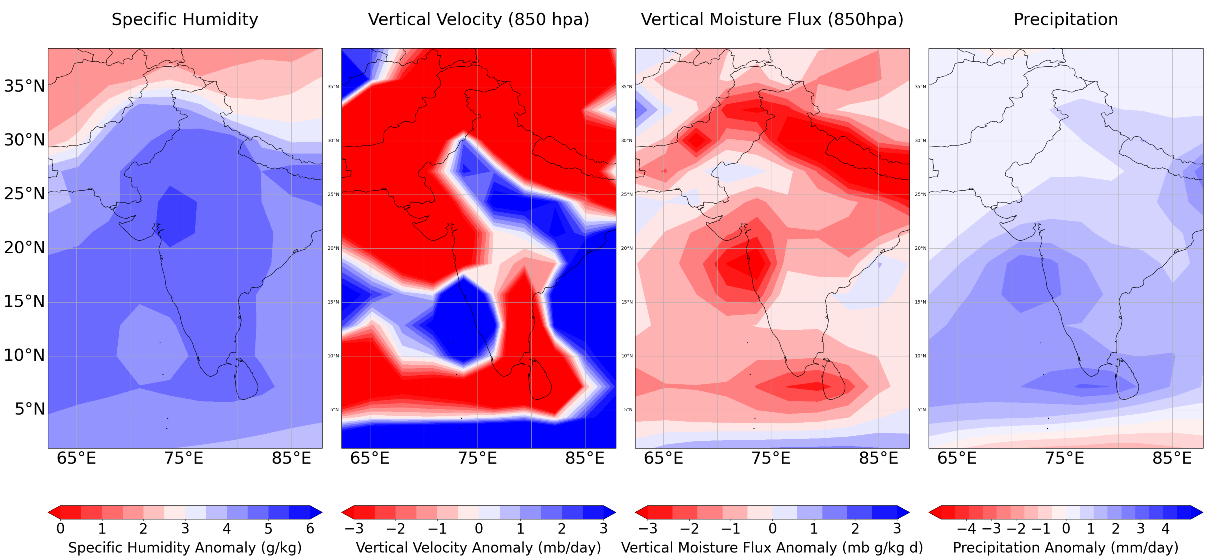


Figure 3.9: The anomalies in mean a) specific humidity (q), b) vertical mass flux (w), c) vertical moisture flux (wq), at 850 hPa and Precipitation in the abrupt-4xCO2 simulation relative to the piControl during the JJAS summer monsoon season.

The patterns in the water vapour flux are closely linked to the SST (Fig: 3.4) anomalies and the westerlies (Fig: 3.7) seen in previous plots. Warmer SSTs in the western Indian Ocean likely enhance evaporation, increasing moisture availability and a stronger flux into the subcontinent.

3.3 Global Perspective of Increased CO2

The Indian Summer Monsoon (ISM) is intricately linked to global atmospheric circulation patterns, and changes in the monsoon can have far-reaching effects beyond the Indian subcontinent. In this section, we broaden our perspective to examine the global impacts of the 4xCO2 scenario simulated by the CMIP6 models, focusing on sea surface temperature (SST), atmospheric circulation, and cloud fraction. The 4xCO2 scenario induces significant warming of the global oceans(Fig: 3.10 (a)), with the most pronounced increases in the western equatorial Pacific and the eastern Indian Ocean, exceeding 5°C in some areas. This warming pattern resembles an El Niño-like state, with a weakened Walker circulation (as evidenced by the vertical velocity anomaly profile) and a shift in the Pacific warm pool eastward. The El Niño-like state in the Pacific could have opposing effects, leading to complex interactions and regional variations in monsoon rainfall.

