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# DROUGHT AND HEATWAVES ASSESSMENT IN DISTRICT SWAT USING CMIP6 UNDER CLIMATE SCENARIOS

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**Abstract**
*This study observed the trends and forecasts the droughts and heatwaves of District Swat, Pakistan on the basis of observed data and 10 CMIP6 Global Climate Models (GCMs). Droughts were characterized in the form of Standardized Precipitation Index (SPI-12) and heatwaves using a threshold-based approach of 5, 7 and 10 days of consecutive occurrences, with moderate and severe heatwaves maximum temperature thresholds of 40 and 45 degrees Celsius, respectively. The SPI trend analysis showed non-significant decreasing tendency in observed data, with Kendall tau of -0.0306 and p value of 0.396, and so there is possibility of increase in the risk of drought. In the SSP2-4.5 scenario, the trend was not significantly increasing either, the tau value was 0.0256, and the p- value 0.225. In comparison, the SSP5-8.5 scenario depicted a steady rise, statistically significant at p<0.000 and a tau of 0.1848, indicating that the probability of a potential decrease in long-term drought severity in high-emission future is present. The SPI classification indicated that most drought values remained within the range of −2 to +2, representing conditions from moderately dry to moderately wet. In case of heatwaves, moderate events were only estimated to be more frequent under SSP5-8.5, especially in the far future, and 5-day heatwaves would be more numerous than 7-day or 10-day heatwaves. Observed, SSP2-4.5, and SSP5-8.5 datasets found no severe heatwaves, or consecutive days whose average temperature exceeds 45 degrees Celsius. These results emphasize the increasingly dangerous nature of heat-related extremes and drought variability in Swat, with the necessity of early warning programs, climate-resilient infrastructure, and adaptation planning to reduce the future climatic hazard particularly in this region.*

## Introduction:

Climate change is a severe problem that exposes the environment, economy, and society to extensive implications that threaten human health and sustainable growth. According to the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report, the average surface temperature of the Earth has already increased by up to 1.1 o C, above the pre-industrial value, and it is likely to increase by 1.5 o C to 5.4 o C at the end of the 21 st century, depending on the scenario of emissions [1], [2]. It is well known that this warming is mainly the effect of man produced greenhouse gases (GHGs) like carbon dioxide (CO 2 ), methane (CH 4 ), and nitrous oxide (N 2 O) which add to the natural greenhouse effect by confining heat in the atmosphere of the earth [3], [4]. Due to this, the world is currently experiencing serious changes in climate systems, such as the number of glaciers melting and rising sea-levels as well as a fluctuation in global precipitations [5], [6].

Another of the most worrying aspects of climate change is that it has led to more extreme weather occurrence and severity in the form of floods, heatwaves, and droughts [7]. The World Meteorological Organization (WMO) reaffirms that weather-related disasters have multiplied by fivefold during the last 50 years with some worst types of weather disasters being heatwaves and droughts [8]. The effects are quite serious in low- and medium-income nations where climate resilience and adaptation infrastructure is low [9]. During 2020 alone floods devastated more than 33 million people around the world, whereas long hot spells resulted in the death of thousands of people due to heat [10]. Since 2008, there have been about 265 million displaced persons caused by natural disasters with loss of their homes in the world, of which more than 26 percent of such displacements occurred in South Asia [11].

Pakistan has been also listed in top ten countries which are the most vulnerable to climate change ranked at number 5 in the Global Climatic Risk Index 2021 by Germanwatch [12]. Due to its varied geography (in coastal lowlands and in glaciated plateau mountains), the country is especially prone to all forms of climate extremities [13]. The Pakistan Meteorological Department (PMD) documented that there were over 150 intense weather incidents across Pakistan since 1998, with 14 major flood outbursts and some major drought instances [14].The 2010 floods displaced 20 million citizens; it washed out 1.6 million houses, and cost the monetary economy considerably greater than 10 billion [15]. Up against this, the worst 50-year drought between 1998 and 2002 caused massive water crises, crop failures and food insecurity, particularly in Balochistan and Sindh [16].

Pakistan has extremely diverse climatic zones. The cool temperature, high precipitation, and glacial systems that are important to the Indus River Basin characterize the northern regions that also include Gilgit-Baltistan, Azad Jammu and Kashmir, and a portion of Khyber Pakhtunkhwa [17].Central Punjab and upper Sindh record moderate climatic conditions; both also record moderate rains and temperatures, and hence these regions are very productive in An agriculture ticklish to climatic changes [18]. On the contrary, the southern parts of Sindh and Balochistan are hot and dry, which are regularly attacked by severe water shortages and periodic droughts [19]. The report also indicated that the Asian Development Bank (ADB) puts the arid or very arid land at more than 80 per cent of the total land mass of Pakistan, which is also at the risk of being affected by long dry periods [20].Heat stress has also become a threat to once-temperate areas, due to increasing temperatures, as it welcomes Pakistan to humanitarian disasters that are climate-induced [21].

The Swat District is a glacially fed mountainous area situated in the upper Swat Valley of the Khyber Pakhtunkhwa province of Pakistan that makes a significant contribution to the hydrology of the north Pakistan. Characterized by moderate climate and high biodiversity levels, Swat is shown to have experienced dramatic changes with regards to variations in climates over the past few decades [22]. This was a devastating flood of 2010 which killed 86 people, killed almost 9,800 livestock and destroyed more than 40,000 houses in the district alone [15]. Besides floods, there is growing dangers of temperature increase and declining snow cover that are re-defining the seasonal water access and crop production in Swat [23]. As the research done by Khan et al., during the last three decades, the average temperature in Swat increased by 0.9 o C, and there has been a significant reduction in winter snowfall and a trend of early snowmelting [24].

The rising dynamics of climatic changes have caused droughts and heatwaves to become major threats to rural and urban populations in Pakistan. Droughts can be characterized as long-term lack of rain, which leads to the decline in soil moisture, crop failures, and a lack of water supply [25]. Conversely, heatwaves refer to extended periods of unseasonal elevated temperatures of the weather system, which in many cases are above the highest temperatures recorded at the place before the advent of a heatwave increasing energy consumption and the death rates [26]. One sobering reminder of the exposure that Pakistan has faced to building heat extremes is the 2015 heatwave in Karachi, which claimed the lives of more than 1200 people in a matter of days [27]. Thar has always been affected by droughts; some of the recent droughts witnessed in Tharparkar and Balochistan put the food and livelihood of thousands of families in jeopardy annually [28].

The frequency and intensity of droughts and heatwaves in Pakistan are projected to rise sharply in the future, as supported by recent climate projections by the Shared Socioeconomic Pathways 2-4.5 and SSP5-8.5 [29]. Such extreme episodes are no longer restricted only to historically hit zones-regions such as Swat are also hit by changing monsoon patterns, increasing temperatures and various declining reserves in glaciers [30]. The spatio-temporal pattern of these extremes in climate is important to formulate effective climate response measures, water resource management, and climate smart agriculture in both Swat Valley and beyond.

