CHAPTER 4
TEMPERATURE, RAINFALL, AND PCI TRENDS OF GUJARAT: A SPATIO-TEMPORAL ANALYSIS

4.1 Introduction

A trend is a general trajectory or pattern observed in a time series (Van Goethem et al., 2017). It denotes a tendency for values to increase, decrease, or remain relatively steady with some regularity. Additionally, it refers to a systematic and consistent direction observed in the data set over time (Li et al., 2015). Trend identification is becoming increasingly important in multiple disciplines worldwide (Marak et al., 2020), and in climate studies, it is crucial for understanding and addressing the complex nature of variables (Ali et al., 2019; Armal et al., 2018). It aids in identifying and understanding long-term climate patterns by analyzing data collected over an extended period, allowing for the detection of gradual changes in climate variables such as temperature, rainfall, etc., and providing insights into climate trends and variability (Bayazit, 2015). It also provides baseline information about climatic conditions in a specific location, helping examine current and prospective observations alongside historical data (Kriticos et al., 2012). This comparison allows for assessing deviations in climate variables from their norms, essential for identifying anomalies and understanding their potential impacts on agriculture, water resources, and human health. Additionally, analyzing long-term trends helps to distinguish between short-term variability and long-term changes (Reckling et al., 2021), which is crucial for developing accurate climate models and empowering policymakers to craft precise interventions and allocate resources effectively. Understanding these trends is crucial for building resilience and sustainability in vulnerable communities and ecosystems.

The statistical trends about the increase in global temperatures and rainfall levels hold profound importance in understanding the evolving dynamics of our planet's climate (Reckling et al., 2021). Over the past decades, detailed analyses by leading scientific institutions have showed a significant increase in the Earth's average surface temperature. According to the IPCC AR4, the global surface temperature increased by approximately 0.74 ± 0.18°C between 1906 and 2005 (IPCC, 2007). This represents an increase from the 0.6°C recorded in the century preceding the AR3. Additionally, the rate of warming was not constant over the 20th century, and it increased in the latter half of the century (Hegerl et al., 2018). The IPCC AR5, stated that the global average surface temperature increased by approximately 0.85°C from 1880 to 2012, indicating a continuation of the warming trend observed in the 20th century (Niang et al., 2015).

A warming scenario projected by the IPCC estimates that global temperatures will increase between 2.5°C to 3°C by 2100 if emissions remain high (Szulejko et al., 2017). While, the WMO's report highlights a concerning projection, indicating a 66% probability that the annual average near-surface global temperature will exceed 1.5°C above pre-industrial levels for at least one year between 2023 and 2027 (WMO, 2022). According to Europe's Copernicus Service Climate Change (C3S), in 2023, the global average temperature increased to 1.48 ± 0.12°C higher than the pre-industrial levels of 1850-1900, and 0.60°C above the 1991-2020 average. The escalation of global temperatures causes a simultaneous increase in the frequency and intensity of extreme events (Pradhan et al., 2022). The worldwide increase in floods and droughts has been tied to changes in rainfall trends (Bhardwaj et al., 2020; Diakakis et al., 2020; Z. Huang et al., 2022) and heatwaves to variations in temperature trends (Rohini et al., 2019; Cartwright, 2024). The relationship between increased global temperatures and the increased extremity of climatic events highlights the importance of adopting comprehensive strategies to mitigate further temperature escalation and its consequent outcomes (Lesk et al., 2022). Trend detection serves as a valuable tool in the climate analysis realm, offering quantifiable metrics for assessing alterations in rainfall and temperature patterns (Ye et al., 2021). This approach facilitates the identification of both the rate and magnitude of variations, aiding in unravelling the extent to which the climate is transforming. Precisely measuring these alterations in climate variables, trend analysis provides essential insights into long-term patterns, offering critical guidance for making informed decisions on adaptation strategies and effective policy formulation in response to evolving climatic conditions and increasing EWE.

This study aims to comprehensively analyse the spatio-temporal distribution of climate variables across the diverse physiographic regions of Gujarat. The analysis utilizes the PCI and basic statistical techniques to provide a detailed understanding of rainfall patterns. Additionally, specific criteria are applied to classify rainfall intensities, heatwaves, and coldwaves, allowing a thorough examination of EWE. The study spans seasonal and decadal intervals, focusing on the period from 1961 to 2020, covering 60 years of daily rainfall and temperature data. This extensive dataset facilitates a comprehensive analysis of long-term trends and short-term variations in rainfall and temperature across Gujarat's regions. The primary objective of this research is to reveal complex shifts and variations in rainfall and temperature trends, as well as the frequency and intensity of EWE over the specified timescales. It provides a valuable understanding of the changing climatic dynamics of the region, laying a solid foundation for the subsequent chapters.

4.2 Methodology

This chapter aims to thoroughly examine temperature and rainfall patterns, including extreme occurrences, across distinct physiographic regions of Gujarat from 1961 to 2020. It also assesses the impact of changing Sea Surface Temperatures (SST) in the Indian and Pacific Oceans, with a focus on phenomena such as the Indian Ocean Dipole (IOD), El Niño, and La Niña, on these variables. The methodology begins by collecting comprehensive datasets from the Indian Meteorological Department Library (IMDLIB), including daily minimum and maximum temperature and rainfall records. Additionally, the Dipole Mode Index (DMI) and Oceanic Niño Index (ONI) are sourced from the National Centers for Environmental Prediction (NCEP), NOAA. After data acquisition, rainfall, and temperature records are prepared and analyzed, addressing missing or erroneous data and aggregating daily values into monthly or seasonal averages. To explore spatio-temporal variations in temperature and rainfall patterns during the study period, rigorous statistical analyses are performed using fundamental measures such as mean, standard deviation, and coefficient of variation (CV). The variability trends are assessed using the IMD daily gridded dataset, with the CV calculated from the mean and standard deviation using the following formula:

$$CV = \sigma / \mu \times 100 \quad (1)$$

The CV helps standardize variability, making it easier to compare across various concentration levels typically experienced in the assay's range of operation (Arachchige et al., 2022). In contrast, Standard Deviation (σ), a statistical measure that quantifies the amount of variation or dispersion of a dataset from its mean, is computed using the following formula:

$$\sigma = \sqrt{\frac{\sum(x_i - \mu)^2}{N}} \quad (2)$$

Here, μ is the Arithmetic mean of the observations.

Additionally, a comprehensive analysis is conducted to examine the spatio-temporal distribution of rainfall, employing a detailed study using the PCI to understand how rainfall is distributed over time and across seasons. This investigation spans seasonal and decadal scales, with a particular emphasis on the SWM season. It examines the diverse physiographic regions within Gujarat, considering variations in rainfall patterns and their impacts over different timescales. These analyses serve as the foundation for subsequent chapters and provide a solid basis for developing a comprehensive understanding of the climatic dynamics under scrutiny.

4.2.1 Precipitation Concentration Index (PCI)

The PCI, developed by Oliver, 1980, is a powerful indicator of the temporal distribution of rainfall (Llano, 2018). This index allows us to quantify the relative distribution of rainfall patterns and estimate their seasonality (Coscarelli & Caloiero, 2012). The following method was used to calculate yearly and seasonal rainfall concentrations:

$$PCI_{annual} = \sum_{i=1}^{12} P_{i^2} / (\sum_{i=1}^{12} P_i)^2 \times 100 \quad (3)$$

The SWM season is crucial for India. To analyze the distribution of rainfall across the SWM months, it is necessary to calculate the Seasonal PCI, or SPCI as follows (Swain et al., 2022):

$$SPCI = \sum_{i=1}^{4} P_{i^2} / (\sum_{i=1}^{4} P_i)^2 \times 33.3 \quad (4)$$

where P_i represents the monthly rainfall for the i^{th} month. Table 4.1 provides the classification of SPCI values.

Table 4.1 SPCI Range and Classification Categories

SPCI values	Significance (Rainfall Distribution)
SPCI ≤ 10	Uniform Rainfall Distribution
15 ≤ SPCI > 10	Moderate Rainfall Distribution
20 ≤ SPCI >15	Irregular Rainfall Distribution
SPCI > 20	Strong Irregularity in Rainfall Distribution

Source- (Oliver, 1980)

SPCI values theoretically range from 8.3 to 100, with 8.3 indicating a uniform distribution and 100 indicating an extremely clustered or aggregated distribution (Reddy et al., 2022). The range allows for the assessment of how evenly or unevenly rainfall is distributed throughout the season. In addition, several criteria have been used to classify temperature and rainfall distribution and extremes.

4.2.2 Criteria for Rainfall Distribution and Intensity Assessment

The distribution of rainfall is classified into distinct levels: Scanty or Large Deficient, Deficient, Normal, Excess, and Surplus or Large Excess (https://www.imdpune.gov.in/Reports/glossary.pdf). Based on IMD criteria, this classification provides a systematic framework for evaluating variations in rainfall patterns and their potential impacts within a given region. This methodology is invaluable for identifying deviations from typical rainfall levels and offers a structured understanding of the dynamic shifts occurring in rainfall.

Table 4.2 Classification of Rainfall Distribution Based on IMD Criteria

Category	Definition
Surplus	Rainfall amount is +60% of normal or more
Excess	Rainfall level ranges from +20% to +59% of normal
Normal	Rainfall level ranges from -19% to +19% of normal
Deficient	Rainfall level ranges from -20% to -59% of normal
Scanty	Rainfall amount is -60% of normal or less

Source- Met Glossary, IMD Pune, 2008 (https://www.imdpune.gov.in/Reports/glossary.pdf).

Following the distribution, the classification of rainfall intensity includes 9 distinct categories. However, the categories of 'No rain,' 'Trace,' and 'Very light' do not fall under the classification of rainy days, as they that do not meet the threshold of 2.5 mm or more within a day. 'No rain' and 'Trace' represent the absence of rainfall and 0.01 to 0.04 mm of rainfall during the day, respectively. According to the IMD criterion, rainy days are those when the rainfall exceeds 2.5 mm. This classification highlights the importance of distinguishing between varying levels of rainfall intensity for accurate meteorological assessments.

Table 4.3 Classification of Rainfall Intensity Levels

Intensity of Rainfall	Definition
Very light rain	Refers to light rainfall, with amounts usually between 0.1 to 2.4 mm, often not enough to cause significant wetness.
Light rain	Refers to gentle rainfall, usually ranging between 2.5 to 7.5 mm, leading to light wetting of surfaces.
Moderate Rain	Refers to rainfall of moderate intensity, ranging from 7.6 to 35.5 mm, resulting in noticeable wetness.
Rather Heavy Rain	Refers to rainfall of considerable intensity, typically between 35.6 to 64.4 mm, causing moderate to heavy wetness.
Heavy rain	Refers to substantial rainfall, usually between 64.5 to 124.4 mm, resulting in significant wetness.
Very Heavy rain	Refers to intense rainfall, with amounts ranging from 124.5 to 244.4 mm, leading to extensive wetness and potential flooding.
Extremely Heavy rain	Refers to exceptionally intense rainfall, typically exceeding 244.5 mm, often resulting in severe flooding and damage.

Source- Met Glossary, IMD Pune, 2008 (https://www.imdpune.gov.in/Reports/glossary.pdf).

4.2.3 Criteria for Defining Heat and Cold Waves

There is no universally agreed-upon definition for Heat Wave and Cold Wave. They represent unusual occurrences marked by temperatures exceeding or falling below normal levels, respectively (Pai et al., 2017). A Heat Wave refers to a period of unusually high temperatures surpassing the typical maximum temperature levels observed during the pre-monsoon season, primarily occurring in North and Northwest India (https://www.ndma.gov.in/Natural-Hazards/Heat-Wave). Table 4.4 shows the detailed criteria for defining Heat Waves. According to the IMD, a Heat Wave is determined based on Tmax as follows: if the temperature in the plains reaches at least 40°C, in coastal areas at least 37°C, and in hilly regions at least 30°C.

Table 4.4 Criteria of Heatwave and Severe Heatwave Conditions

Condition	Temperature Criteria *Departure from Normal	Notes
Normal Max Temp ≤ 40°C		
Normal	-1°C to 1°C	When the normal max temperature of a station is less than 10°C, the term 'moderate cold wave' will not be used.
Above Normal	2°C	
Appreciably Above Normal	3°C to 4°C	
Markedly Above Normal/ Moderate Heat Wave	5°C to 6°C	
Severe Heat Wave	7°C or more	
Normal Max Temp > 40°C		
Normal	-1°C to 1°C	
Above Normal	2°C	
Heat Wave	3°C to 4°C	
Severe Heat Wave	More than 5°C	
When the normal maximum temperature of the station is ≥ 45°C for 2 days or more		Declared as Heat Wave.

Source- Met Glossary, IMD Pune, 2008 (https://www.imdpune.gov.in/Reports/glossary.pdf).

Similarly, a Cold Wave refers to a prolonged period of exceptionally cold weather, characterized by temperatures falling significantly below the average for a particular region. Detailed criteria outlining the classification of cold waves by IMD are presented in Table 4.5.