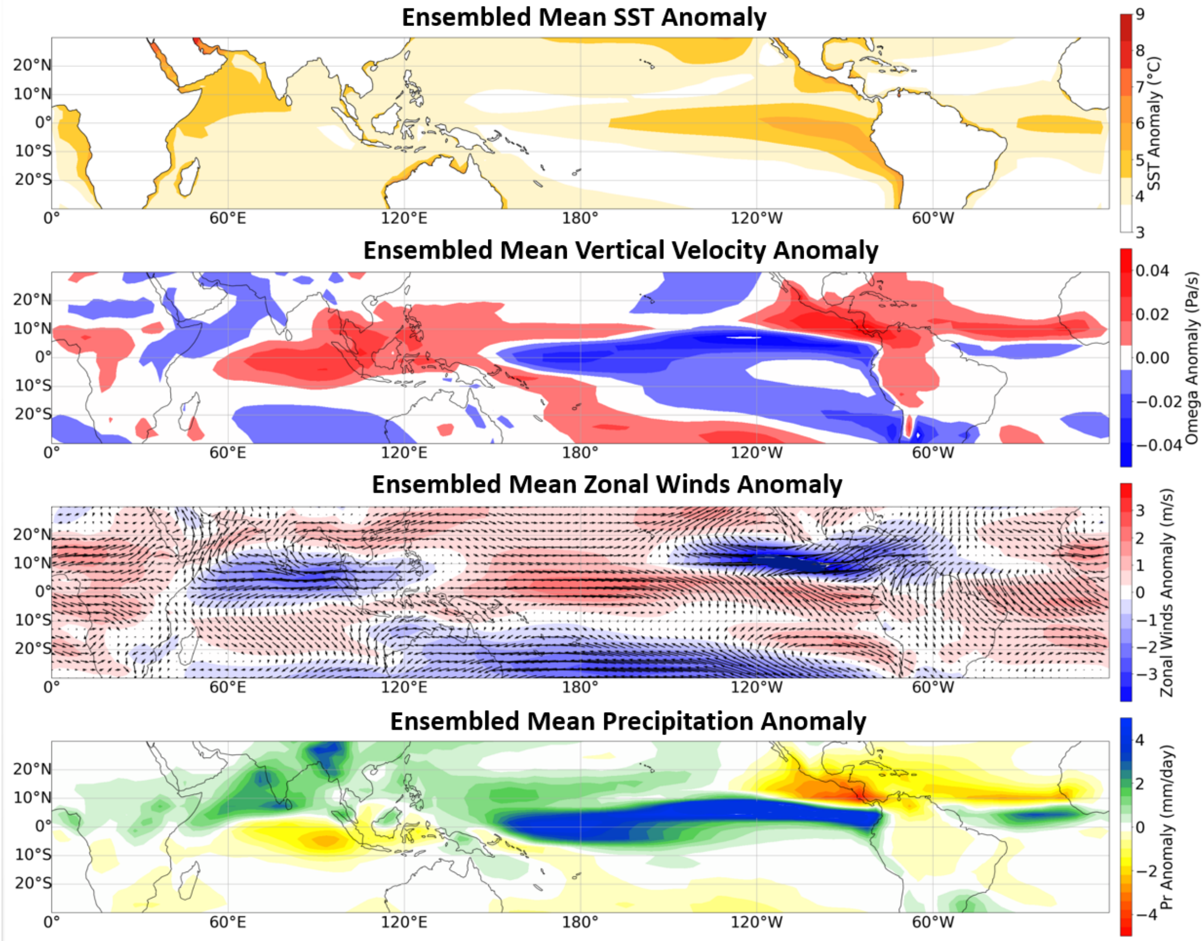


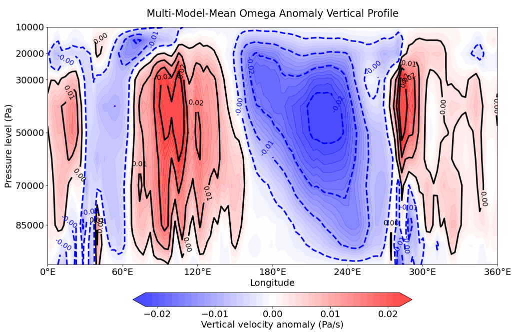
Figure 3.10: Ensemble Mean Anomalies for (a) SST (°C), (b) Vertical velocity anomalies at 500 hPa (mb/day), (c) Zonal wind anomalies at 850 hPa (m/s), (d) Precipitation anomalies (mm/day) for 30N-30S, in the abrupt-4xCO2 simulation relative to the piControl during the JJAS season.

The vertical velocity anomalies(Fig: 3.10 (b)) reveal a weakening of the upward motion in the tropical troposphere, particularly over the Indian subcontinent and the western Pacific. This suppressed ascent indicates increased atmospheric stability, which could inhibit convection and cloud formation(Fig: 3.10 (a)). The decreased upward motion over India is consistent with the weakening of the monsoon circulation observed in previous sections. The global profile(Fig: 3.11a) also shows a weakening of the walker cell circulation, strengthening our previous hypothesis.

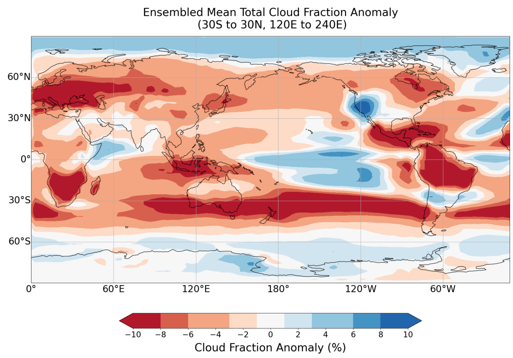
The zonal wind anomalies at 850 hPa(Fig: 3.10 (c)) reveal a complex pattern of changes. Notably, the easterly trade winds are weakening over the central and eastern Pacific, associated with the El Niño-like warming pattern also evident in Yong et al. ([10]). This weakening is accompanied by anomalous westerlies in the western Pacific and a northward shift of the Pacific jet stream. Over the Indian Ocean, the low-level westerlies associated with the Somali Jet are weakening, along with an intensification of the easterlies near the equator.