District Swat is becoming susceptible to climate extremes like droughts and heatwaves. Localized studies evaluating these events in future climates are limited.. In order to address this gap and foster effective climate adaptation and risk management, this study uses SPI-12 and threshold-based techniques to analyze drought and heatwave patterns in Swat, using CMIP6 projections under SSP2-4.5 and SSP5-8.5.

**Methodology:**

**Study Area:**

District Swat is a riverine valley in Khyber Pakhtunkhwa province, with an average annual precipitation of 700 to 800 mm. The climate of District Swat is marked by heavy rainfall from June to September in the summer and harsh cold weather from December to February in the winter. The average temperature in the summer and winter is between 20 and 30 degrees Celsius and 0 and 10 degrees Celsius, appropriately.

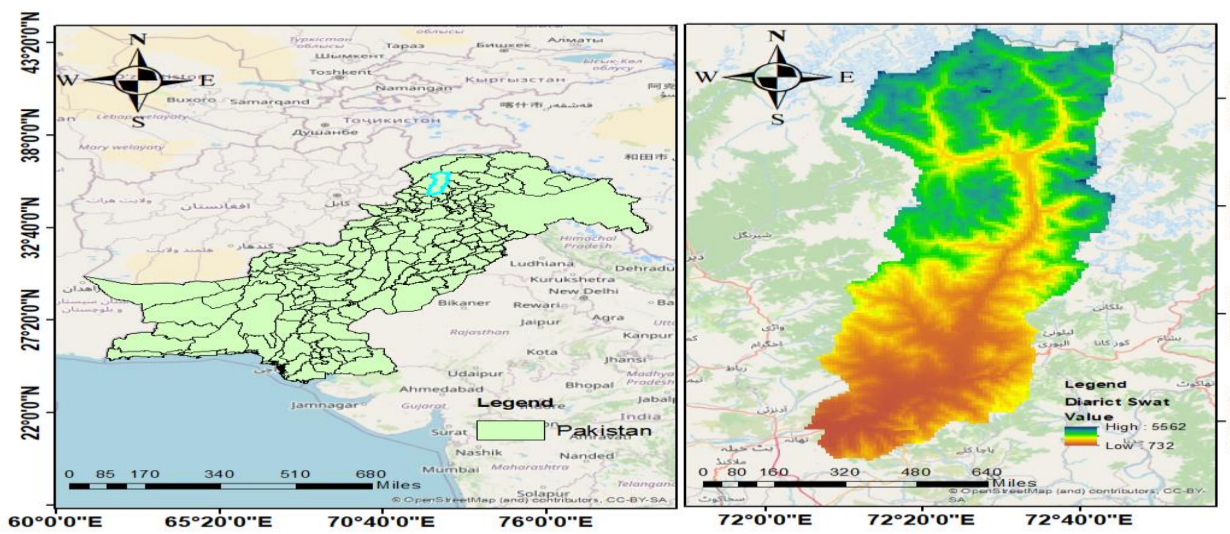
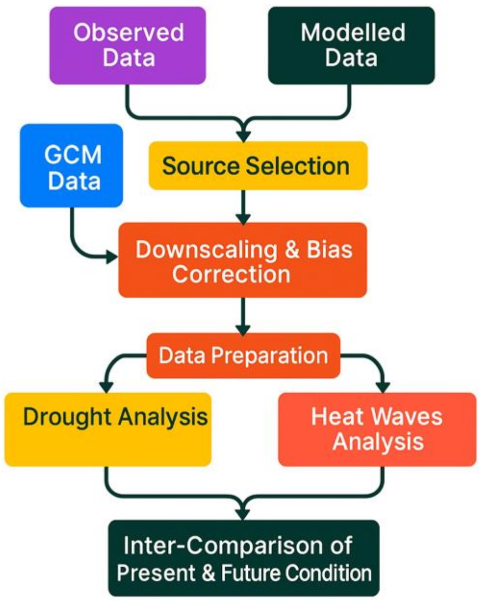



*Figure 1: Study Area*

**Data Collection:**
Pakistan is a data-scarce nation, as there is limited data availability. In this study, the data on precipitation and mean temperatures were collected at the Pakistan Meteorological Department (PMD). Further temperature data sets, such as daily maximum and minimum temperature were obtained through multiple global data sets: Climate Forecast System (CFS), Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS), Climate Prediction Center Unified Precipitation Project (CPC UPP), ERA5-L and data relevant to agricultural applications (ERA5 Ag), Modern-Era Retrospective Analysis for Research and Applications Version 2 (MERRA-2), Prediction of Worldwide Energy Resources (NASA POWER), and the PERSIANN-C Maximum and minimum temperature and daily precipitation data were obtained from 10 General Circulation Models (GCMs) was also used. These models are INM-CM4-8 and INM-CM5-0 (Russia), NESM3 (China), EC-Earth3-Veg-LR (Europe), GFDL-ESM4 (USA), CMCC-ESM2 (Italy), CNRM-CM6-1 and CNRM-ESM2-1 (France), MIROC6 and MRI-ESM2-0 (Japan). The result of GCM was sourced within two shared socioeconomic pathways (SSPs) of the coupled mode of comparison of project sixth, SSP2-4.5 and SSP5-8.5(CMIP6), which provide a moderate and extreme level of greenhouse emission scenarios, respectively, on the CMIP6 online repository.




**Flow Chart 1: Methodology**

**Data pre-treatment:**
Pakistan is a data-poor nation where access to data is a major problem. The Pakistan Meteorological Department provided the observed precipitation and mean temperature. Data about the highest and lowest temperatures have been collected from the internet. The XGBoost approach was used to provide the best possible online data source for temperature and precipitation. Likewise, the XGBoost technique was used to emphasize the most essential GCMs.

**Drought index:**
The Standardized Precipitation Index (SPI) is a drought index that captures how observed precipitation deviates from the climatological

average over a given time period. The SPI quantifies the precipitation deficit or surplus over different time scales. It is particularly useful for understanding and monitoring drought conditions across various climatic regions. The SPI is computed as:

$$SPI = x - \frac{\mu}{\sigma}$$

Where $x$ is the observed precipitation total for a given time-period (e.g., monthly, seasonal), $\mu$ is the long-term mean precipitation for the same time-period, and $\sigma$ is the standard deviation of the long-term precipitation distribution.

In this study SPI–12 was computed. SPI-12 looks at long-range precipitation, useful for determining hydrologic conditions, including groundwater levels, reservoir storage and longer term crop impacts. This longer-term look provides for the sense of drought that prolonged over a year, affecting water supply systems and the general environmental condition[31]. It is used for management of water resources, hydrology, and the analysis of long term drought effects on ecosystems and the water supply infrastructure.

**Drought classification:**

The SPI values used in characterizing the level of drought occur, starting with the perfectly wet (with SPI values of either 2.0 or more) to the very dry (with SPI values of less than -2.0). The values of SPI that fall between 1.5 and 1.99 are classed as very wet, whereas the values between 1.0 and 1.49 are termed as moderately wet. SPI ranging between -0.99 and +0.99 are indicators of near-normal situations. The moderately dry conditions are categorized as having SPI that range between -1.0 and -1.49 and the severely dry conditions have a range between -1.5 and -1.99. Such a classification presents a detailed scheme of evaluating the severity of drought lines applying SPI levels. Table 1 has the details of different classes*[32]*.