Table 4.5 Criteria of Coldwave and Severe Coldwave Conditions

Condition	**Temperature Criteria** ***Departure from Normal**	**Notes**
Normal Max Temp ≥ 10°C		
Normal	-1°C to 1°C	When the normal max temperature of the station is less than 10°C (The term moderate cold wave will not be used)
Below Normal	-2°C	
Appreciably Below Normal	-3°C to -4°C	
Markedly Below Normal/ Moderate Cold Wave	-5°C to -6°C	
Severe Cold Wave	-7°C or above	
Normal Max Temp < 10°C		
Normal	-1°C to 1°C	
Below Normal	-2°C	
Cold Wave	-3°C to -4°C	
Severe Cold Wave	-5°C or less	

Source- Met Glossary, IMD Pune, 2008 (https://www.imdpune.gov.in/Reports/glossary.pdf).

4.2.4 Criteria for Categorizing IOD and ENSO Phases

The Indian Ocean Dipole (IOD) and the El Niño-Southern Oscillation (ENSO) are critical climate phenomena characterized by SST anomalies. The IOD phases are categorized using the Dipole Mode Index (DMI), which measures the SST difference between the western and eastern equatorial Indian Ocean (K. Huang et al., 2024). A positive IOD phase occurs when the DMI is +0.4 or higher, indicating warmer than average SSTs in the western Indian Ocean and cooler than average SSTs in the eastern Indian Ocean. In contrast, a negative IOD phase is defined by a DMI of -0.4 or lower, with cooler SSTs in the west and warmer SSTs in the east (Marchant et al., 2007). Neutral IOD conditions prevail when DMI values range between -0.4 and +0.4, signifying no significant SST anomalies (Ratna et al., 2024). For ENSO, the phases are determined using the Oceanic Niño Index (ONI), which assesses SST anomalies in the Niño 3.4 region of the central and eastern equatorial Pacific Ocean (Z. Huang et al., 2022). El Niño is identified when the ONI is +0.5°C or higher for at least 5 consecutive overlapping 3-month seasons, indicating sustained warming. La Niña is marked by an ONI of -0.5°C or lower over the same duration, reflecting sustained cooling. Neutral ENSO conditions occur when ONI values lie between -0.5°C and +0.5°C, indicating average SSTs (Revadekar et al., 2009).

4.3 Results and Discussion

Gujarat's diverse climatic patterns are shaped by its distinct physiographic regions, including Central Gujarat, Kutch, North Gujarat, Saurashtra, and South Gujarat (Srivastava et al., 2023). Each region exhibits distinct climatic characteristics influenced by geography and seasonal patterns. From 1961 to 2020, substantial differences in average rainfall are evident, with South Gujarat receiving the highest (1410.7 mm), followed by Central Gujarat (853.3 mm), North Gujarat (729.2 mm), Saurashtra (675.6 mm), and Kutch receiving the least (436.6 mm). During the winter months (JF), T_{min} ranges from 10°C to 20°C, while T_{max} remains between 25°C and 30°C, accompanied by negligible rainfall. In the pre-monsoon season (MAM), temperatures increase substantially across Gujarat, particularly in Central and South Gujarat, where T_{max} often exceeds 40°C and T_{min} ranges between 20°C and 25°C. Rainfall remains low during this period, generally below 20 mm, while May is considered the hottest month across Gujarat.

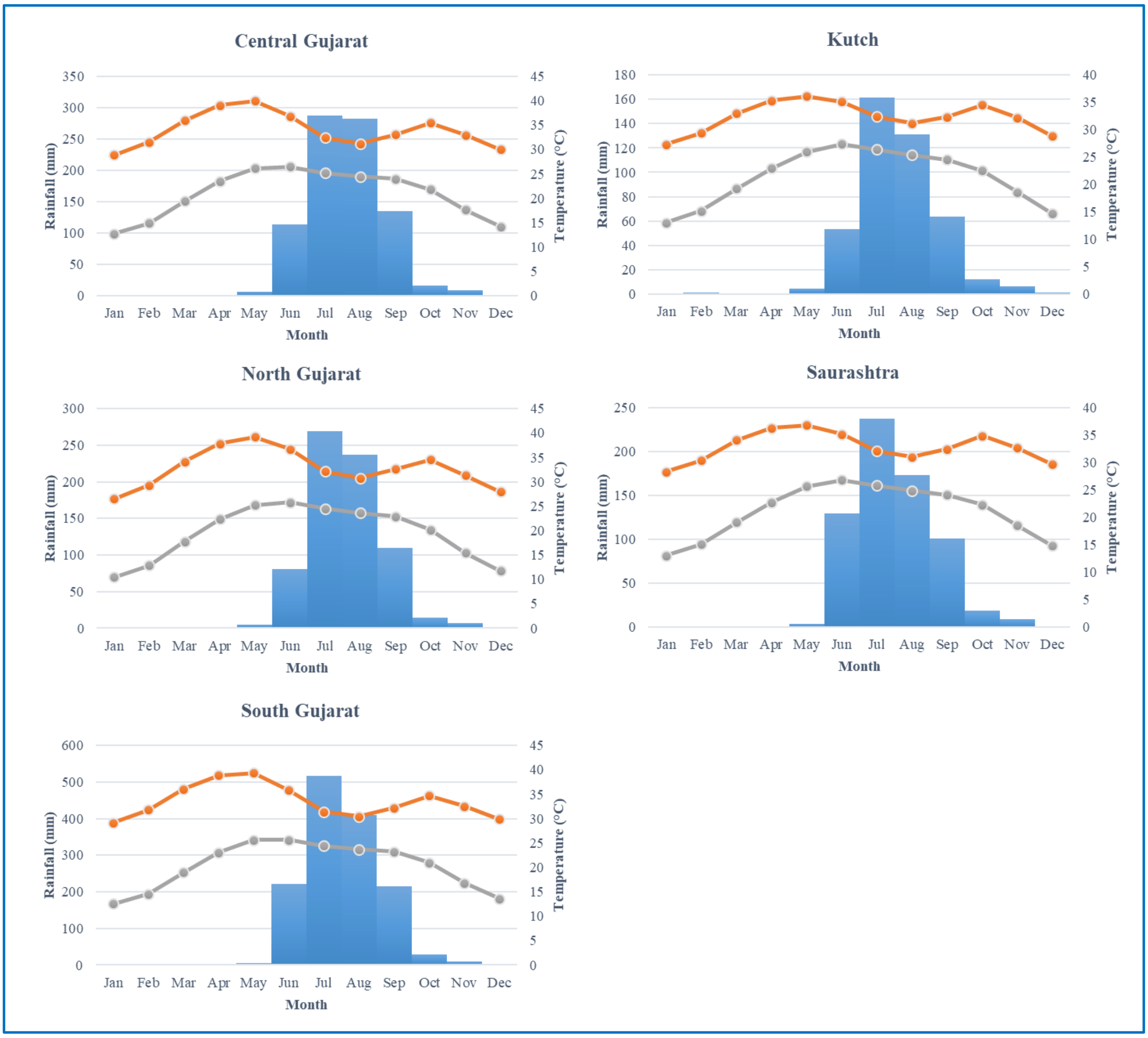

Figure 4.1 Average Monthly Distribution of Rainfall and Temperature (T_{min} and T_{max}) Across the Physiographic Regions of Gujarat (1961-2020).

The onset of the SWM (JJAS) season brings a substantial shift, with 96% of the annual rainfall occurring during this period. July usually records the highest rainfall, followed by August across the regions. During the SWM, T_{min} varies between 25°C to 28°C, and T_{max} ranges from 30°C to 35°C. As the SWM withdraws, rainfall begins to decline, though certain regions may still receive rainfall in early October, contingent upon the timing of the SWM's withdrawal. During the post-monsoon season (OND), T_{min} drops to around 20°C, while T_{max} ranges between 30°C and 35°C. These seasonal dynamics highlight the climatic diversity and variability of Gujarat, which is essential for effective water management and informed agricultural planning.

Figure 4.2 shows the variability in rainfall and temperature across the physiographic regions, highlighting substantial regional disparities. While rainfall data exhibits high variability, characterized by outliers, temperature data is relatively less complex. During winter, South Gujarat records the highest median T_{max}, followed by Central Gujarat. In contrast, Saurashtra, followed by Kutch, experiences the highest median T_{min} during winter. North Gujarat records the lowest temperature in winter. Additionally, Kutch exhibits a wide interquartile range (IQR) for both T_{min} and T_{max} during winter, indicating large variability in temperature within that region. Although the contribution of winter rainfall to the total annual rainfall is negligible, the presence of outliers indicates occasional extreme events across regions. Central Gujarat has a narrow IQR for winter rainfall, suggesting relatively consistent but low rainfall, although outliers point to sporadic rainfall events. Kutch and North Gujarat exhibit higher median rainfall with substantial variability, while Saurashtra and South Gujarat show lower median rainfall and fewer outliers. During the pre-monsoon season, temperatures increase across the regions, with Central Gujarat showing the highest median T_{max} and T_{min}, followed by South Gujarat. In contrast, Kutch and North Gujarat exhibit the lowest T_{max} and T_{min}. North Gujarat shows a wide IQR for pre-monsoon T_{min}, indicating large variability. Similar to winter, pre-monsoon rainfall remains negligible to the total annual rainfall. However, it exhibits large variability across regions compared to winter. This variability is essential to consider, as it can influence the availability of water resources in the subsequent SWM season. The presence of outliers in the rainfall data further highlights the potential for occasional extreme rainfall events, which may pose risks of flooding and waterlogging in vulnerable areas. South Gujarat recorded the highest median rainfall during pre-monsoon, while Kutch recorded the least. Meanwhile, North Gujarat exhibits a wide IQR for pre-monsoon rainfall, indicating substantial variability. Overall, the rainfall patterns during the pre-monsoon season across these regions highlight the complexities of water resource management and agricultural planning in Gujarat.

Figure 4.2 Spatiotemporal Variability of Rainfall and Temperature (T_{max} and T_{min}) Across the Physiographic Regions of Gujarat.

During the SWM season, the difference between T_{max} and T_{min} is the smallest across regions compared to any other season. Central Gujarat shows the highest median T_{max}, while South Gujarat shows the lowest. Conversely, Kutch and North Gujarat exhibit the highest and lowest median T_{min}, respectively. Kutch shows the least difference between T_{max} and T_{min} during this period. Meanwhile, SWM brings abundant rainfall across regions, with South Gujarat receiving the maximum, while Kutch is the least with substantial outliers. Central Gujarat, North Gujarat, and Saurashtra exhibit moderate rainfall variations. During post-monsoon, North Gujarat recorded the least T_{min} and T_{max}. Central Gujrat and Kutch observed maximum T_{max} and T_{min}, respectively. However, non-monsoon months together contribute only 4-6% to the annual rainfall but exhibit large variability, especially during the pre-monsoon and post-monsoon periods. This variability is concerning as it can lead to unpredictable water availability and agricultural challenges. During the post-monsoon period, South Gujarat receives the maximum rainfall and exhibits a wide IQR, indicating substantial variability. In contrast, Kutch receives the least rainfall during this period. Meanwhile, the presence of outliers across regions during the post-monsoon period raises concerns, primarily due to the delayed withdrawal of the SWM.

Figure 4.2 exhibits data distribution, highlighting medians, quartiles, and potential outliers, essential for understanding overall spread and skewness. It effectively shows the range and variability within the dataset, facilitating easy comparison across different periods and identifying anomalies. To gain deeper insights into annual variations and trends, Figure 4.3 shows patterns, cycles, and trends within data, providing a comprehensive view of spatiotemporal dynamics. Over 60 years, Gujarat has observed apparent spatiotemporal changes in temperature and rainfall across its distinct physiographic regions. The changes are observable in the increasing T_{min} and T_{max} in recent decades across the regions. However, except for T_{max} in Kutch during the pre-monsoon and South Gujarat during the SWM season, North Gujarat consistently experiences the lowest T_{min} and T_{max} across all seasons. Meanwhile, Kutch, followed by Saurashtra, records the highest T_{max} during the SWM and post-monsoon seasons across the regions. Additionally, the rainfall pattern during non-SWM seasons exhibits substantial variability, particularly in the last two decades. South Gujarat consistently receives the maximum SWMR, while Kutch receives the minimum across regions. Meanwhile, an increasing SWMR pattern has been observed in the recent decades, particularly in Saurashtra, followed by Kutch. These long-term seasonal patterns help understand the variables and their variations over time, providing insights into trends and potential future changes. To gain deeper insights, Tables 4.6 and 4.7 present the descriptive statistics of average monthly and seasonal rainfall and temperature. This detailed statistical analysis further explains the characteristics of these variables, enhancing the understanding of their behaviour about changing climatic conditions. Such insights are crucial for effective planning and management of resources.