The precipitation anomalies(Fig: 3.10 (d)) reveal a pattern of changes across the globe. The most prominent feature is the increased precipitation over Pacific and South Asian regions, consistent with the intensified monsoon discussed earlier. However, there are also significant decreases in precipitation over the southern coast of Mexico, Indonesia and parts of the southern Indian Ocean, linked to the El Niño-like warming pattern and suppressed convection.

The cloud fraction anomalies(Fig: 3.11b) show decreased cloud cover over most tropical oceans, particularly in the western Pacific and eastern Indian Ocean. This is consistent with the reduced upward motion and increased atmospheric stability observed in these regions. However, there is an increase in cloud cover over parts of the Indian subcontinent, potentially associated with enhanced moisture availability and increased precipitation.



(a) Vertical profile of Omega



(b) Total Cloud fraction anomaly

Figure 3.11: Ensemble mean (a) vertical profile of the omega anomaly, (b) Total cloud fraction anomaly for JJAS under the abrupt-4xCO2 scenario relative to the piControl simulation.

Chapter 4

Conclusion

This thesis comprehensively investigated the projected changes in the Indian Summer Monsoon (ISM) under a quadrupled CO2 scenario. Leveraging a multi-model ensemble approach with CMIP6 data, we aimed to assess the robustness of these changes and delve into the underlying physical mechanisms. The results paint a complex yet revealing picture of the monsoon's response to a warming climate, with significant implications for the Indian subcontinent.

4.0.1 Robust Features of the ISM Response

Our analysis unequivocally demonstrates a consistent, robust intensification of the Indian summer monsoon in the 4xCO2 scenario across multiple CMIP6 models. This intensification manifests as an overall increase in mean monsoon precipitation over India, particularly pronounced over the western coast and Bay of Bengal. The spatial pattern of precipitation change reveals a dipole structure, with enhanced rainfall over the subcontinent and a significant decrease over the equatorial Indian Ocean. This dipole pattern likely arises from shifts in the large-scale atmospheric circulation, including a weakening of the Hadley circulation and displacement of the Intertropical Convergence Zone (ITCZ).

Critically, we observed a consistent weakening of the Somali Jet, a crucial component of the ISM circulation responsible for moisture transport. This weakening is likely linked to factors such as increased atmospheric stability, changes in large-scale circulation patterns, and warming sea surface temperatures (SSTs) in the western Indian Ocean. Additionally, the models consistently project a weakening of the Walker circulation, a key driver of global atmospheric circulation.

Thermodynamic changes, including a significant increase in specific humidity and moisture flux over the Indian subcontinent, contribute to the overall intensification of the monsoon. This increased moisture availability is consistent with the warming of the ocean surface and the Clausius-Clapeyron relationship. However, the increased moisture content does not uniformly translate into increased precipitation across the entire region. The increased atmospheric stability and reduced upward motion could suppress convection, potentially leading to decreased rainfall in certain areas, particularly over the equatorial Indian Ocean and parts of northern India.

4.0.2 Proposed Mechanism for ISM Changes

A multi-faceted mechanism can explain the observed changes in the ISM (Fig: 4.1) involving:

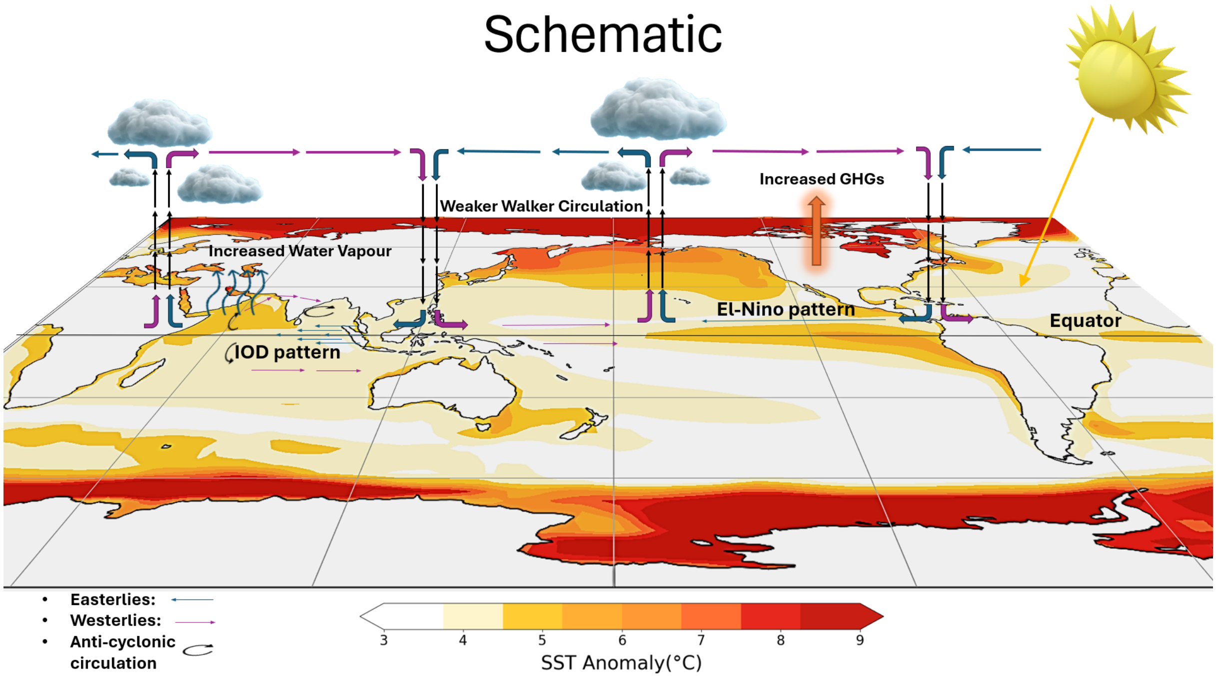


Figure 4.1: Global Schematic for the Mechanism

Radiative Forcing: Increased CO2 concentrations lead to enhanced radiative forcing, causing widespread climate system warming, particularly in the tropics and subtropics.
Ocean-Atmosphere Coupling: The warming of the Indian Ocean, especially in the west, intensifies the land-sea thermal contrast, initially favouring a stronger monsoon.
Atmospheric Stability Changes: Differential warming of the troposphere (greater warming aloft) increases atmospheric stability, suppressing convection and upward motion, particularly over India.
Weakening of Somali Jet and Walker Circulation: The increased stability, along with changes in large-scale circulation and potentially warmer SSTs, weakens the Somali Jet and Walker circulation, reducing cross-equatorial moisture transport and further suppressing upward motion.
Shifts in Moisture Transport and Precipitation: The combined effects of increased moisture availability and altered circulation patterns result in a dipole pattern of precipitation changes, with increased rainfall over India but decreased rainfall over the equatorial Indian Ocean.

The South Asian Summer Monsoon is a critical climatic phenomenon that profoundly impacts South Asia's livelihoods and economic stability. Understanding its response to increased atmospheric CO2 concentrations is essential for developing effective adaptation and mitigation strategies. This research comprehensively analyses the SASM's response to an abrupt quadrupling of CO2 concentrations, integrating findings from multiple climate models and observational data sources. By addressing the uncertainties and variability in monsoon projections, this study contributes to the broader field of climate science and supports informed decision-making for climate resilience in South Asia.

4.0.3 Future Research Directions

While this research provides significant insights into the SASM's response to increased CO2 concentrations, it also highlights the need for further studies to address remaining uncertainties. Future research should focus on:

- **Improving Model Resolution:** Higher-resolution models can provide more detailed projections of monsoon patterns, capturing local-scale processes that are critical for accurate predictions.

- **Integrating More Observational Data:** Enhanced observational datasets can help validate model projections and reduce uncertainties, leading to more reliable predictions.

- **Exploring Regional Impacts:** Understanding the regional variations in monsoon response can help tailor adaptation strategies to specific areas, addressing local vulnerabilities and needs.

- **Assessing Socio-Economic Impacts:** Studying the socio-economic impacts of projected monsoon changes can provide valuable insights for policy development, ensuring that adaptation strategies are both effective and equitable.

By addressing these areas, future research can build on the findings of this study, contributing to a more comprehensive understanding of the SASM and its response to global warming.

Chapter 5

Tables and Figures

Table 5.1: CMIP6 models used in this study.

Sno.	**Model**	**Resolution (lat x lon)**	**Country of Origin**
1	AWI-CM-1-1-MR	192 x 384	Germany
2	BCC-CSM2-MR	160 x 320	China
3	CAMS-CSM1-0	160 x 320	China
4	CanESM5	64 x 128	Canada
5	CESM2	192 x 288	USA
6	CESM2-FV2	96 x 144	USA
7	CESM2-WACCM	160 x 320	USA
8	CESM2-WACCM-FV2	96 x 144	USA
9	E3SM-1-0	180 x 288	USA
10	EC-Earth3-Veg	256 x 512	EU
11	FGOALS-g3	80 x 180	China
12	GFDL-ESM4	192 x 288	USA
13	GISS-E2-1-G	90 x 144	USA
14	GISS-E2-1-G-CC	90 x 144	USA
15	GISS-E2-1-H	90 x 144	USA
16	HadGEM3-GC31-MM	160 x 320	UK
17	IITM-ESM	94 x 192	India
18	INM-CM4-8	120 x 180	Russia
19	INM-CM5-0	120 x 180	Russia
20	IPSL-CM6A-LR	143 x 144	France
21	KACE-1-0-G	289 x 384	USA
22	KIOST-ESM	192 x 192	South Korea
23	MIROC6	128 x 256	Japan
24	NESM3	96 x 192	China
25	NorCPM1	96 x 144	Norway
26	TaiESM1	192 x 288	Taiwan