**Table 1: Classification of drought conditions as per SPI values**

| SPI Values | Classification |
|---|---|
| 2.0+ | Extremely Wet |
| 1.5 to 1.99 | Very Wet |
| 1.0 to 1.49 | Moderately Wet |
| -0.99 to 0.99 | Near Normal |
| -1.0 to -1.49 | Moderately Dry |
| -1.5 to -1.99 | Severely Dry |
| -2 and less | Extremely Dry |

**Heat waves assessment:**

Heatwaves were defined and characterized in this study in terms of a threshold-based approach to the daily maximum temperature results of 10 CMIP6 Global Climate Models (GCMs). Heatwaves were characterized by 5, 7 and 10 days of consecutive days when the highest temperature of the day was above some pre-determined values as associated with the South Asian weather. On the basis of climatic conditions of the region and the studies conducted earlier, heatwaves were split up into two groups, namely moderate heatwaves between 40 and 45 o C of heat, and severe heatwaves above 45 oC of heat [33]. This grouping is consistent with the current heat stress conditions in the different regions and the historical extreme events in Pakistan that occurred due to high temperatures, therefore, allowing us to identify dangerous temperatures in the past and simulated sources of datasets similarly.

In the study, the daily maximum temperature data of ten GCMs that were extracted in the two scenarios suggested in the Shared Socioeconomic Pathways, SSP2-4.5 (medium emissions) and SSP5-8.5 (high emissions), were analyzed. These scenarios reflect distinct pathways of greenhouse gas concentrations and socioeconomic development and enable the comparative comprehension of how the behavior of the heatwaves will change in future under the conditions of the climate. Bias correction of the chosen models was done in statistical downscaling with the observed temperatures to fit the region of interest in terms of spatial and temporal accuracy. This made the production of model outputs more realistic of local temperature dynamics needed to detect extreme heat events.

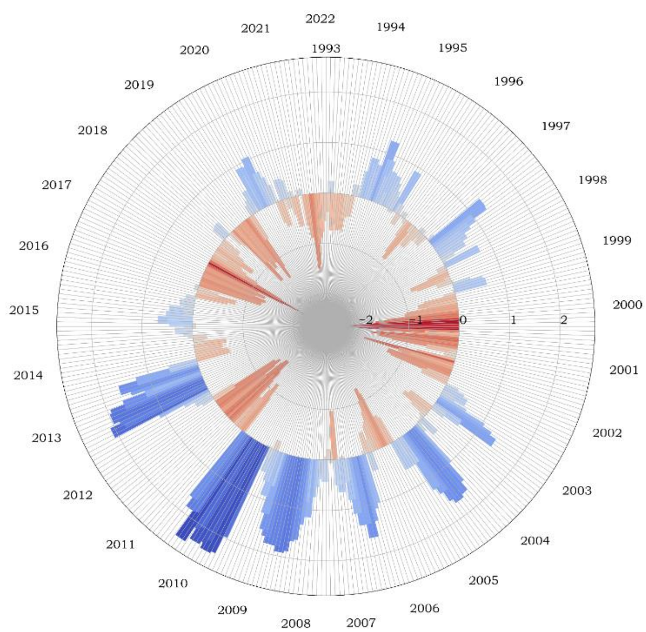
The heatwave events frequency and duration was then computed under each scenario and time period that enabled a vivid comparison between historical and future heatwave conditions. Such a method allowed quantifying the estimated alterations of the heatwave attributes expressed in terms of timing of their onset, strength, and duration. The findings of such analysis have important implications to the increasing threat of heatwaves in the context of climate change especially in sensitive regions such as Pakistan where work has been done to help adapt to these events. The approach is valuable to the future risk assessment of climate changes and adds to the preparation of the early warnings and heatwave mitigation plans in impacted regions [34], [35].

**Results and Discussion:**

**Drought assessment**

**Drought trend assessment:**

Drought causes the reduction in stream/river flows that in turn affects the soil moisture level, irrigation scheduling and ultimately growth and development. In this project SPI–12 was computed for historical and future conditions using two CMIP6 scenarios namely SSP245 and SSP585. The SPI–12 values for observed data vary between -3.6 and 3.6. Majority of the drought values are greater than -2 which falls in severely dry, moderately dry and near normal drought categories. For SSP245 and SSP585, majority of the drought values are greater than -2 which falls in severely dry, moderately dry and near normal drought categories as obvious from Figure 1