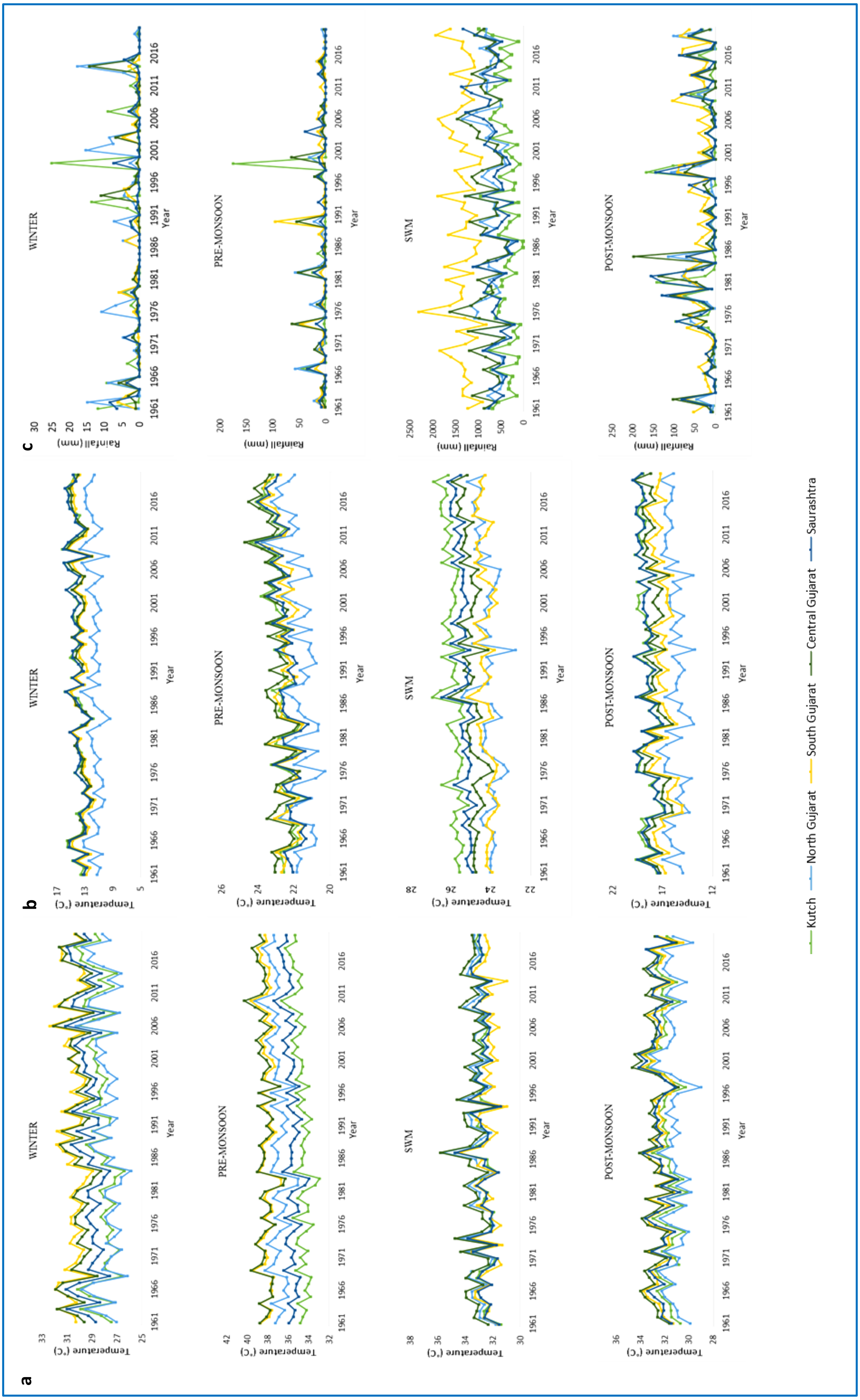

Figure 4.3 Spatiotemporal Variations in (a) T_{max}, (b) T_{min}, and (c) Rainfall Across Gujarat's Physiographic Regions (1961-2020)

Table 4.6 Statistical Summary of Monthly and Seasonal Rainfall Variability Across the Physiographic Regions of Gujarat

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Win	PreM	SWM	PostM	Ann
Mean Rainfall																	
Central Gujarat	0.81	0.34	0.91	0.72	5.77	113.96	293.44	278.74	132.75	15.92	8.46	1.45	1.15	7.41	818.44	26.28	853.28
Kutch	0.55	1.26	0.98	0.26	4.47	53.63	161.10	130.87	63.52	12.15	6.29	1.60	1.81	5.71	409.12	20.04	436.67
North Gujarat	1.65	0.85	1.54	1.36	5.01	80.72	269.06	237.37	109.55	14.22	6.46	1.42	2.50	7.91	696.70	22.10	729.21
Saurashtra	0.31	0.65	1.00	0.59	3.61	129.49	237.45	173.03	100.60	18.99	9.16	0.73	0.96	5.20	640.57	28.88	675.62
South Gujarat	0.62	0.33	0.88	0.61	6.04	220.37	516.96	409.33	214.89	28.41	9.92	2.39	0.96	7.53	1361.55	40.73	1410.76
SD																	
Central Gujarat	2.40	0.95	4.59	1.70	14.67	92.03	118.77	162.09	108.73	30.65	23.88	4.45	2.54	15.27	293.83	37.25	291.83
Kutch	1.43	3.91	5.83	0.83	22.84	62.58	137.97	139.18	84.27	29.14	17.29	5.11	4.21	23.39	241.76	34.96	245.77
North Gujarat	3.66	1.97	7.53	3.06	11.08	62.71	130.60	150.48	106.40	27.10	17.62	4.71	4.11	13.46	253.13	31.03	252.72
Saurashtra	0.65	1.59	4.55	1.95	6.97	98.79	124.53	142.01	85.69	29.67	26.54	2.88	1.86	8.18	270.76	39.26	272.97
South Gujarat	1.17	0.85	2.59	1.44	13.58	112.53	136.62	148.65	102.03	22.66	15.98	6.33	1.56	13.91	289.57	26.41	289.99
CV																	
Central Gujarat	295.47	282.36	503.44	234.84	254.13	80.76	40.47	58.15	81.91	192.56	282.11	306.05	221.67	206.15	35.90	141.72	34.20
Kutch	260.99	310.02	594.77	321.37	511.43	116.68	85.65	106.35	132.67	239.81	274.80	320.16	232.54	409.93	59.09	174.49	56.28
North Gujarat	222.16	230.74	488.22	225.14	221.25	77.68	48.54	63.40	97.13	190.55	272.76	332.26	164.41	170.11	36.33	140.43	34.66
Saurashtra	211.99	244.59	455.79	328.19	192.81	76.29	52.45	82.08	85.17	156.26	289.77	391.34	193.76	157.12	42.27	135.92	40.40
South Gujarat	187.29	254.53	293.60	236.63	224.83	51.06	26.43	36.31	47.48	79.77	161.04	264.55	163.17	184.77	21.27	64.84	20.56
Minimum																	
Central Gujarat	0.00	0.00	0.00	0.00	0.00	2.69	41.82	28.68	0.65	0.00	0.00	0.00	0.00	0.00	300.20	0.00	368.23
Kutch	0.00	0.00	0.00	0.00	0.00	0.10	2.39	0.62	0.09	0.00	0.00	0.00	0.00	0.00	19.63	0.00	22.66
North Gujarat	0.00	0.00	0.00	0.00	0.00	2.16	27.42	21.92	1.23	0.00	0.00	0.00	0.00	0.00	205.49	0.00	275.18
Saurashtra	0.00	0.00	0.00	0.00	0.00	4.03	22.25	9.65	4.01	0.00	0.00	0.00	0.00	0.00	146.40	0.00	153.22
South Gujarat	0.00	0.00	0.00	0.00	0.00	53.77	216.23	164.40	52.15	2.62	0.00	0.00	0.00	0.00	829.28	3.58	944.36
Maximum																	
Central Gujarat	13.88	6.86	34.75	8.84	64.23	411.64	565.46	687.14	413.69	198.30	129.19	25.90	14.34	64.63	1630.88	198.30	1709.11
Kutch	9.39	24.43	45.11	45.60	175.13	313.79	573.48	731.22	299.97	167.56	89.09	27.49	25.20	175.13	995.46	167.56	1028.41
North Gujarat	17.09	4.34	57.57	12.23	54.50	296.50	666.28	679.89	396.74	114.42	83.81	29.16	17.73	58.12	1352.65	114.94	1362.23
Saurashtra	3.75	7.32	34.14	14.14	22.43	488.47	561.14	644.60	421.57	142.45	150.93	20.85	8.53	39.59	1377.61	156.90	1397.58
South Gujarat	4.42	3.26	17.10	7.27	95.77	596.61	947.90	968.49	449.06	86.16	66.74	37.92	6.28	95.77	2316.39	104.38	2384.37
Range																	
Central Gujarat	13.88	6.86	34.75	8.84	64.23	408.95	523.64	658.46	413.04	198.30	129.19	25.90	14.34	64.63	1330.68	198.30	1340.88
Kutch	9.39	24.43	45.11	45.60	175.13	313.69	571.09	730.60	299.88	167.56	89.09	27.49	25.20	175.13	975.83	167.56	1005.75
North Gujarat	17.09	4.34	57.57	12.23	54.50	294.34	638.86	657.97	395.51	114.42	83.81	29.16	17.73	58.12	1147.16	114.94	1087.05
Saurashtra	3.75	7.32	34.14	14.14	22.43	484.44	538.89	634.95	417.56	142.45	150.93	20.85	8.53	39.59	1231.21	156.90	1244.36
South Gujarat	4.42	3.26	17.10	7.27	95.77	542.84	731.67	804.09	396.91	83.54	66.74	37.92	6.28	95.77	1487.11	100.80	1440.01

Figure 4.7 Statistical Summary of Monthly and Seasonal Temperature Variability Across the Physiographic Regions of Gujarat

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Win	PreM	SWM	PostM	Ann
Tmax (°C)																	
Central Gujarat	28.86	31.50	35.98	39.05	39.95	36.86	32.41	31.21	33.02	35.46	32.94	30.00	30.13	38.32	33.35	32.86	33.95
Kutch	27.31	29.36	32.98	35.30	36.08	35.12	32.36	31.15	32.35	34.52	32.21	28.84	28.30	34.78	32.73	32.73	32.32
North Gujarat	26.53	29.30	34.19	37.82	39.22	36.72	32.15	30.77	32.63	34.55	31.33	27.95	27.87	37.07	33.04	33.04	32.78
Saurashtra	28.30	30.39	34.09	36.32	36.85	35.20	32.10	31.02	32.45	34.92	32.70	29.67	29.31	35.75	32.67	32.67	32.85
South Gujarat	29.17	31.82	36.04	38.91	39.38	35.81	31.44	30.42	32.19	34.74	32.55	29.93	30.45	38.10	32.44	32.44	33.54
Tmin (°C)																	
Central Gujarat	12.74	14.91	19.39	23.47	26.11	26.47	25.20	24.44	23.94	21.79	17.62	14.21	13.79	22.98	25.01	17.95	20.89
Kutch	13.03	15.19	19.28	22.97	25.99	27.39	26.43	25.38	24.56	22.53	18.60	14.68	14.08	22.74	25.94	18.68	21.37
North Gujarat	10.46	12.87	17.80	22.31	25.21	25.77	24.48	23.63	22.93	20.16	15.44	11.78	11.63	21.77	24.20	15.88	19.44
Saurashtra	13.08	15.12	19.08	22.74	25.67	26.85	25.84	24.91	24.11	22.31	18.52	14.85	14.06	22.50	25.43	18.63	21.12
South Gujarat	12.51	14.59	18.95	23.06	25.61	25.67	24.45	23.74	23.20	20.98	16.80	13.62	13.52	22.54	24.26	17.20	20.30
Mean Temp (°C)																	
Central Gujarat	20.80	23.20	27.68	31.26	33.03	31.67	28.81	27.83	28.48	28.63	25.28	22.10	21.96	30.65	29.18	25.40	27.42
Kutch	20.17	22.28	26.13	29.14	31.04	31.25	29.40	28.27	28.46	28.52	25.40	21.76	21.19	28.76	29.33	25.70	26.84
North Gujarat	18.50	21.08	25.99	30.06	32.22	31.25	28.31	27.20	27.78	27.36	23.39	19.87	19.75	29.42	28.62	24.46	26.11
Saurashtra	20.69	22.76	26.59	29.53	31.26	31.03	28.97	27.97	28.28	28.62	25.61	22.26	21.69	29.12	29.05	25.65	26.99
South Gujarat	20.84	23.21	27.50	30.98	32.50	30.74	27.94	27.08	27.70	27.86	24.67	21.78	21.98	30.32	28.35	24.82	26.92
SD (°C)																	
Central Gujarat	1.03	1.25	1.07	0.90	0.76	0.91	0.70	0.68	0.90	1.11	1.26	0.73	0.93	0.70	0.60	0.86	0.49
Kutch	0.98	1.28	1.05	0.86	0.64	0.59	0.67	0.64	0.75	1.00	1.13	0.70	0.98	0.68	0.51	0.79	0.50
North Gujarat	1.01	1.35	1.19	1.02	0.81	0.90	0.80	0.73	0.98	1.13	1.26	0.73	0.97	0.78	0.65	0.88	0.53
Saurashtra	0.98	1.23	1.02	0.84	0.63	0.66	0.63	0.63	0.72	0.99	1.14	0.66	0.96	0.66	0.51	0.78	0.48
South Gujarat	1.02	1.16	0.99	0.78	0.70	0.88	0.62	0.60	0.78	1.07	1.29	0.74	0.88	0.62	0.53	0.84	0.44
CV (%)																	
Central Gujarat	5.98	6.08	4.08	2.97	2.34	2.82	2.38	2.37	3.10	4.00	5.94	3.91	4.97	2.39	2.03	3.76	1.90
Kutch	5.66	6.31	4.17	3.00	2.10	1.87	2.25	2.22	2.62	3.59	5.02	3.60	5.27	2.46	1.71	3.34	1.93
North Gujarat	6.81	7.41	4.86	3.54	2.59	2.84	2.75	2.63	3.46	4.33	6.54	4.46	5.93	2.81	2.26	4.15	2.18
Saurashtra	5.63	6.05	4.04	2.94	2.07	2.08	2.13	2.19	2.52	3.55	5.15	3.45	5.14	2.41	1.72	3.33	1.90
South Gujarat	6.10	5.71	3.87	2.62	2.19	2.76	2.14	2.15	2.76	3.91	6.48	4.20	4.86	2.17	1.83	3.86	1.78