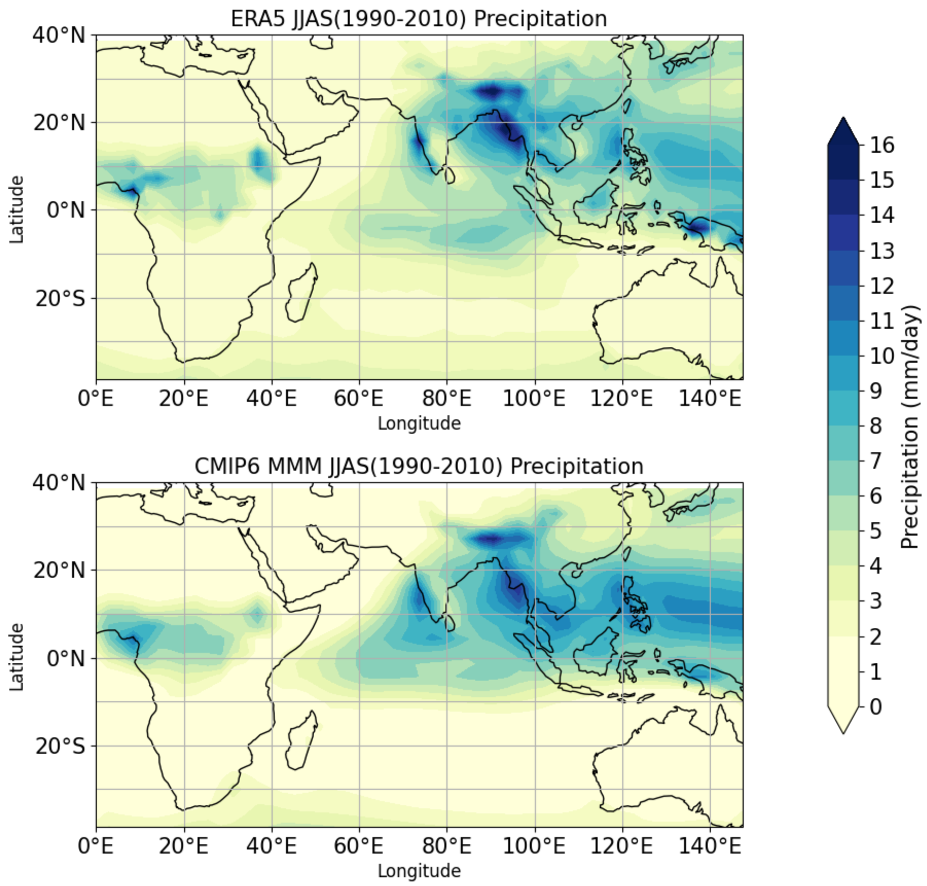


Figure 5.1: Reference State of both ERA5 and CMIP6

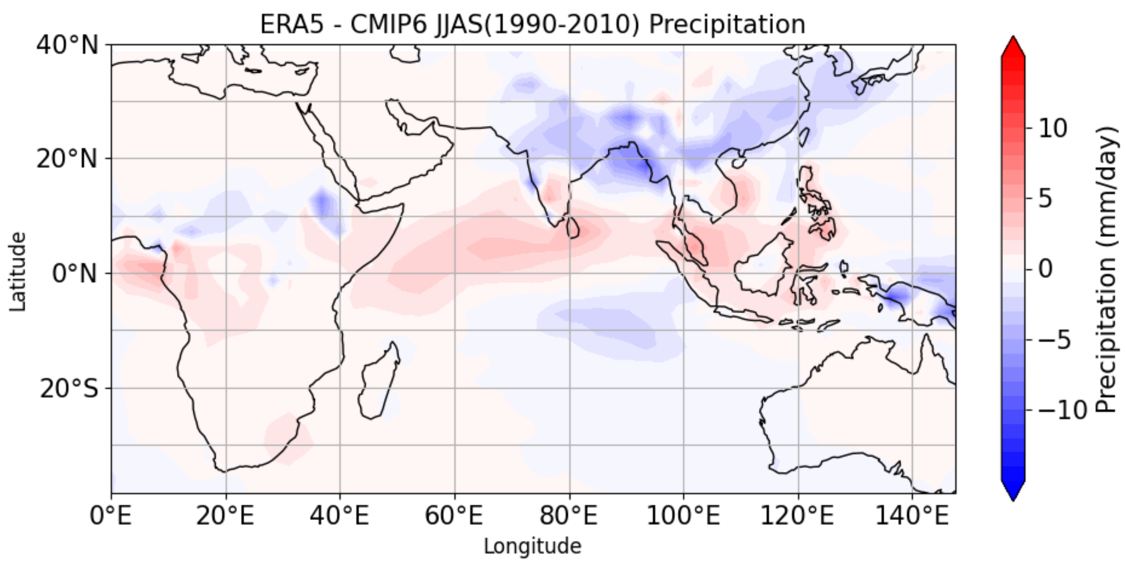


Figure 5.2: Precipitation Bias plot

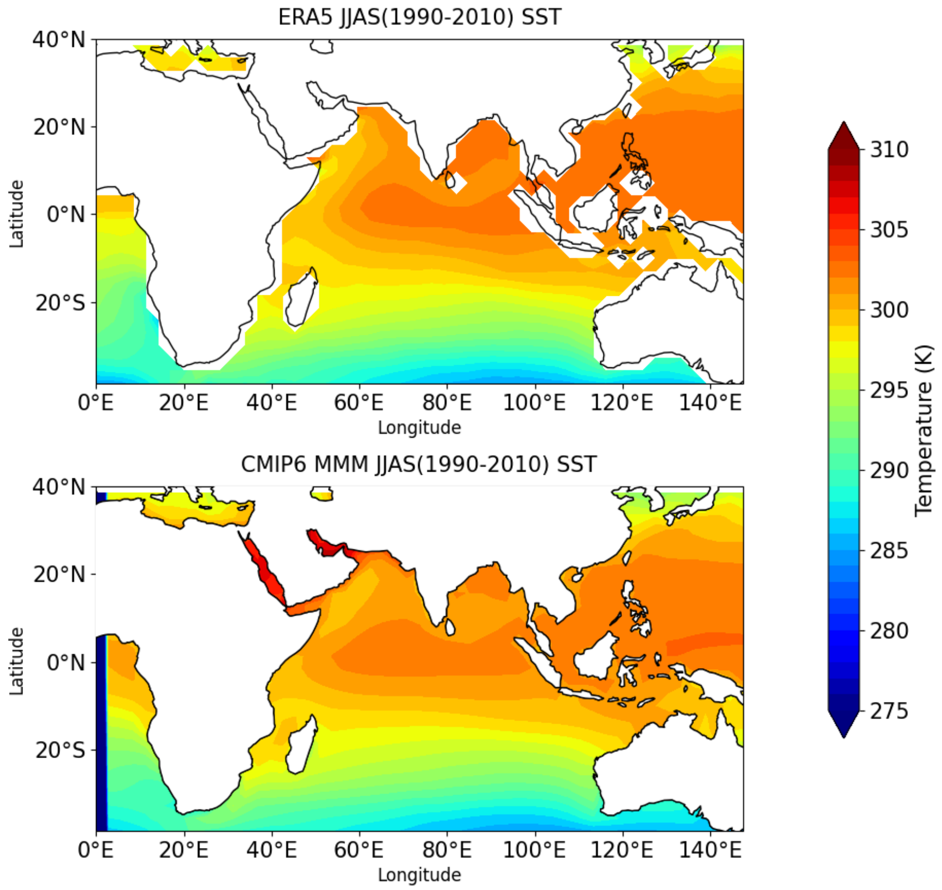