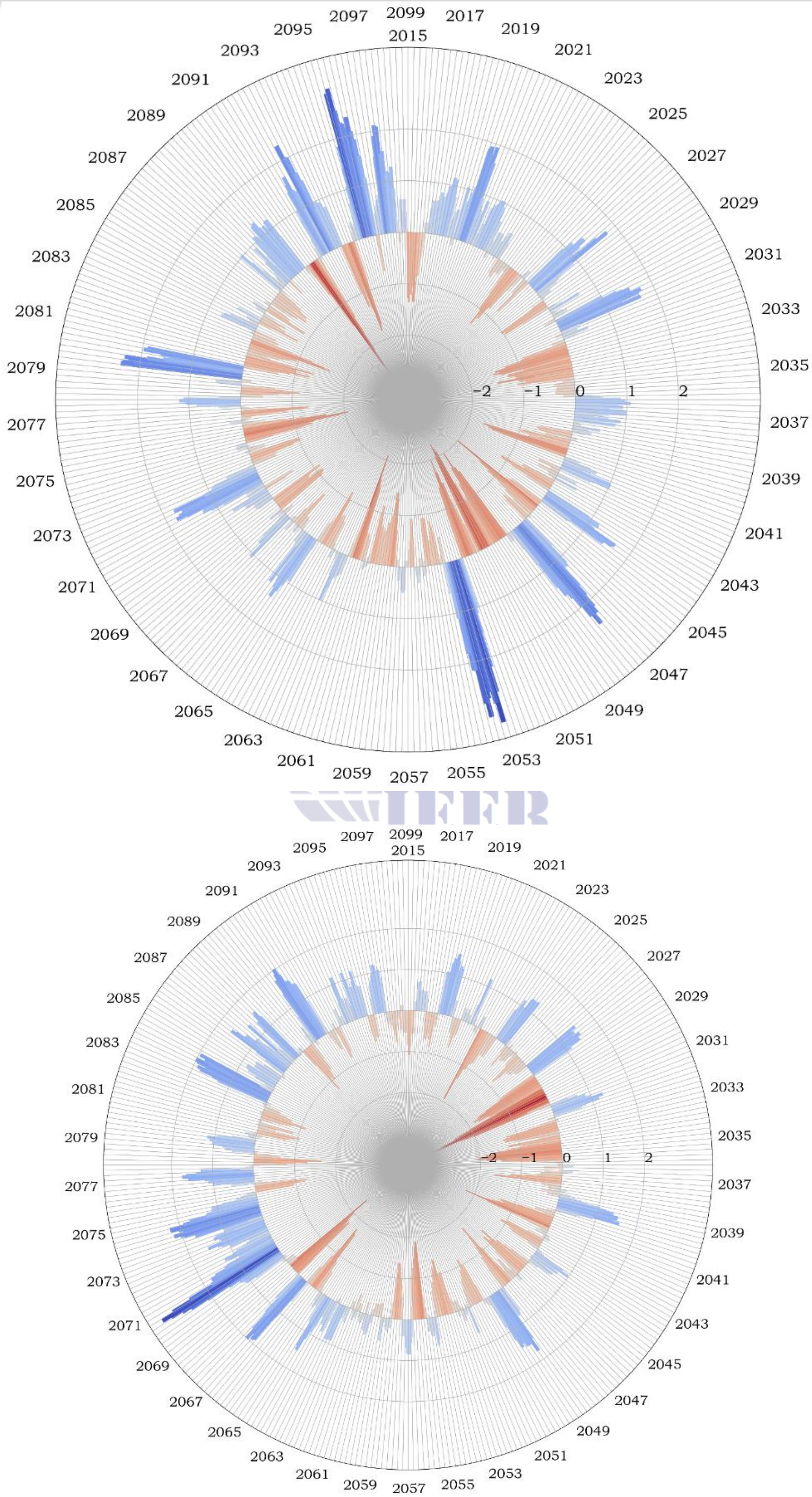



**Figure 2: SPI for (a) observed data, and future conditions under (b) SSP245 and (c) SSP585 scenarios**

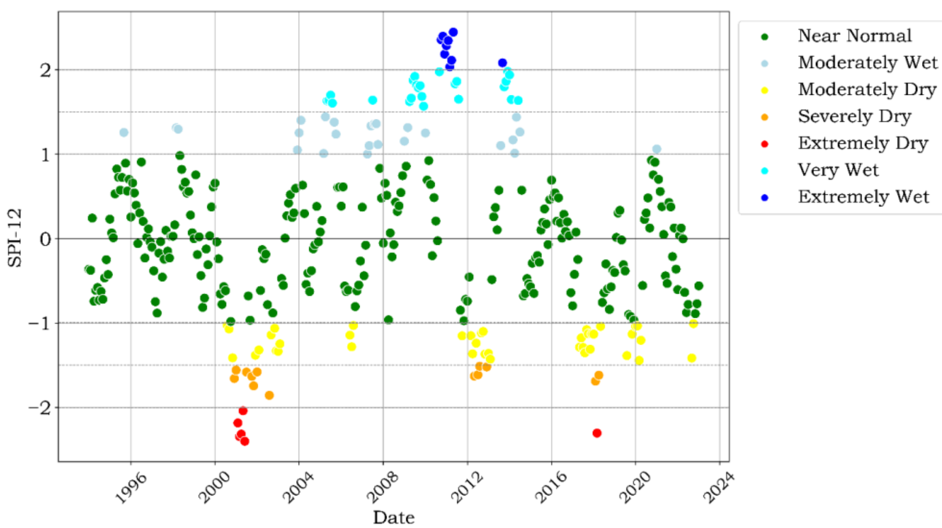
The SPI trend analysis shows varying behavior under the observed and SSP scenarios as obvious from Table 2. The observed SPI revealed statistically non-significant decreasing trend which indicates increasing drought condition. In contrast, statistically significant increasing trend was observed in SPI under SSP585 scenario which suggests potential reduction in drought over time. Non-significant statistically increasing trend was observed in SPI under SSP245 scenario.

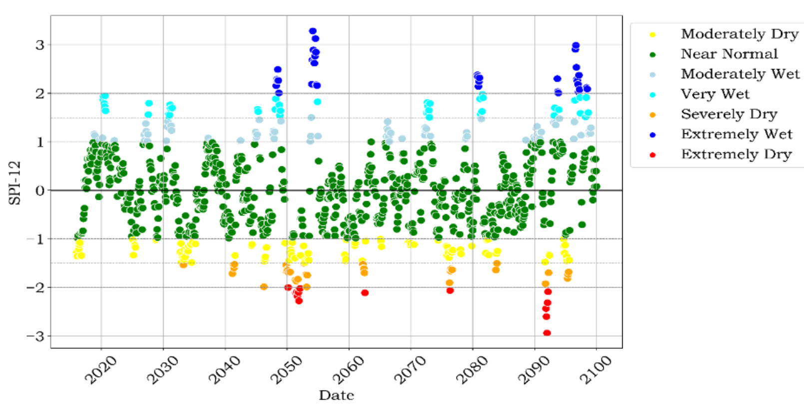
**Table 2: Trend analysis of SPI for Swat**

| Variable | Scenario | P value | Tau | Sen's slope | Trend |
|---|---|---|---|---|---|
| SPI | Observed | 0.395701418 | -0.030610706 | -0.000462073 | Not Significant |
| | SSP 245 | 0.224985679 | 0.025550181 | 0.000138167 | Not Significant |
| | SSP 585 | 0 | 0.184754162 | 0.000942909 | Significant Increasing |

**Drought classification:**

SPI is classified based on the Table 1. It is worth noting that the frequency of occurrence increases from extremely dry to near normal in observed and both SSPs scenarios as obvious from Figure 2. Moreover, the frequency of extremely dry class is negligible in comparison to severely and moderately dry class.



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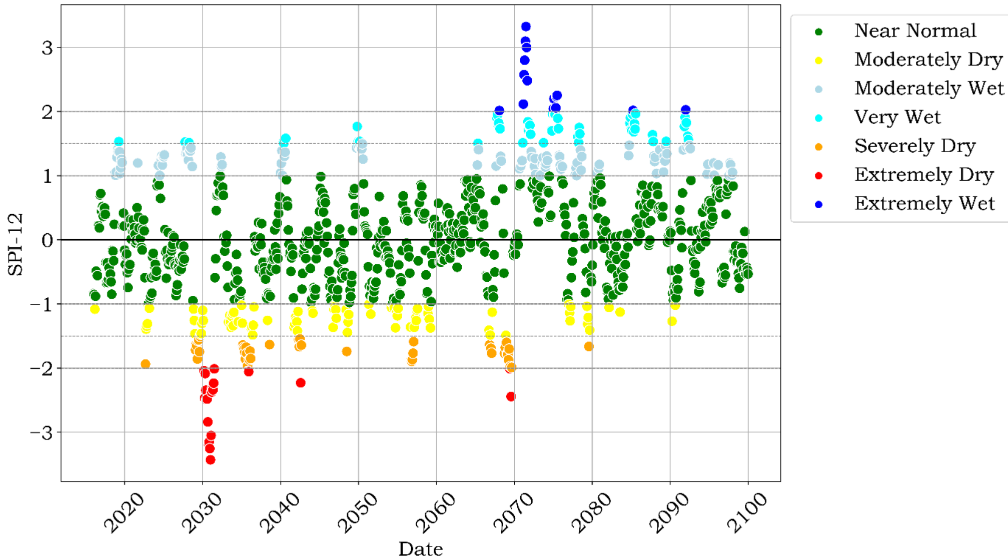