4.3.1 Variability of Rainy Days in Gujarat

In Gujarat, the maximum number of rainy days generally occurs during the SWM season, mainly in July, followed by August. According to the IMD, a day is classified as a 'Rainy Day' if it receives at least 2.5mm of rainfall (https://www.imdpune.gov.in/Reports/glossary.pdf). This threshold is used to distinguish days with measurable rainfall from dry days. The state exhibits substantial disparity in the distribution of rainy days, with South Gujarat receiving the maximum rainy days and Kutch receiving the least. As the SWM arrives by mid to late June, the frequency of rainy days increases, reaching a peak in July. However, as September approaches, the frequency of rainy days begins to decline, signalling the retreat of the SWM.

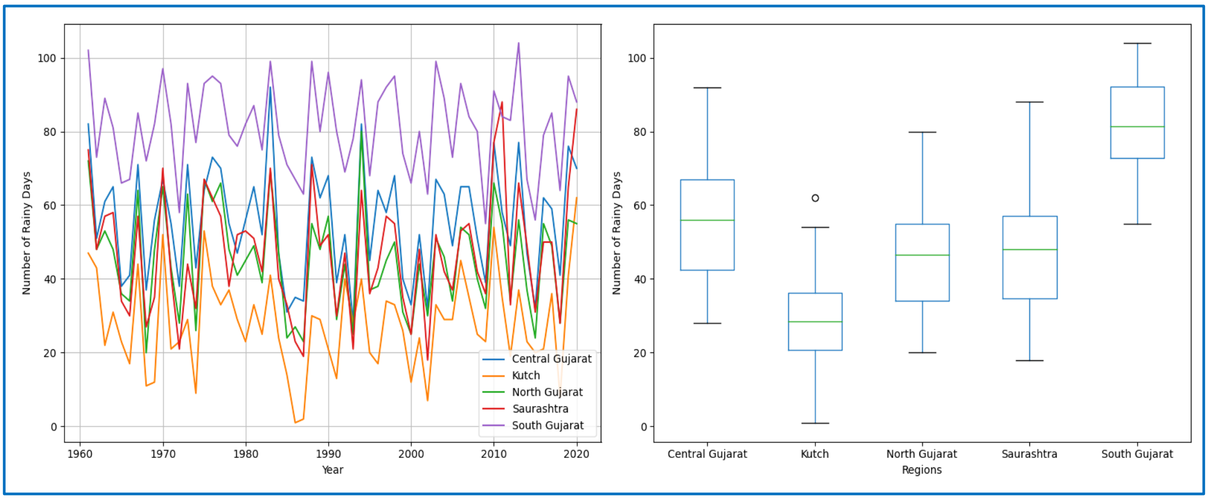

Figure 4.4 Annual Variability of Rainy Days Across the Physiographic Regions of Gujarat.

Figure 4.4 highlights the variability in the distribution of rainy days across distinct regions of Gujarat, exhibiting the maximum variability observed in Kutch, followed by Saurashtra and North Gujarat, with the least variability observed in South Gujarat, which exhibits the highest median and large interquartile range (IQR), indicating it consistently experiences the maximum rainy days, along with substantial variability, as evidenced by long whiskers and outliers reflecting years with extreme deviations in the number of rainy days. Central Gujarat follows with a relatively high median, but its narrower IQR suggests a more stable pattern of rainy days with fewer extreme variations. North Gujarat and Saurashtra show moderate variability, sharing a similar IQR, while North Gujarat has a slightly higher median, both regions experience less variability, indicating a more stable with occasional years of extreme rainy days as indicated by outliers. Conversely, Kutch has the lowest median and IQR, signifying it has the lowest number of rainy days among all regions, while the presence of outliers indicates occasional years with anomalously high numbers of rainy days. Kutch has experienced a large spectrum of rainy days, varying from a week to 62 days. Meanwhile, Saurashtra and North Gujarat experienced ranges of 18 to 88 days and 20 to 60 days, respectively, during the study years. This variability highlights the region's susceptibility to extreme events and highlights the challenges in predicting rainfall patterns. In contrast, South Gujarat showed a relatively consistent pattern of rainy days, except for 2009, when the region recorded 55 days of rainfall, which is lower than the average of 81 days. However, the other regions, such as Central Gujarat, Saurashtra, North Gujarat, and Kutch, experienced significantly lower average annual rainy days, receiving 56, 47, 45, and 28 rainy days, respectively. While substantial variability is observed on an annual scale, examining decadal pattern is crucial for identifying long-term changes in the rainfall patterns. Decadal analysis provides a broader perspective on how rainy days have fluctuated over time, helping to capture sustained shifts or emerging trends that may not be evident in annual variations, thereby providing valuable insights for long-term planning.

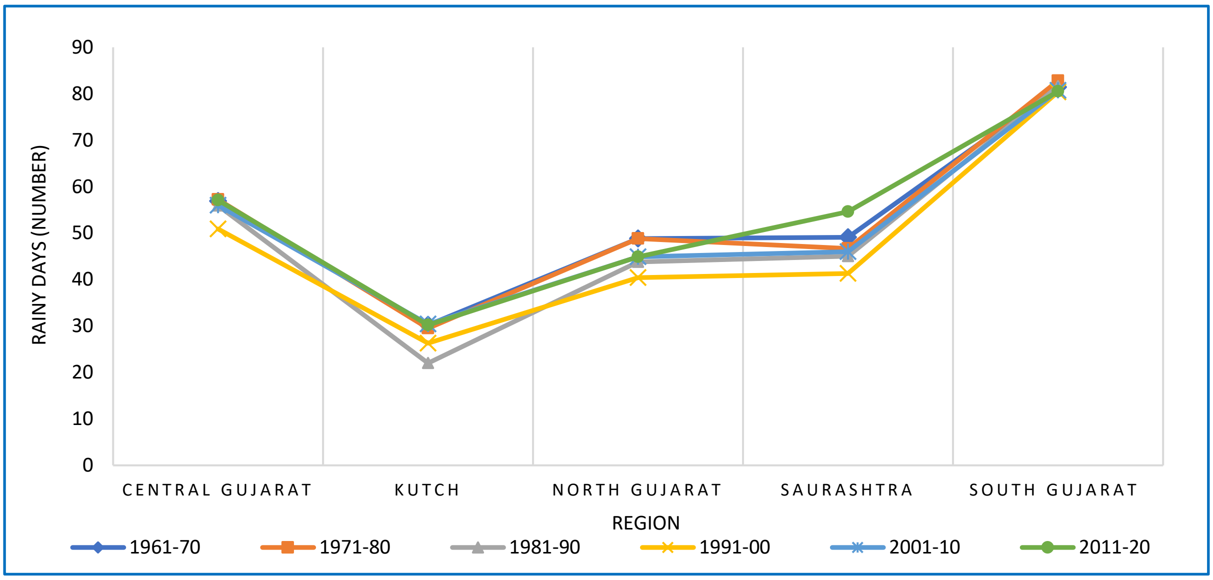

Figure 4.5 Decadal changes in Rainy Days Across the Physiographic Regions of Gujarat.

The shift from analyzing individual years to examining decadal changes highlights a substantial increase in the average number of rainy days in Kutch and Saurashtra, suggesting a significant shift in climatic patterns that has resulted in more frequent or intense rainfall events in recent decades. In contrast, Central, North, and South Gujarat have experienced a slight decrease in their average number of rainy days over the recent decade. This decrease could indicate a trend toward drier conditions or, alternatively, an increase in the frequency of extreme rainfall events, especially if overall rainfall amounts are rising in these regions. Such changes can have important implications for water resource management, agricultural productivity, and ecosystem health. Understanding these decadal changes is crucial for developing effective adaptation strategies to mitigate the impacts of changing rainfall patterns on local communities and economies, particularly in areas such as agricultural planning and disaster preparedness.

4.3.2 Distribution of Annual Rainfall Anomalies

The analysis of annual rainfall anomalies shows substantial disparities across the physiographic regions of Gujarat, highlighting critical concerns for water resource management and agricultural sustainability. Kutch stands out with 45% of the years classified as deficient (below 20% from normal levels), indicating that the region frequently experiences rainfall below the normal threshold (Figure 4.6). This deficiency poses significant challenges for agriculture and water availability, particularly in a region already known for its arid conditions. In contrast, South Gujarat and Central Gujarat recorded no years of scanty rainfall (60% below normal levels), indicating a stable rainfall pattern in these regions. In terms of normal rainfall (-19% to +19% of normal levels) years, South Gujarat experienced the highest occurrence at 65%, while Saurashtra and North Gujarat followed closely at 46.6% and 41.6%, respectively. While Kutch has the highest proportion of years falling under the scanty category, it also experiences a significant surplus rainfall year, accounting for 18.3%, followed by Saurashtra at 10%. Over the recent two decades, nearly half of the total years have witnessed above-normal rainfall levels, exceeding 20% of the long-term average, indicating an increase in rainfall compared to historical norms and suggesting a shift toward wetter conditions in the region. Additionally, Saurashtra experienced 8 out of the last 20 years with rainfall exceeding 20% of normal levels. The substantial disparities in rainfall patterns, especially in Kutch and Saurashtra, highlight the immediate implementation of adaptive strategies to manage water resources effectively and sustain agricultural productivity, ensuring resilience against increased water scarcity risks.

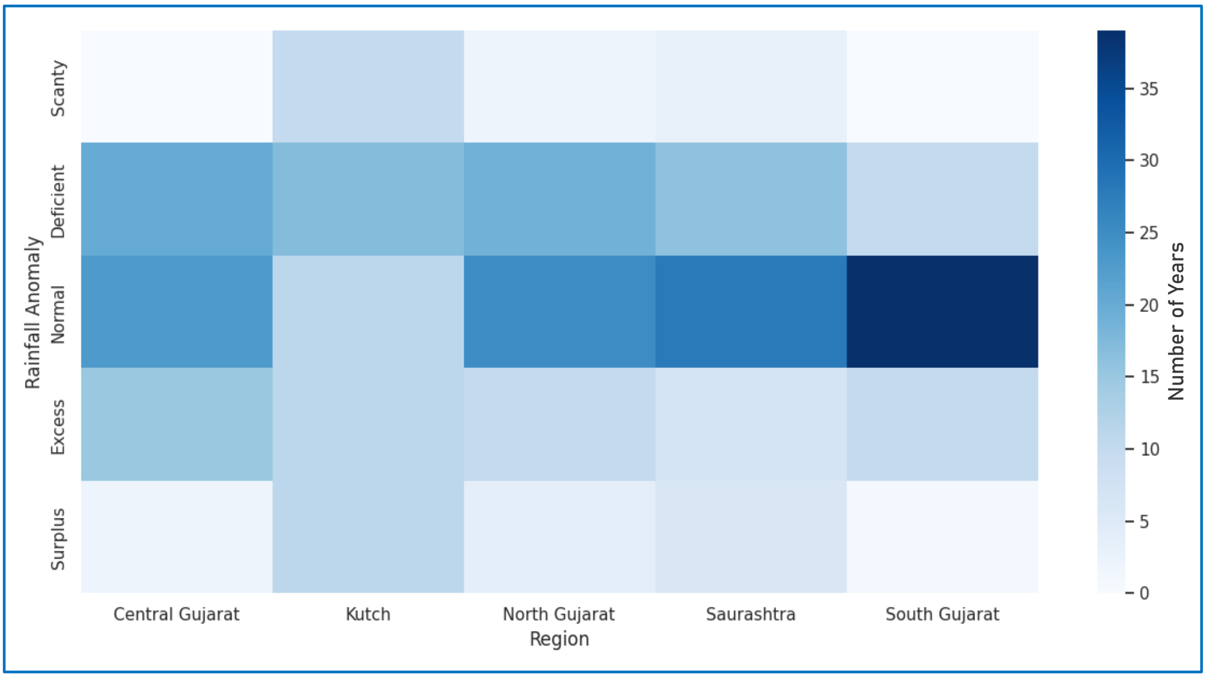

Figure 4.6 Spatiotemporal Distribution of Rainfall Anomalies Across Physiographic Regions

4.3.3 Rainfall Intensity Analysis in Gujarat

When considering 'Very Light Rainfall' events, they account for approximately 40% of all rainfall occurrences across regions. Although these events involve less than 2.4 mm of rainfall and are often not classified as rainy days (Barde et al., 2020), they still contribute to the overall rainfall profile. This minimal rainfall, though insufficient to significantly impact water availability, plays a crucial role in understanding the overall dynamics of rainfall (Kumar et al., 2021). Analyzing these events is essential as they can influence soil moisture levels, vegetation, and localized climate patterns, highlighting the need for comprehensive rainfall studies that extend beyond heavy downpours. Figure 4.7 shows the variability and intensity pattern rainfall across Gujarat's physiographic regions, revealing distinct patterns in rainfall events. Very Light Rain emerges as a significant event, particularly in Kutch and Saurashtra, where it constitutes over half of the total rainy days. This pattern was observed in North and Central Gujarat, accounting for more than 40% of rainfall events. In contrast, South Gujarat has the lowest proportion, with 37% of the total rainy days. Meanwhile, when excluding 'Very Light Rainfall' events, there is a substantial prevalence of 'Moderate' and 'Light Rainfall' events.