Figure 5.3: Reference State of both ERA5 and CMIP6

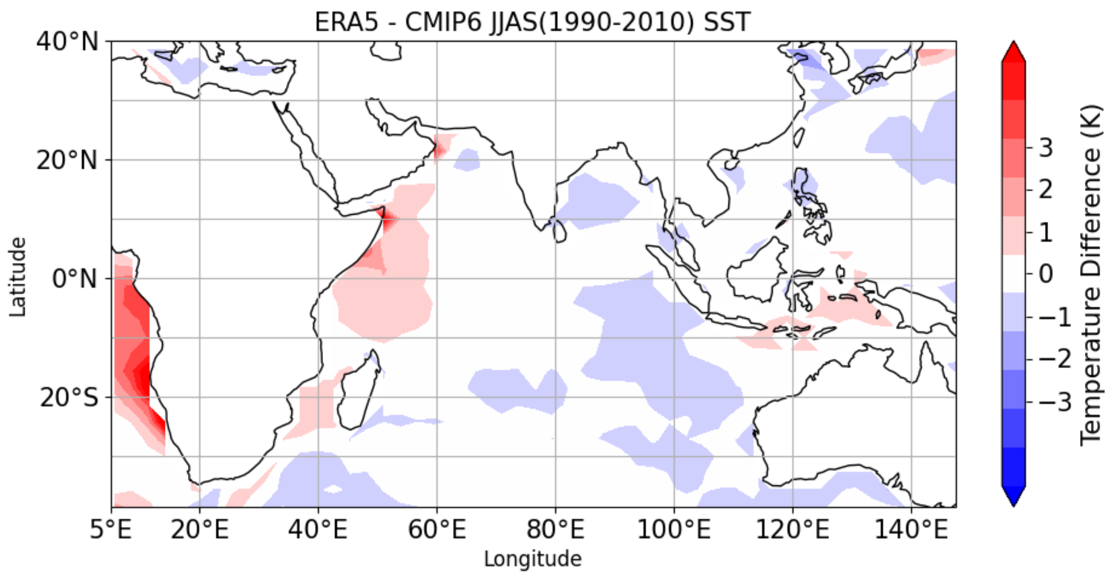


Figure 5.4: SST Bias plot

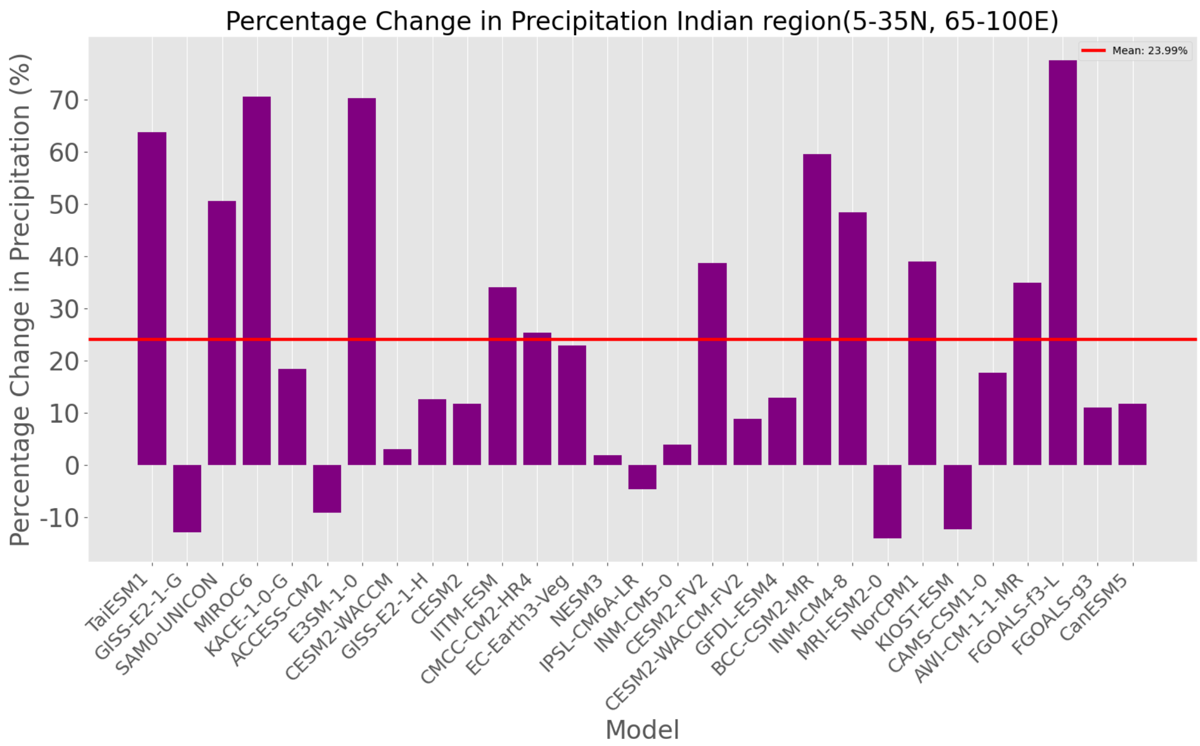


Figure 5.5: Percentage change in mean June-July-August-September (JJAS) precipitation over the Indian region (5-35°N, 65-100°E) in each CMIP6 model under the abrupt-4xCO2 scenario relative to the piControl simulation. The red line indicates the multi-model mean (MMM) change of 23%.