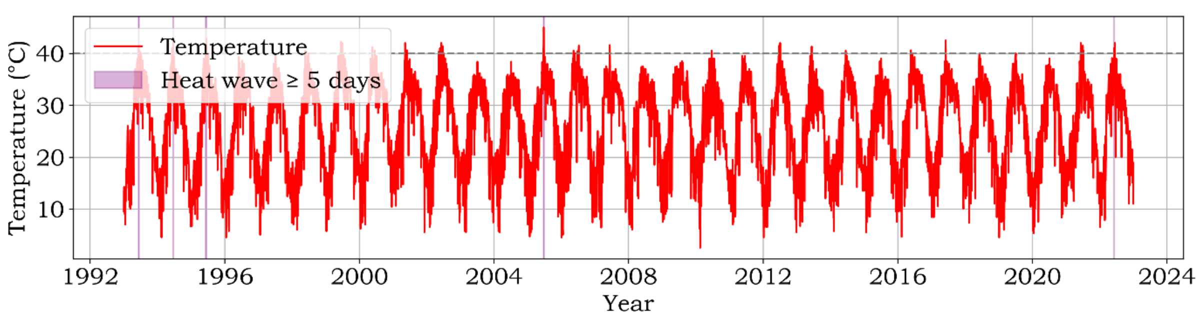

**Figure 3: Drought classification for (a) observed data, (b) SSP245 and (c) SSP585 scenarios**

**Heat waves:**

Heat waves result from climate extremes and are becoming more frequent and intense during summer across much of the world. They not only cause fatalities among living beings but also alter evapotranspiration rates and soil moisture levels, potentially leading to crop failure. Elevated temperatures are anticipated to increase the frequency of heat waves in the future. The duration of heat waves is crucial to their harmful effects, as it can disrupt the water cycle by enhancing convection, evapotranspiration, condensation, and precipitation rates.

In this project, heat waves for consecutive 5, 7 and 10 days were computed for observed and SSPs scenarios. Heat waves were categorized into two main classes namely moderate and severe based on temperature maximum threshold value of 40°C and 45°C respectively.

The observed record and SSP245 is free from moderate heatwaves while SSP585 contain moderate heat waves as obvious from Figure 3, Figure 4 and Figure 5. The intensity of moderate heat waves increases in far future under SSP585 scenario. The frequency of 5 days heat wave > 7 days heat wave > 10 days heat wave. In contrast, the observed record, SSP245 and SSP585 are free from severe heat waves as obvious from Figure 6, Figure 7 and Figure 8. These findings suggests that the residents of Swat district will face frequent moderate heat waves in future.



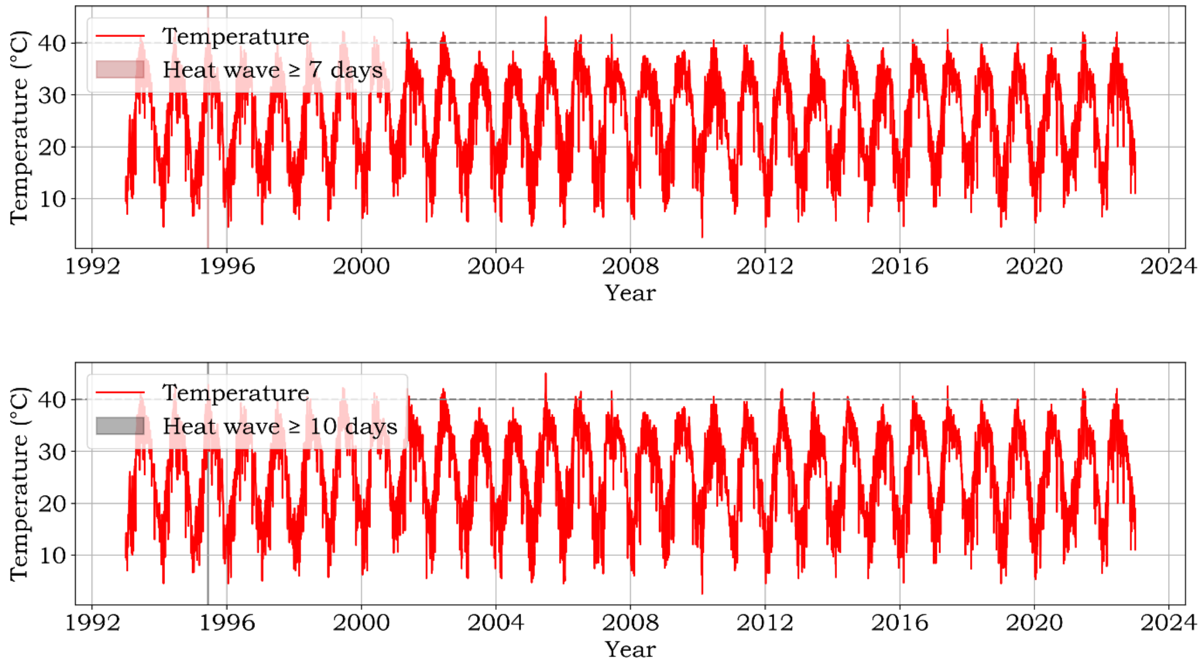
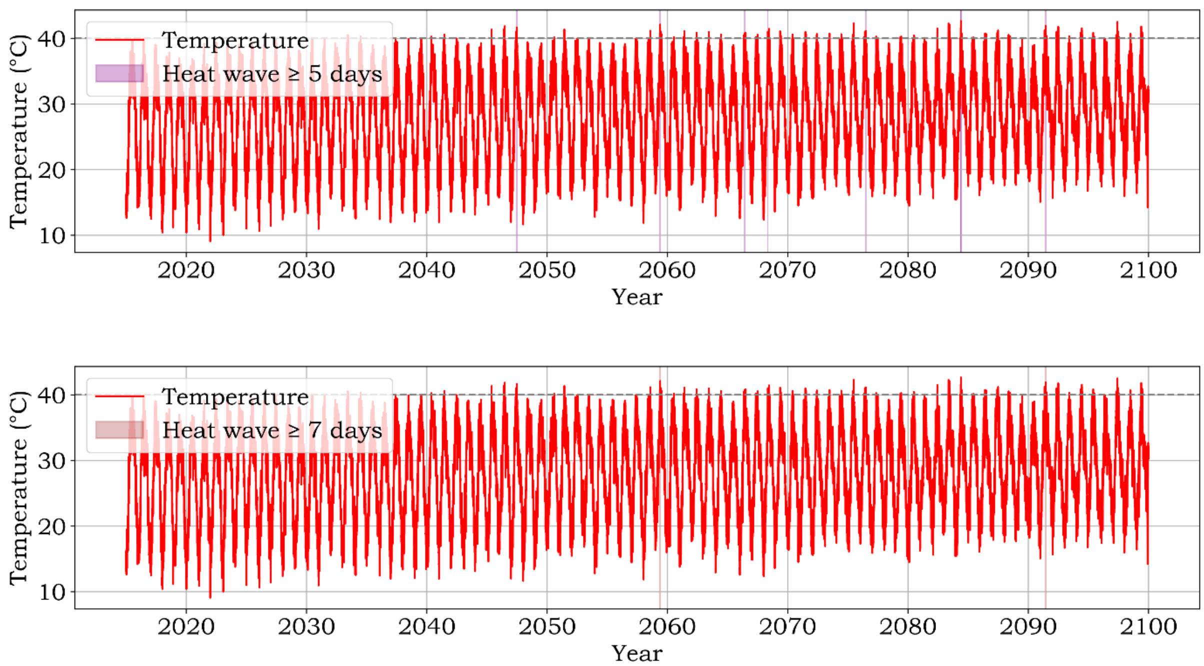