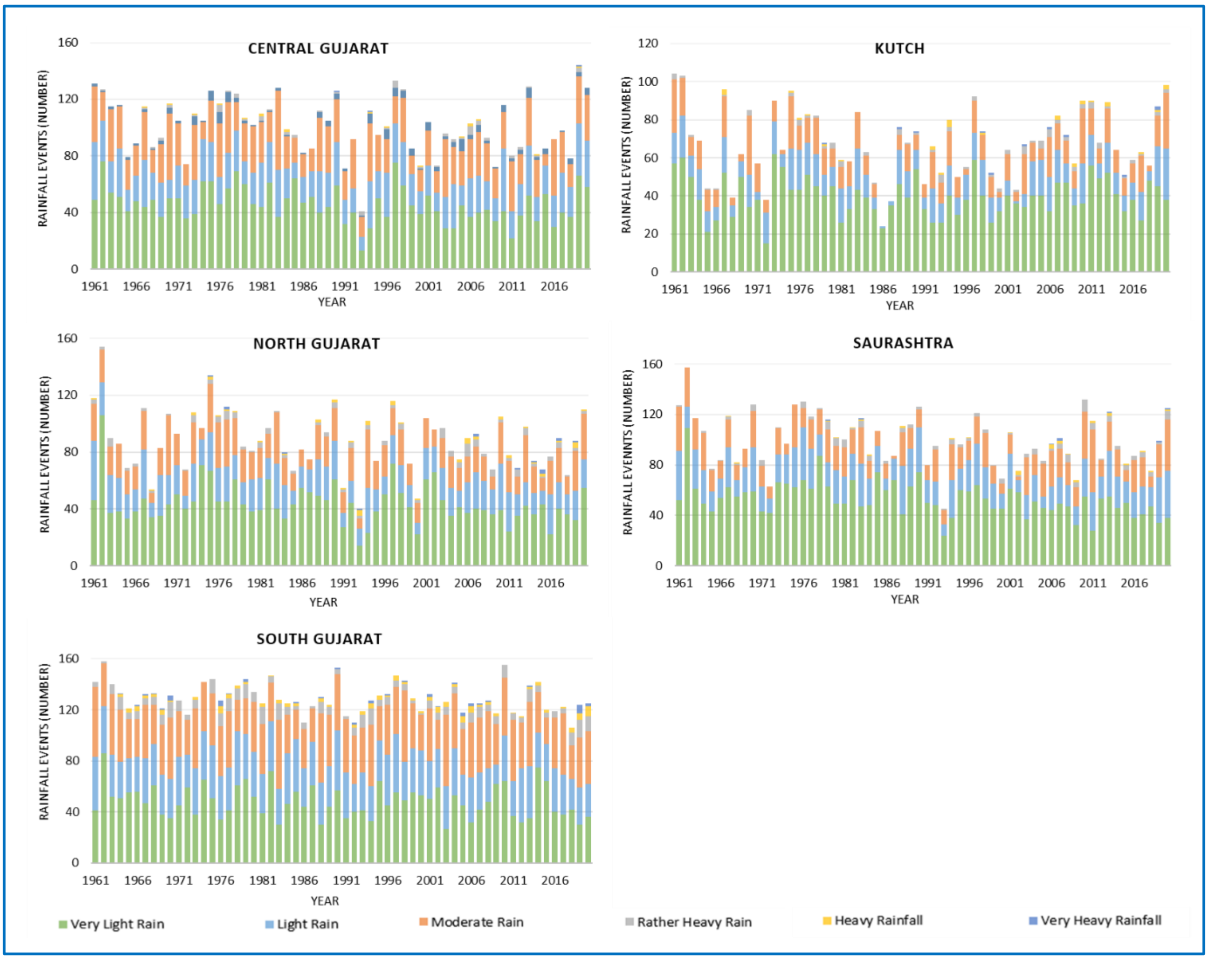

Figure 4.7 Regional Variability and Intensity Patterns of Rainfall Across Gujarat.

When examining Light Rainfall (2.5 to 7.5 mm) events, it emerges as the most common category in both Kutch (46.5%) and Saurashtra (49.2%) when excluding Very Light Rainfall events. It also holds significance in North Gujarat (45.2%), Central Gujarat (43.2%), and South Gujarat (40.5%). While this frequent occurrence can benefit agriculture, its low intensity may not adequately support crops during prolonged dry spells, particularly in water-scarce regions. However, Moderate Rainfall events constitute 48.1%, 47.3%, 46.1%, 45.7%, and 43.1% in Central Gujarat, South Gujarat, Kutch, North Gujarat, and Saurashtra, respectively. This prevalence of moderate rainfall indicates that, while light and very light rains are common, there is a significant occurrence of rainfall that can provide greater benefits to agriculture. Moderate rainfall can support crop growth and enhance soil moisture, making it a critical component of the region's overall hydrological dynamics. Meanwhile, Categories such as 'Rather Heavy Rain,' 'Heavy Rainfall,' 'Very Heavy Rainfall,' and 'Extreme Heavy Rainfall' together account for only a small percentage of total rainy days, comprising approximately 7.5%, 4.3%, 4.1%, 3.3%, and 3.1% for South Gujarat, Central Gujarat, North Gujarat, Saurashtra, and Kutch, respectively, when 'Very Light Rain' is included. When excluding 'Very Light Rain,' these categories represent 12.0%, 7.9%, 8.2%, 7.1%, and 7.7%, respectively. This observation highlights the predominance of light to moderate rainfall intensities in the region's rainfall profile and the relatively infrequent occurrence of heavy downpours. However, the last few decades have seen a substantial increase in rainfall events categorized as RHTE (Rather Heavy to Extremely Heavy), raising concerns about their potential impacts on both the environment and local communities. These intense rainfall events can lead to sudden and severe flooding, exacerbating the risks of soil erosion, crop damage, and infrastructure strain.

4.3.4 Precipitation Concentration Index (PCI)

The PCI is a robust metric for analyzing rainfall distribution. It effectively measures the degree of rainfall concentration, facilitating comparisons of rainfall patterns across regions (K. Zhang et al., 2019). The analysis of rainfall variability and seasonal rainfall concentration, particularly during the SWM season, was conducted using the Seasonal PCI (SPCI). The SWM exhibits a range of rainfall patterns across physiographic regions. Figure 4.8 shows that Kutch exhibits the highest median SPCI, reflecting a significant concentration of rainfall within a short period, further supported by a broader spread and a few outlier values. In contrast, South Gujarat demonstrates a lower median SPCI, suggesting a more even distribution of rainfall throughout the SWM season. However, Central Gujarat and North Gujarat show moderate SPCI values with relatively narrow interquartile ranges, indicating less variability in rainfall distribution.

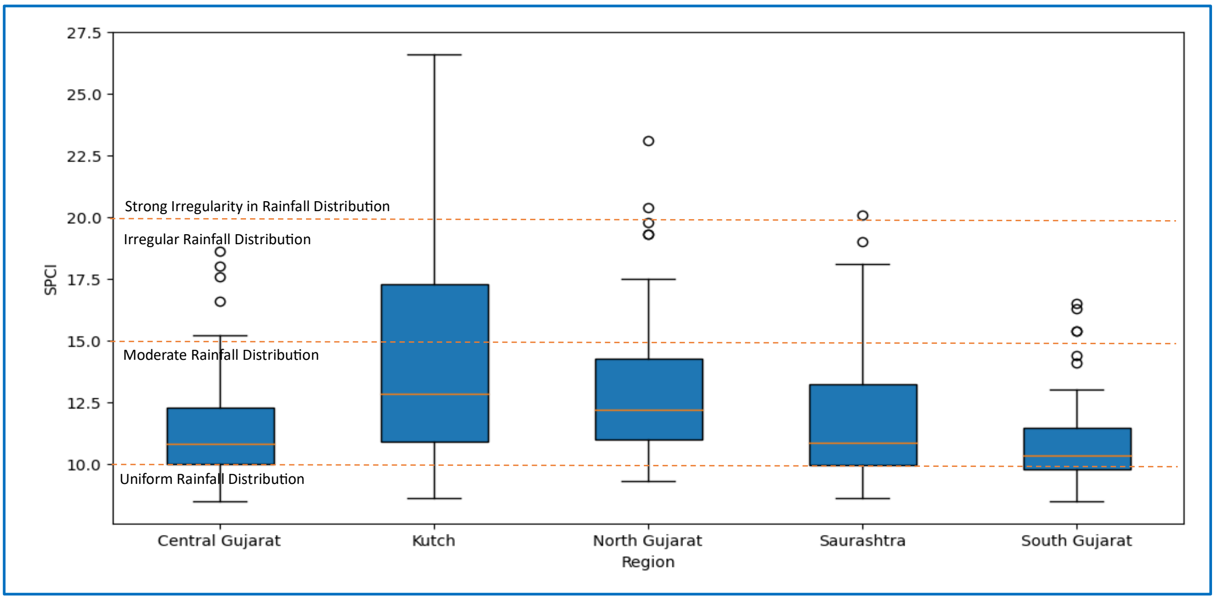

Figure 4.8 Analysis of SPCI Variability Among Gujarat's Physiographic Regions.

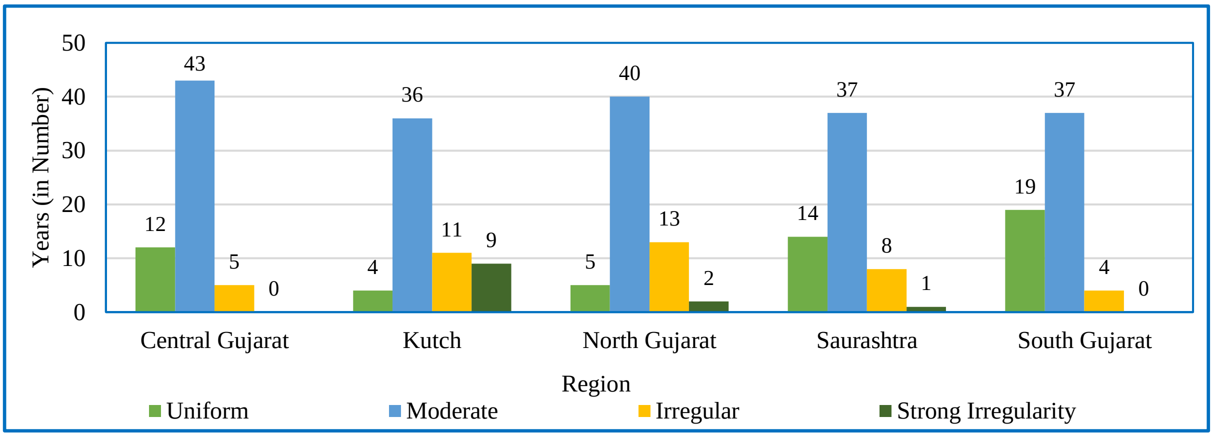

Figure 4.9 Comparative Analysis of SPCI Values Across Distinct Regions of Gujarat.