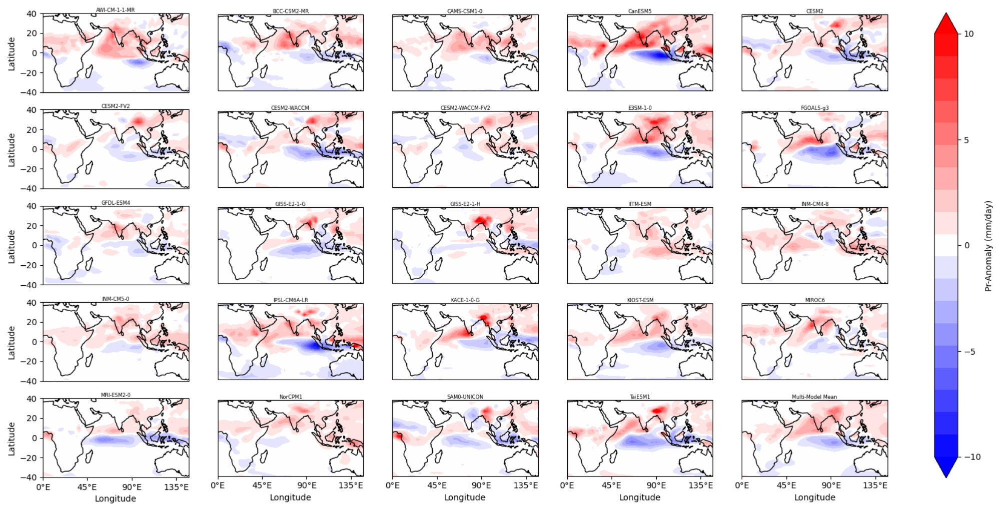
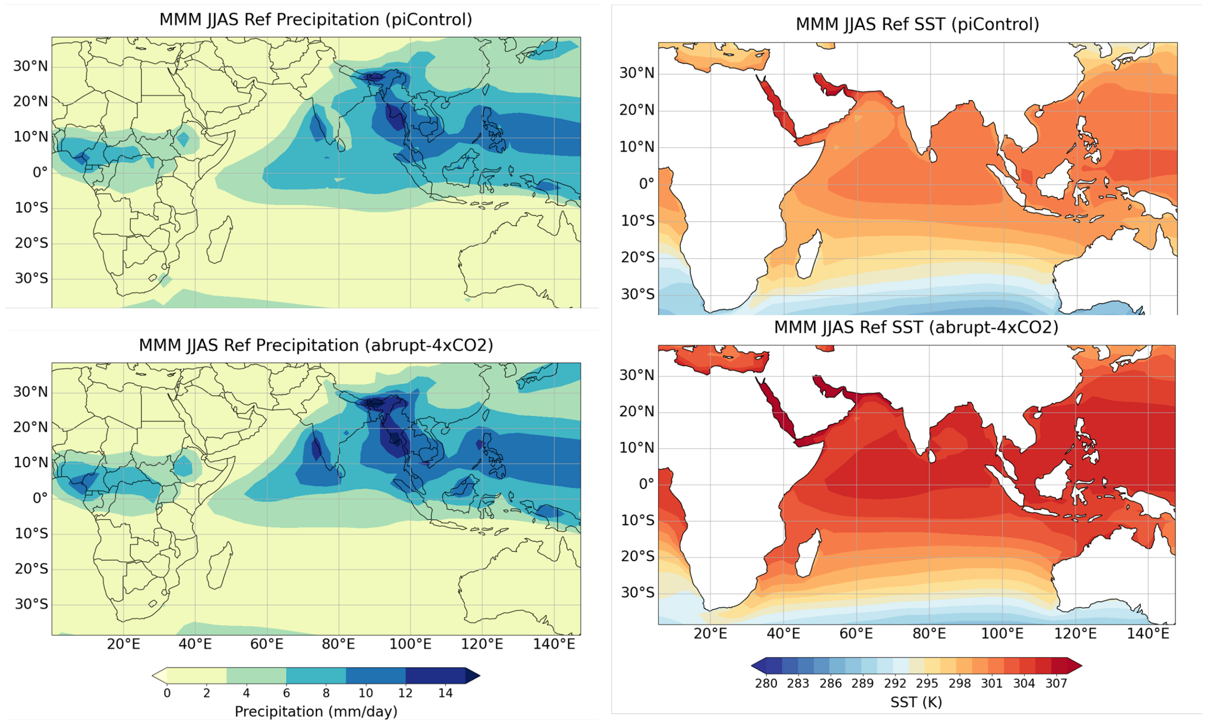


Figure 5.6: JJAS rainfall Anomaly (mm/day) for the period last 20y under abrupt-4xCO2 scenario and for the period last 50y for piControl. The majority of the models capture an increase in summer monsoon mean rainfall by about 0–3 mm/day in most parts of India



(a) Mean Precipitation State

(b) Mean SST state

Figure 5.7: (a) Ensemble mean precipitation (mm/day) and (b) Ensemble mean SST (K) for the period last 20y under abrupt-4xCO2 scenario and for the period last 50y for piControl.

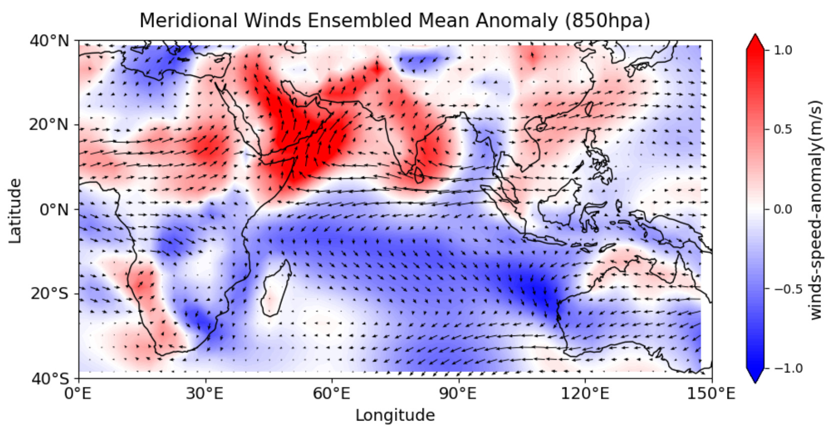


Figure 5.8: Ensemble mean Meridional winds anomalies(m/s) at 850 hPa for JJAS under the abrupt-4xCO2 scenario relative to the piControl simulation. Positive values (red) indicate Northwards motion

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