**Figure 4 : Moderate heat waves for 5, 7 and 10 consecutive days for observed data**



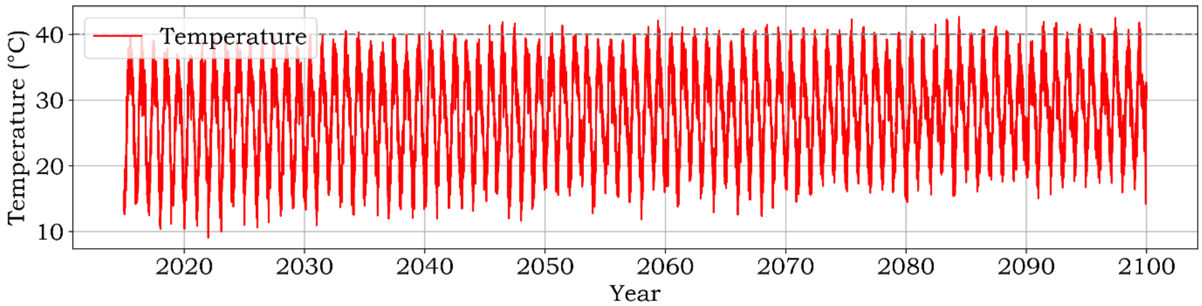



**Figure 5: Moderate heat waves for 5, 7 and 10 consecutive days under SSP245**

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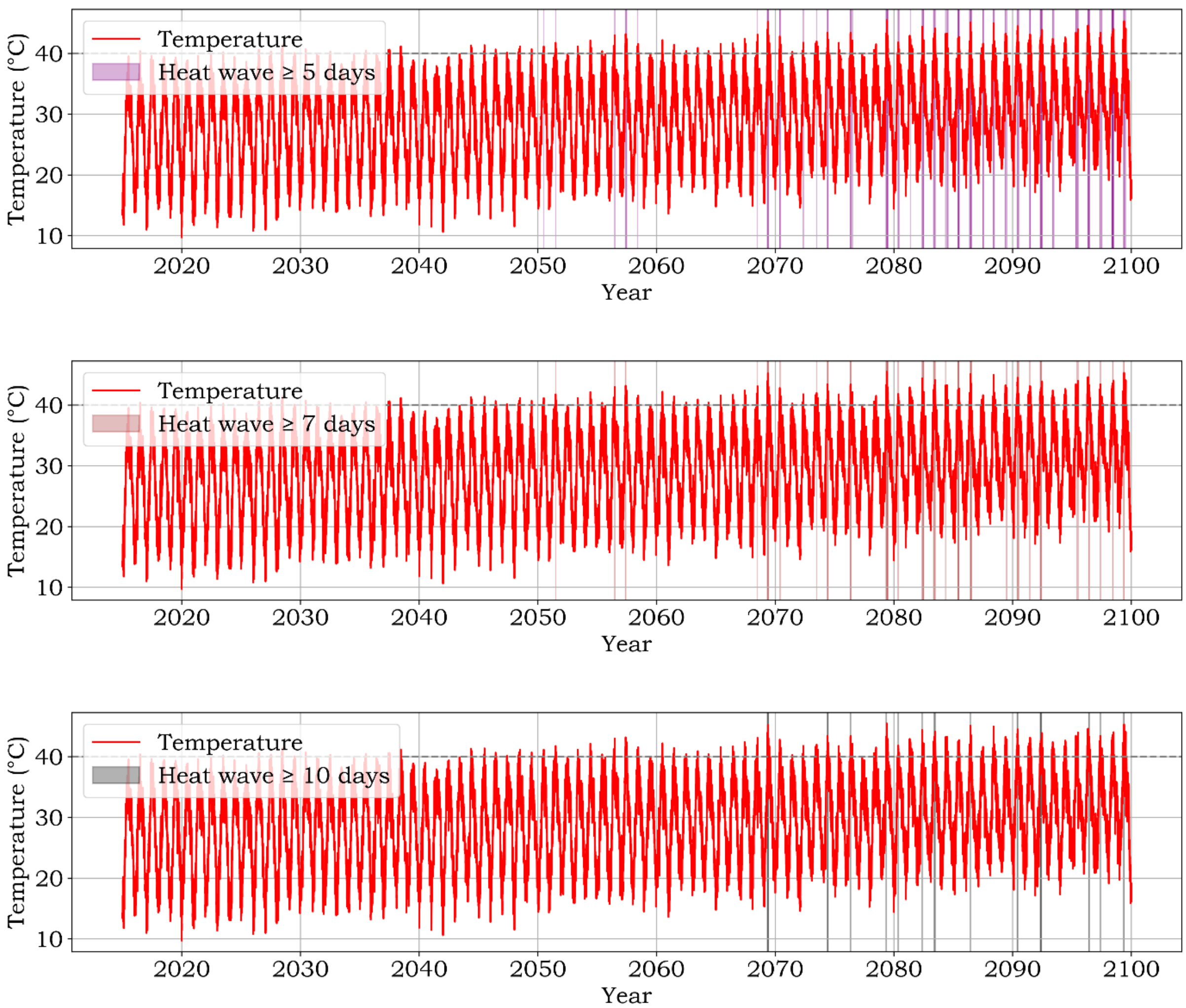