Throughout the studied period, South Gujarat and Central Gujarat did not experience any events with an SPCI greater than 20, indicating an absence of extremely irregular SWMR distribution in these regions. South Gujarat recorded the most years with uniform rainfall distribution (19), followed by Saurashtra with 14 years and Central Gujarat with 12 years, highlighting relatively stable rainfall patterns in these regions. In contrast, Kutch and North Gujarat experienced fewer than five years of uniform distribution out of the 60 years studied, indicating higher variability in SWMR distribution. Additionally, most years across all regions fell under the moderate rainfall distribution category, with an SPCI between 10 and 15. Central Gujarat experienced the maximum number of years (43, or 71%), showing a significant tendency towards moderate rainfall variability. Kutch, however, had the lowest proportion of moderate distribution, with 30 years (60%). Regarding strong irregularity in rainfall distribution, defined by an SPCI greater than 15, Kutch experienced the maximum number of years (20), followed by North Gujarat with 13 years and Saurashtra with 9 years. In contrast, Central Gujarat and South Gujarat experienced fewer than five years each with an SPCI greater than 15, indicating a more stable rainfall pattern compared to Kutch and North Gujarat.

As the analysis transitions from annual to decadal scales, it unveils deeper insights into rainfall patterns. Figure 4.10 shows the decadal changes in SPCI across Gujarat's physiographic regions during the SWM season from 1961 to 2020. The period from 1961 to 1970 exhibited moderate SPCI values, while the subsequent decade (1971-1980) recorded the lowest combined SPCI of 11.35, indicating a more uniform rainfall distribution, especially in South Gujarat. During this period, Kutch and South Gujarat recorded their lowest SPCIs of 12.98 and 10.09, respectively, indicating a relatively more uniform SWMR distribution. Conversely, the decade from 1981 to 1990 marked a shift towards higher variability, with a SPCI of 13.05. In the 1991-2000 period, Kutch reached its highest SPCI of 15.98, reflecting significant irregularity, while Central Gujarat maintained moderate conditions. The 2001-2010 decade highlighted improved rainfall patterns in Central Gujarat. However, the recent decade (2011-2020) revealed a concerning decline in mean SPCI in Central Gujarat, alongside increased irregularity in North Gujarat and Saurashtra, indicating a trend towards more unpredictable rainfall behaviour in these regions.

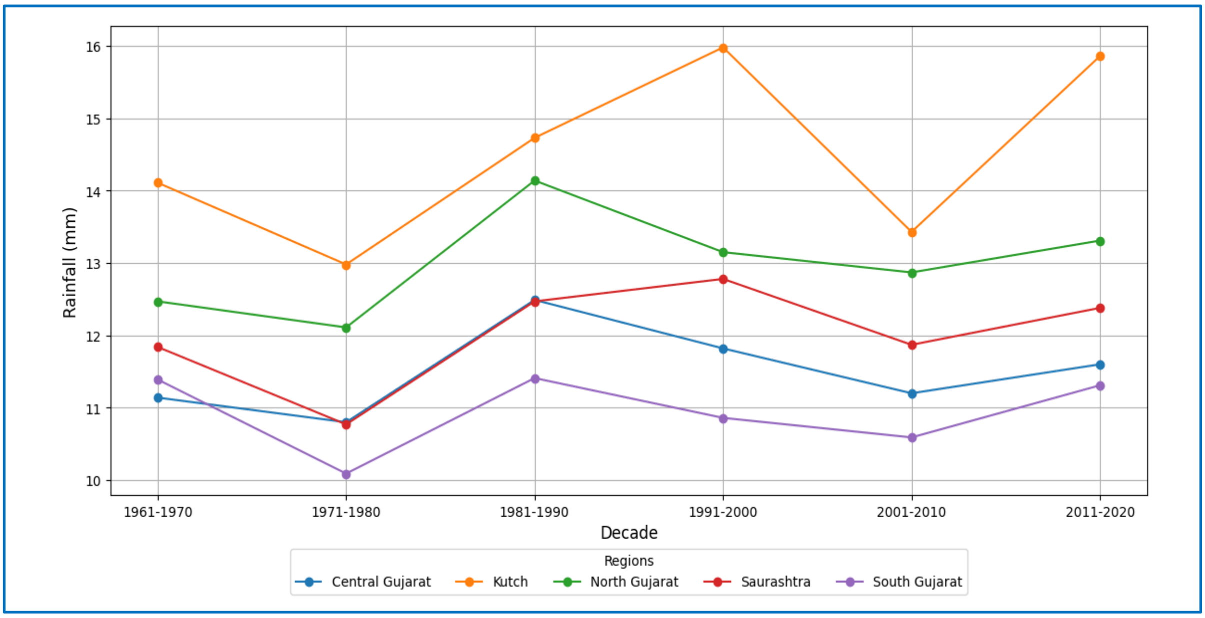

Figure 4.10 Decadal Variations in SPCI Statistics Across Distinct Regions of Gujarat

The analysis of individual years reveals several instances of uniform SWMR distribution across regions, a pattern not captured by the decadal statistics, indicating that while certain years may exhibit consistent rainfall, long-term trends show substantial variability. South Gujarat recorded the lowest decadal SPCI, ranging from 10.09 to 11.41, showing more stable and less erratic rainfall over extended periods. In contrast, Kutch showed the highest decadal SPCI, from 12.98 to 15.98, highlighting significant variability and irregularity in its rainfall patterns. Central Gujarat's decadal SPCI varied from 10.80 to 12.49, reflecting moderate variability in rainfall. North Gujarat showed a broader range of 12.11 to 14.14, suggesting higher variability and more unpredictable rainfall. However, Saurashtra had decadal SPCI values ranging from 10.77 to 12.78, indicating variability that is less extreme than that of North Gujarat and Kutch, although recent decades show slight variations in SWMR distribution. These findings highlight the urgent need for targeted water management strategies to address distinct rainfall patterns across physiographic regions and mitigate the potential risks to agriculture and water resources.

4.3.5 Analysis of Extreme Heat and Cold Events

The analysis of extreme heat and cold events across distinct regions reveals significant shifts in temperature patterns over recent decades, highlighting the evolving climate dynamics, including an examination of events that either exceed or fall below a specified threshold. The increasing frequency of extreme heat events has emerged as one of the most prominent patterns in recent decades, particularly since 2000, with most regions experiencing a substantial increase in heatwaves and severe heatwave conditions. Historically, regions such as Kutch, North Gujarat, and Saurashtra, where T_{max} seldom exceeds 40°C, have shown increased susceptibility to these extreme temperature events. In these regions, occurrences of 'heatwaves' (defined as T_{max} 3°C to 4°C above normal) and 'severe heat waves' (T_{max} exceeding 5°C above normal) have become alarmingly common over the past two decades, showing an apparent shift toward warmer conditions. Central Gujarat has experienced a substantial increase in the frequency of severe heat waves. These extreme conditions are particularly concerning as they exacerbate drought risks, leading to reduced crop yields, increased water demand, and significant public health concerns, especially during prolonged heatwave periods. South Gujarat also experienced an increase in above-normal temperature events in recent decades. Though heatwave conditions in South Gujarat are less frequent than in Central Gujarat, the steadily increased pattern in extreme heat events signals increasing vulnerability in this region.

Meanwhile, the prevalence of ‘Above-Normal Temperature’ days has also intensified across Gujarat, compounding the risks associated with extreme heat. This sustained increase in above-normal temperatures amplifies the strain on water resources, intensifies drought conditions, and threatens agricultural productivity. The cumulative effects of increasing heatwave frequencies and prolonged above-normal temperature days exhibit the urgent need for adaptive strategies to safeguard agriculture, water resources, and public health across Gujarat. Figure 4.11 shows the occurrences of temperature extremes across physiographic regions of Gujarat.

Figure 4.11 Frequency of Extreme Heat and Cold Events Across Physiographic Regions.

However, while extreme heat events have become more prevalent, there has been an apparent decrease in cold events across the regions. Earlier decades, particularly the 1960s and 1970s experienced higher frequencies of extreme cold events, which occur during the winter season (JF) or in late post-monsoon in December. These events included 'Below-Normal' (-2°C below the average T_{min}), 'Appreciably Below-Normal temperatures' (-3°C to -4°C below normal T_{min}), and 'Cold Waves' or 'Moderate Cold Waves' (-5°C to -6°C). However, in recent decades, the number of cold events has substantially reduced. Severe cold waves, once common across the region (-7°C or below), have become increasingly rare, with no occurrences recorded in the recent decade. This shift toward more frequent and intense heat events, coupled with the decline in cold events, shows a warming trend in Gujarat. Examining the frequency of extreme cold events on a decadal scale exhibits a substantial decline across the regions. The frequency of 'Below-Normal Temperatures' has decreased across Gujarat. 'Appreciably Below-Normal Temperatures' reduced from 9.8 to 6.4 days in Central Gujarat. Kutch declined from 10.8 to 6.5 days, North Gujarat from 9.6 to 6.9 days, Saurashtra from 11.8 to 6.0 days, and South Gujarat from 12.1 to 5.5 days. Additionally, the frequency of moderate and severe cold waves has substantially reduced across regions, with occurrences falling to 0 - 0.1 days, mainly in Central Gujarat, highlighting an alarming situation that necessitates urgent attention and action.

4.3.6 Regional Climate Variability Influenced by Global Phenomena

India's climatic conditions are substantially shaped by global phenomena, including El Niño, La Niña, and the Indian Ocean Dipole (IOD) (Hrudya et al., 2021). These large-scale climate drivers influence weather patterns across the country, affecting SWM intensity, temperature fluctuations, and rainfall distribution (Ashok et al., 2004). Specifically, in the state of Gujarat, situated in the western part of India, the effects of these global phenomena are particularly pronounced (Bhatla et al., 2023). During El Niño events, Gujarat often experiences drier than normal conditions, leading to decreased rainfall and potential drought conditions. Conversely, during La Niña episodes, Gujarat may witness above-average rainfall, sometimes resulting in flooding and waterlogging, affecting both rural and urban areas (Iyer et al., 2021). The IOD significantly influences Gujarat's climate, with positive phases associated with enhanced SWM rainfall and negative phases leading to below-average rainfall (Choudhary et al., 2014).

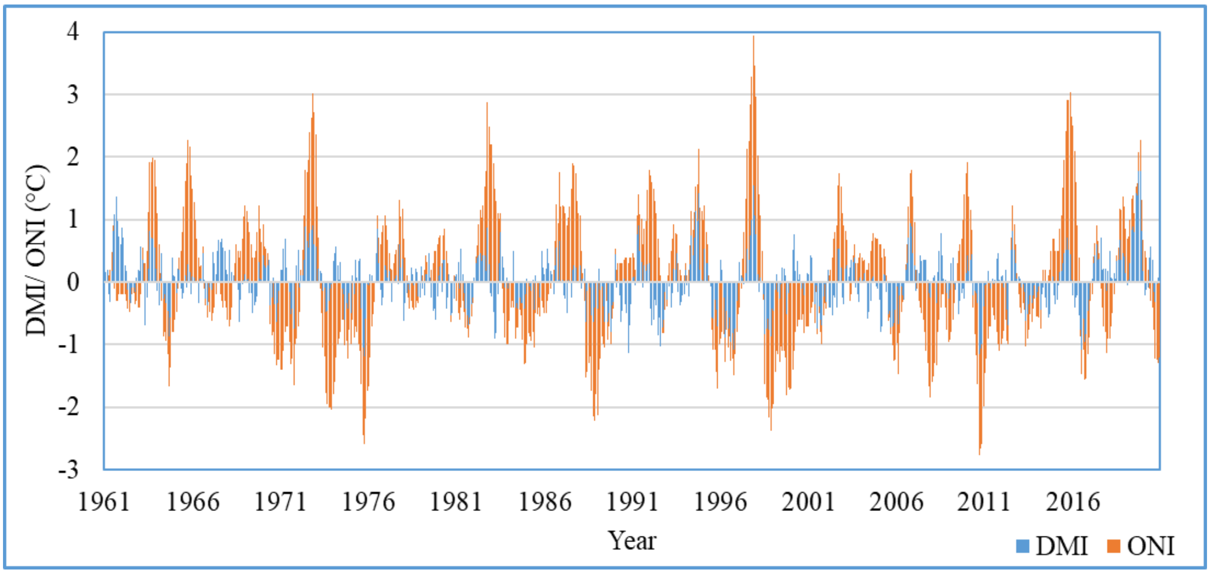

Figure 4.12 Analysis of DMI and ONI Trends (1961-2020).

Source: ERSST.V5 (B. Huang et al., 2017); Climate Prediction Center, NCEP (Climate Prediction Center, 2023).

Figure 4.12 shows a comprehensive analysis of the indices from 1961 to 2020. The DMI, which measures the SST difference between the WTIO and the SETIO, provides insights into the phases of the IOD (Iskandar et al., 2022). These phases are classified based on the DMI magnitude: weak positive IOD (0.4 to 0.7), moderate positive IOD (0.7 to 1.0), strong positive IOD (greater than 1.0), weak negative IOD (-0.4 to -0.7), moderate negative IOD (-0.7 to -1.0), and strong negative IOD (less than -1.0) (Jiang et al., 2021). Similarly, the ONI assesses SST anomalies in the Niño 3.4 region of the central and eastern equatorial Pacific Ocean to define the phases of the ENSO (Lasut et al., 2021). ENSO phases are categorized as weak El Niño (0.5°C to 0.9°C), moderate El Niño (1.0°C to 1.4°C), strong El Niño (1.5°C to 1.9°C), very strong El Niño (2.0°C or higher), weak La Niña (-0.5°C to -0.9°C), moderate La Niña (-1.0°C to -1.4°C), strong La Niña (-1.5°C to -1.9°C), and very strong La Niña (-2.0°C or lower) (Glantz & Ramirez, 2020). These climatic phenomena influence global climate variability, impacting temperature and rainfall patterns. For IOD events, the positive phase was recorded with weak intensity during the studied period in 1982, 1983, and 2012, while strong intensity was observed in 1963, 1967, 1972, 1997, 2006, and 2015. In contrast, the negative phase of the IOD featured weak intensity in 1964, 1974, 1982, and 1989, with strong events occurring in 1990, 1992, 1996, 1998, 2010, and 2016. Meanwhile, ENSO events revealed substantial variability in intensity, particularly in the El Niño phase. Weak El Niño events were recorded in 1968, 1969, and 1980, while moderate intensities in 1963, 1966, and 1987. Strong El Niño occurrences were recorded in 1965 and 1972, with very strong events occurring in 1982, 1998, and 2016. In contrast, the negative phase, La Niña, exhibited weak events recorded in 1984, 1995, and 1998. Moderate La Niña events were recorded in 1964, 1974, and 2020, while strong events occurred in 1975 and 1988, culminating in a more intense event in 2010.

Understanding the complex relationships between global climate phenomena and regional variability is essential for developing effective climate adaptation and mitigation strategies for India and Gujarat. Additionally, this analysis highlights significant concerns regarding the combined effects of IOD and ENSO events on weather patterns (Hrudya et al., 2021). For example, the concurrent occurrence of negative IOD and La Niña in 1964, 1974, 1989, 1998, and 2010 resulted in enhanced cooling effects in the equatorial Pacific Ocean and reduced rainfall over the western Indian Ocean (Z. Huang et al., 2022). This often led to drought conditions in eastern Africa and increased rainfall in Australia and Indonesia (Hong et al., 2010). The rare combination of negative IOD and El Niño in 2016 moderated the warming effects of El Niño with the cooling influence of negative IOD, assembling complex weather patterns that pose challenges to SWMR predictability (L. Zhang et al., 2021). Meanwhile, the concurrent positive IOD and El Niño phases raise further concerns for SWMR. This event leads to below-average rainfall across the subcontinent, with impacts that depend on the intensity of the events (Behera & Ratnam, 2018). The warming of the Pacific Ocean during El Niño weakens the Indian SWM circulation, further suppressing rainfall, while the positive phase of the IOD exacerbates this impact, resulting in additional reductions in rainfall (Sreekala et al., 2018). Identifying and addressing these events is crucial for effectively managing climate-related challenges, highlighting the necessity for robust adaptation and mitigation strategies.

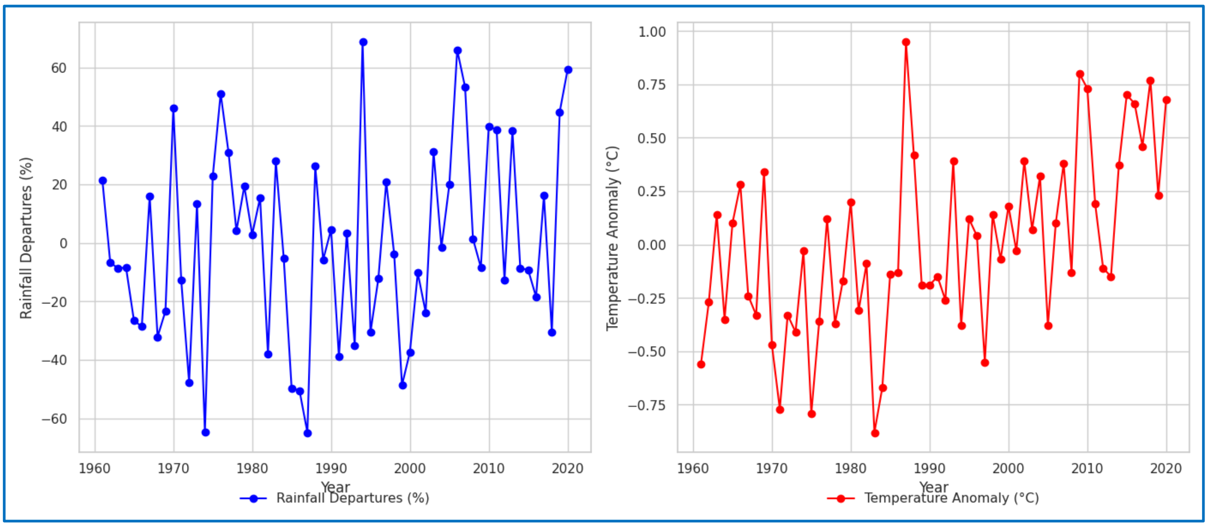

Figure 4.13 Annual Variability of Rainfall Departures (%) and Temperature Anomalies (°C) from Normal Levels in Gujarat (1961–2020)

Figure 4.13 shows the deviations in rainfall and temperature from normal levels, highlighting the substantial differences observed during the studied period and providing critical insights into regional climate patterns and anomalies. When considering the concurrent phases of the IOD and ENSO, distinct trends emerge. During years characterized by a negative IOD and La Niña, Gujarat experienced varying degrees of deviation from its usual rainfall patterns. In 1964, the departure from normal rainfall was recorded at -8.43%, indicating drier conditions than usual. However, the situation was significantly more severe in 1974, with a departure of -64.66%, marking a drought year. In 1989, the departure was relatively less extreme at -5.80%, and in 1998, it was -3.71%, indicating slightly below-normal conditions. However, 2010 exhibited a departure of 39.89%, indicating wetter conditions than usual. These fluctuations highlight the significant variability in rainfall patterns experienced in Gujarat. In contrast, during years of a negative IOD and El Niño, the region tends to experience drier conditions, as evidenced by a departure of -18.47% in 2016. Meanwhile, during years characterized by a positive IOD and El Niño, the state experienced significant variability in rainfall levels, showing the complex relationship between these climatic phenomena and regional weather patterns. In 1963, the departure from normal rainfall was recorded at -8.68%, exhibiting slightly drier conditions than the region's usual levels. The year 1972 witnessed a substantial reduction in rainfall, with a departure of -47.64%, marking a period of severe drought. Similarly, 1982 experienced a departure of -38.08%. In contrast, 1994, 1997, and 2006 experienced an increase in rainfall, with a departure of 68.84%, 20.84%, and 65.97% above normal. However, 2015 recorded slightly drier conditions, with a departure of -9.26%. These variations highlight the diverse impacts that concurrent positive IOD and El Niño years can exert on regional rainfall patterns, ranging from severe droughts to substantial increases in rainfall. Similar to rainfall, temperature exhibits substantial deviations from normal levels, particularly during El Niño years. In 1987, a moderate El Niño year, the region experienced a reduction in rainfall alongside increased temperatures. Additionally, from 2011 to 2020, average temperatures exceeded normal levels by more than 0.5ºC, indicating an increase in temperature anomalies compared to historical averages. This analysis highlights the variability in the region's rainfall and temperature patterns, influenced by different phases of the IOD and ENSO. The variability highlights the complex relations between these climatic phenomena and the broader impacts of global climate dynamics on local weather patterns, emphasizing the need for further studies across different regions in Gujarat to detailed understand these localized climate impacts.

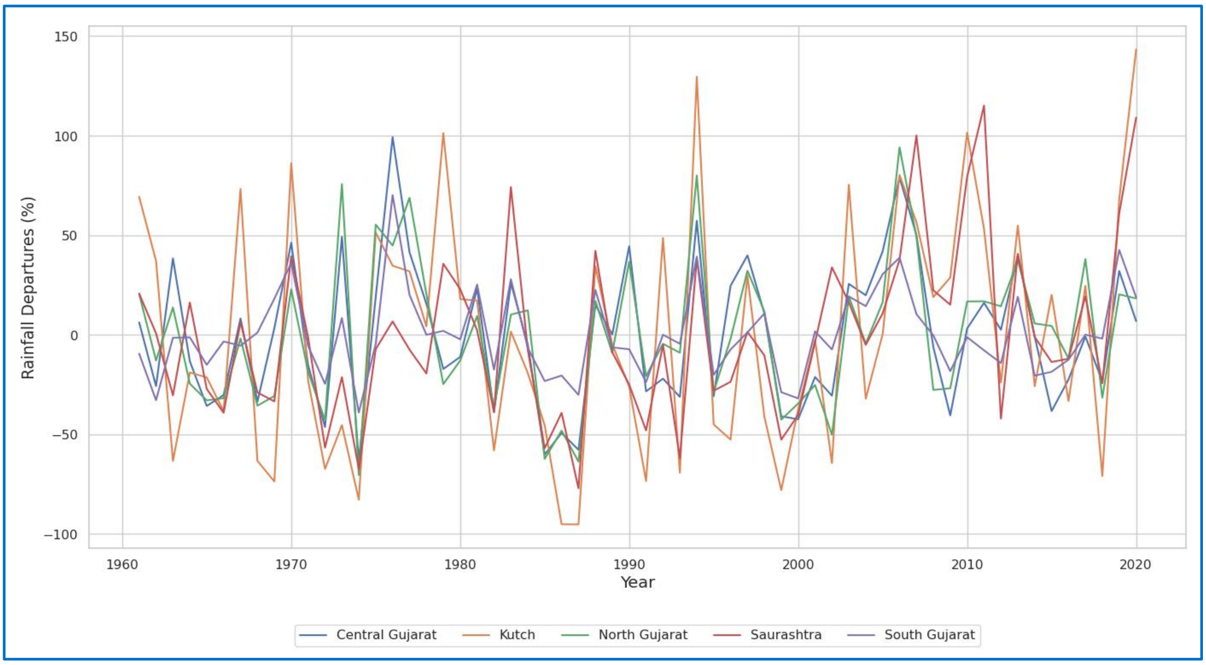

Figure 4.14 Annual Rainfall Departure (%) from Normal Levels Across Gujarat's Physiographic Regions (1961–2020).

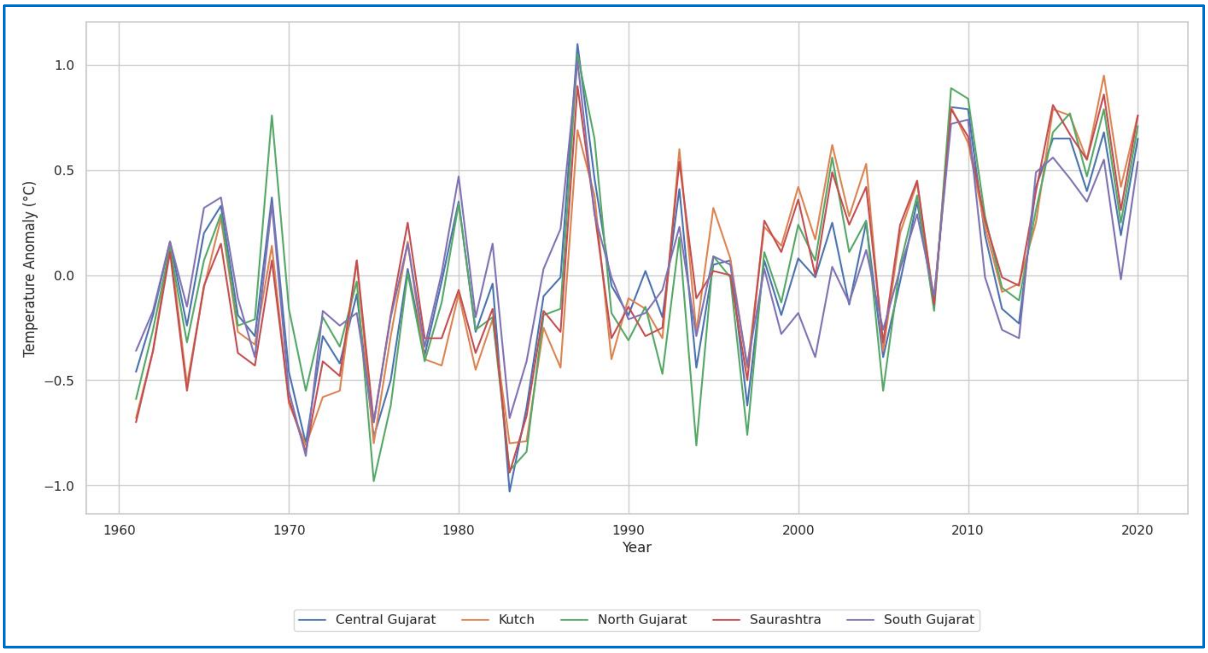

Figure 4.15 Annual Temperature Anomaly (ºC) from Normal Levels Across Gujarat's Physiographic Regions (1961–2020).