**Figure 6: Moderate heat waves for 5, 7 and 10 consecutive days under SSP585**

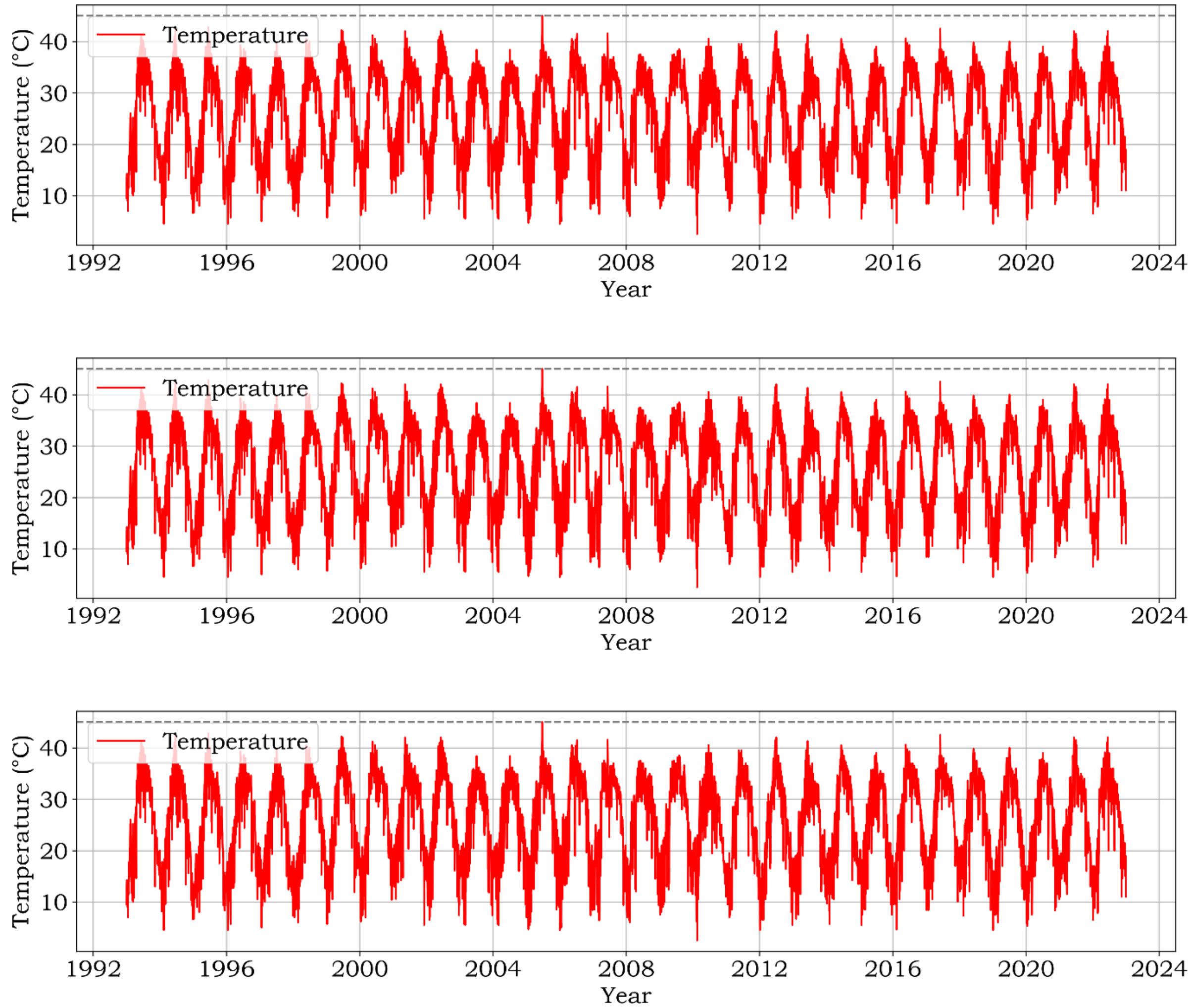
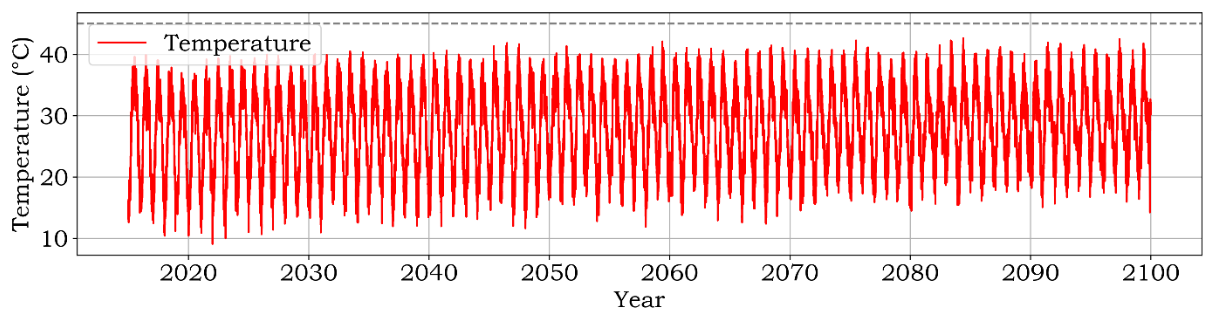



**Figure 7: Severe heat waves for 5, 7 and 10 consecutive days for observed data**



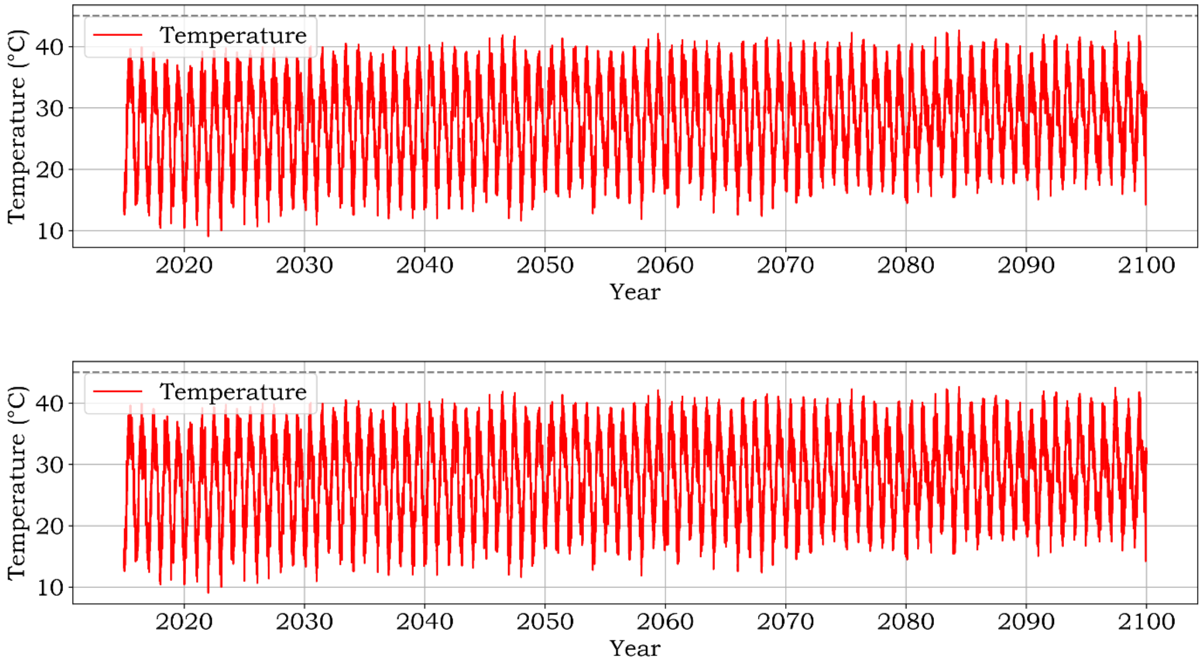
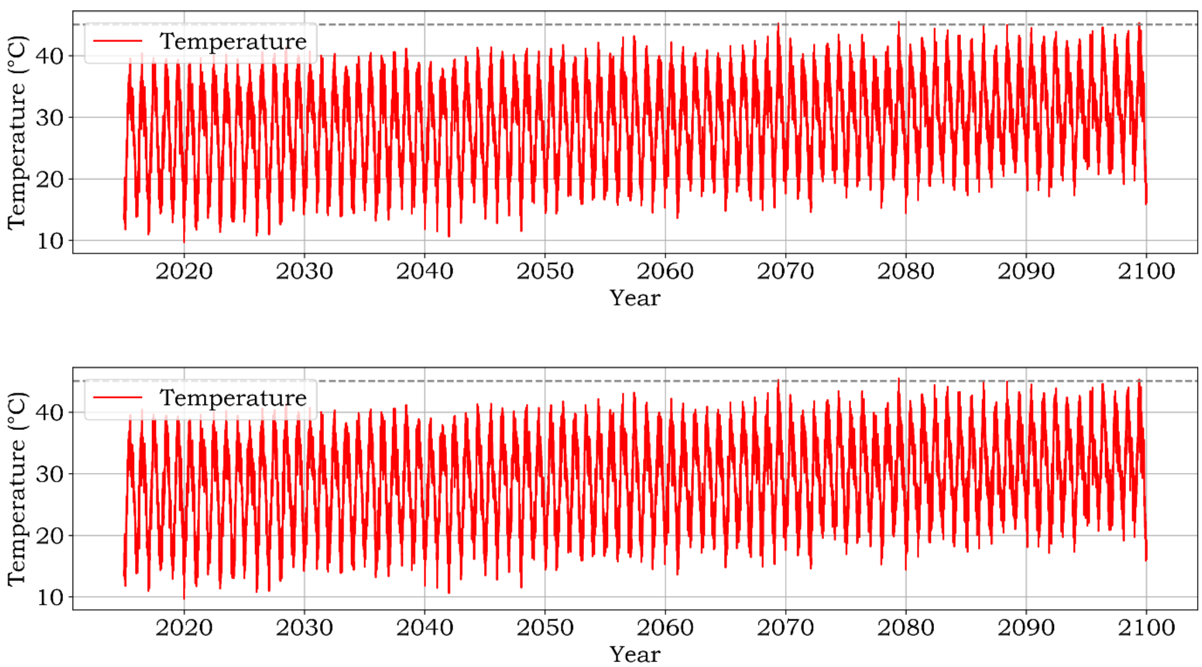



Figure 8: Severe heat waves for 5, 7 and 10 consecutive days under SSP245



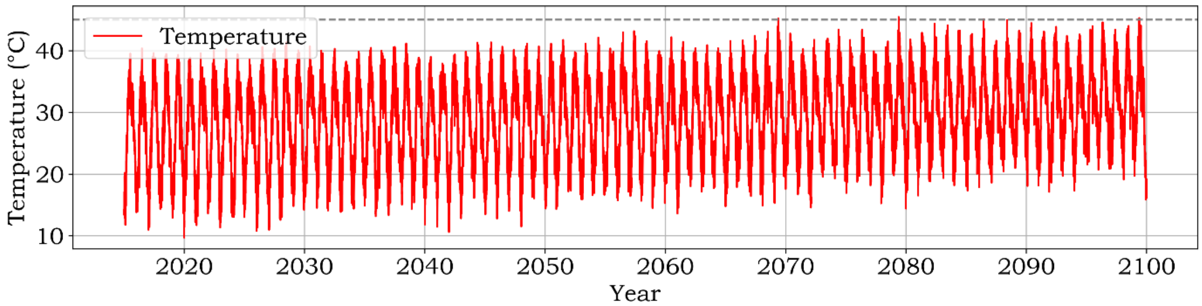



**Figure 9: Severe heat waves for 5, 7 and 10 consecutive days under SSP585**

**Discussion:**

The results of this study demonstrate a clear indication of the growth of climate extremes in District Swat a particular growth of occurrence and intensity of moderate heatwaves in the high-emission scenario SSP5-8.5. These findings are in line with other predictions that indicate that high-density agricultural zones of South Asia would encounter deadly heatwaves due to the rising global temperatures[36] . The lack of extreme heatwave events (temperature defined as a 45°C heatwave or larger at least) in the observed and modeled data aligns with previous studies that have shown that although heavily populated areas in general will experience an increase in the frequency of heatwaves, the occurrence of extreme heat events frequently hinges on elevation, urbanization and baseline climatology all factors that can mitigate experience of heatwaves in Swat [37]. Drought analysis based on the SPI-12 indicated that the observed data showed a non-significant decline on the one hand and a significant increase on the other hand with SSP5-8.5, pointing to a possible likelihood of enhancing long-term drought conditions. It is similar to the results that forecast comparable hydrologically positive long-term changes at high altitude under future conditions of emissions, despite short-term periods of dry weather [38]. Due to the continued presence of moderately and severely dry conditions across all scenarios, the lack of SPI seasonal values to reflect localized water stress, particularly in sensitive agricultural basins, is once again confirmed as previously may have been previously suggested[39]. The study also helps in reinforcing national level results, which showed that Pakistan is becoming prone to monsoon extremes and drought conditions [40], [41]. It indicates that even the comparatively more cold and rainy areas such as District Swat are showing up signs of climate stress operating under similar patterns as those seen in the drier areas of Tharparkar and Balochistan. Increase in 5-day heatwave events in line with the SSP5-8.5 fits the regional projections that in future South Asia will record more frequent, shorter but extreme warm events [42]. Collectively, the results point to a greater requirement of local adapted early warning systems, climate-resistant infrastructures, and flexible agriculture. The research will contribute to reducing the research gap on the impact of high-altitude regions such as Swat, which will contribute to region-specific adaptation planning, in line with global recommendations on climate resilience [43].



**Conclusion:**

This study investigate the distribution of Droughts and heatwaves in District Swat, Pakistan in both observed and future climates across ten CMIP6 GCMs and two Shared Socioeconomic Pathways (SSP2-4.5 and SSP5-8.5). The Standardized Precipitation Index (SPI-12) was applied to assess the changes in long-term drought trends and the threshold-based detection of heatwaves was carried out on 5, 7 and 10 consecutive days with maximum temperature thresholds of moderate (40 o C) and severe (45 o C) heatwaves. The integrated evaluation gives important projections into the changing hydro-climatic hazards in a region that was already prone to climatic extremes.The SPI evaluations demonstrated a pattern of variability in the drought's intensity.The observed SPI indicated an insignificant declining trend that indicated the increasing drought risk whereas SSP2-4.5 indicated an insignificant rising trend, and SSP5-8.5 showed an insignificant increasing trend. This implies that long-term drought conditions Swat may be potentially reduced in the case of high-emission scenario, but the number of moderate and severe dry conditions is still prominent in all scenarios. SPI classification also highlights that the majority of the values came on the near-normal, moderately dry spectrum with very limited cases of severe drought. The heatwave assessment indicated that future climate is expecting an increase in moderate heatwaves (≥40oC), especially in far future (SSP 5 -8.5), but not severe heatwaves (>45oC) during the observed and modeled times. Moderate heatwaves and extreme 5-day events are on the rise in frequency and severity, posing more threats to human health, water resources, and agriculture. Such results reveal the necessity of early warning systems, heatwave preparedness plans, and climate-resilient infrastructure in Swat and other mountainous areas in Pakistan. Overall this study improves the knowledge of regional climate risk and establishes the framework for reducing the negative consequences of climate change by giving stakeholders helpful data for disaster preparedness and adaptive planning.



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