Analyzing rainfall and temperature departures from normal levels across Gujarat's regions reveals substantial variability during concurrent events, particularly during Negative IOD and La Niña years. Central Gujarat witnessed a rainfall reduction of 13.3% in 1964 and -63.3% in 1974, followed by a slight increase of 10.7% in 1998. North Gujarat experienced significant variations, with departures of -24.6% and -70.5% in 1964 and 1974 and increases of 11.7% and 16.7% in 1998 and 2010, respectively. Kutch showed extreme variations, ranging from a deficit of 82.9% in 1974 to a surplus of 101.5% in 2010. Saurashtra exhibited similar extremes, with -67.5% in 1974 and a surplus of 79.3% in 2010. South Gujarat's rainfall ranged from -1.3% in 1964 to -39.1% in 1974, with deviations of -6.4% in 1989 and an increase of 10.7% in 1998. Temperature deviations were most negative in 1974 across all regions, except in South Gujarat.

In 2016, during the concurrent occurrence of a Negative IOD and El Niño, Central Gujarat experienced a rainfall departure of -22.5% from the normal levels. Besides, Kutch, North Gujarat, Saurashtra, and South Gujarat experienced declines in rainfall, with departures of -33.4%, -11.9%, -12.0%, and -12.6%, respectively, reflecting significant deviations from normal rainfall patterns that could impact diverse sectors. Additionally, Gujarat's temperature increased by 0.66ºC above normal, with North Gujarat recording the highest deviation at 0.77ºC and South Gujarat the lowest at 0.46ºC. However, the concurrent occurrence of the Positive IOD with the El Niño phenomenon has yielded diverse impacts on climatic variables across Gujarat. In Central Gujarat, rainfall levels exhibited substantial fluctuations over the examined years. In 1963, the region experienced a surplus of 38.3%, indicating higher than usual rainfall. Conversely, 1972 and 1982 witnessed deficits of -46.4% and -39.0%, respectively. However, in 1994, 1997, and 2006, Central Gujarat recorded surpluses of 57.2%, 39.9%, and 79.1%, respectively, with a slight deficit of -0.9% observed in 2017. Meanwhile, Kutch experienced deficits in 1963, 1972, and 1982, with departures of -63.4%, -67.4%, and -58.1%, respectively. Contrasting patterns emerged in 1994 and 2006, when Kutch witnessed extreme surpluses of 129.6% and 80.3%, respectively. Similarly, North Gujarat observed rainfall deficits in 1972 and 1982, with departures of -42.9% and -36.9%, respectively, while 1994 and 2006 recorded surpluses of 80.0% and 94.2%. In Saurashtra, significant rainfall deficits were evident in 1963 and 1972, with departures of -30.5% and -56.8%, respectively. Conversely, the region experienced surpluses in 1994 and 2006, recording increases of 38.1% and 37.6%, respectively. South Gujarat also recorded deficits in 1963 and 1972, with departures of -1.5% and -24.7%, respectively, but observed substantial surpluses of 39.2% and 38.7% in 1994 and 2006. Temperature deviations during these concurrent events varied significantly. Severe negative departures occurred in 1972, with -0.58ºC in Kutch and -0.41ºC in Saurashtra, and in 1994, with -0.21ºC in North Gujarat. Conversely, increasing departures were observed in 2015, with 0.81ºC in Saurashtra, 0.79ºC in Kutch, and 0.68ºC in North Gujarat. These patterns highlight complex and varied impacts of climatic phenomena on Gujarat, affecting rainfall patterns and temperature deviations across distinct regions. Understanding these dynamics is crucial for mitigating risks and adapting to future climate challenges in the region.

The analysis also highlights the substantial impact of temperature variations, especially during moderate and strong El Niño events. In Gujarat, pre-monsoon temperatures have frequently deviated (±) from historical norms in recent decades, contributing to an increase in heat-related phenomena, mainly the frequency of days marked by heatwaves and severe heat conditions that tend to increase during the El Niño phase. In the recent decade (2011-2020), several years were influenced by El Niño, with intensity varying from weak to very strong. Specifically, the years 2014 and 2015 experienced weak El Niño effects, while 2018 and 2019 were characterized by moderate strength. While, 2016 was marked by a strong El Niño event. Throughout these years, there has been a significant increase in the frequency of heatwaves and the number of days with above-normal temperatures in Gujarat (Figure 4.35). In Central Gujarat, the average number of above normal temperature days has consistently increased in the recent decade to the long-term average of 26.38 days. During El Niño years, particularly in 2014, 2015, and 2016, the region experienced a substantial increase in the number of above-normal days, with 36, 42, and 29 days respectively. The region also experienced an increase in heat wave days, with 2015 and 2016 observing 7 days each, compared to the long-term average of 3.83 days. The frequency of severe heat wave days has also increased. Meanwhile, in Kutch, above normal temperature days during El Niño years such as 2015 (51 days) and 2018 (56 days) far exceeded the long-term average of 19.22 days, accompanied by an increase in heat wave days. Similar trends were observed in North Gujarat, Saurashtra, and South Gujarat, indicating a growing concern over increasing heat-related events during El Niño years.

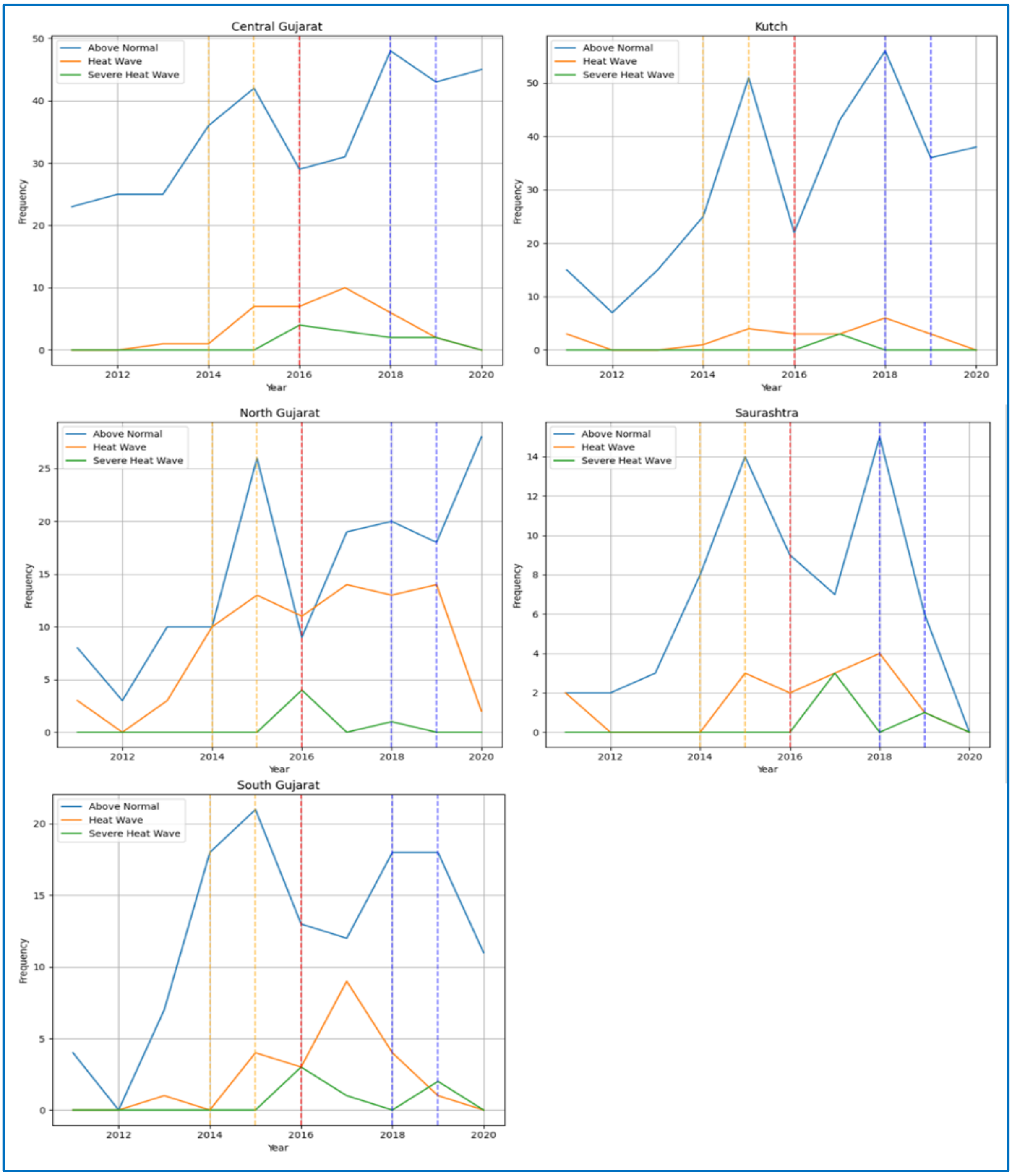

Figure 4.16 Impact of El Niño Phase Intensity on the Frequency of Extreme Heat Events in Gujarat (2011-2020)

Figure 4.16 exhibits a clear pattern of increasing extreme heat-related events in Gujarat, with significant peaks occurring during El Niño years, regardless of their intensity. The recent decade has witnessed an increase in heatwave and severe heatwave days, far exceeding long-term averages. This trend highlights the influence of El Niño phenomena on regional climate, highlighting the urgent need for adaptive measures to mitigate heat-related risks.

4.4 Conclusion

The analysis of rainfall and temperature patterns of Gujarat yields crucial insights. With nearly 96% of rainfall occurring during the SWM months, the region exhibits diverse rainfall distribution: South Gujarat receives the highest at approximately 1,410.76 mm, while Kutch experiences the least, at below 440 mm. July emerges as the peak rainfall month, followed by August. The number of rainy days varies across regions, with South Gujarat having the maximum and Kutch the minimum. A decadal analysis shows an increase in the frequency of rainy days, particularly in Kutch and Saurashtra, while a decreasing pattern was observed in South and Central Gujarat. Additionally, rainfall intensity classification indicates a high concentration of ‘Light’ to ‘Moderate’ rainfall days during the studied period. However, the frequency of RHTE (Rather Heavy to Extremely Heavy) rainfall events has been increasing in the recent decade across all regions. Following rainfall, extreme temperature events exhibit a distinct pattern characterized by an increase in extreme heat occurrences across the regions. In contrast, there has been a decline in cold extreme events in recent decades, which were once common till late 1990s. This shift emphasizes the substantial changes in temperature dynamics, highlighting the urgent need for adaptive measures to mitigate the impacts of increasing temperatures. Meanwhile, Gujarat generally experiences bimodal peaks for T_{max}, specifically in May and October. This pattern indicates that these months have the highest T_{max} of the year, with a substantial difference between them, resulting in two distinct periods of intense heat.

Regarding the SPCI, Kutch shows strong irregularity throughout the studied period, contrasting with South Gujarat's uniformity in rainfall distribution. However, recent decades have revealed increasing irregularities in North Gujarat, followed by Saurashtra, raising concerns about the implications of these shifting rainfall patterns. When considering the variability in regional rainfall and temperature levels, influenced by global phenomena, Kutch exhibits the most substantial deviation from normal rainfall, while South Gujarat shows the least variation. El Niño events usually result in reduced rainfall, whereas La Niña events lead to increased SWMR across Gujarat. However, when these events coincide with phases of the IOD, either negative or positive, their impacts become more pronounced, depending on the intensity of the phases, which can range from weak to strong. The findings highlight that during the negative phase of the IOD, Gujarat generally experiences reduced rainfall, even when occurring concurrently with La Niña events. This creates a complex climatic scenario where the expected benefits of La Niña, which typically brings increased SWMR, are undermined by the prevailing negative IOD conditions. Conversely, during the positive phase of the IOD, Gujarat tends to experience rainfall levels that exceed the long-term average, even in conjunction with weak and moderate intense El Niño events. This counter-intuitive relationship suggests that the positive IOD can enhance rainfall, effectively mitigating some of the drier impacts typically associated with El Niño. The influence of the positive IOD on rainfall patterns highlights the importance of considering multiple climatic factors and their interactions when assessing regional rainfall variability. However, when El Niño and La Niña occur with strong intensity, they substantially affect the SWMR across Gujarat, leading to decreased rainfall during El Niño years and increased rainfall during La Niña years. Additionally, the influence of El Niño has led to an increase in extreme heat events, particularly evident in recent decades. There has been a substantial rise in the number of heatwaves and severe heatwave days that far exceed long-term averages. This trend raises significant concerns about the potential impacts on public health, agriculture, and overall climate stability, as prolonged exposure to extreme temperatures can adversely affect human health and crop yields. These outcomes exhibit the impact of global climatic phenomena on regional climate patterns, showing how changes in SST in the Pacific and Indian Ocean can influence local weather systems.