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Spatiotemporal assessment of drought under historical and projected scenarios in the Himalayan region of Uttarakhand, India

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Abstract— Mountainous regions such as Uttarakhand, India, are highly vulnerable to climate change owing to their complex terrain and dependence on climate-sensitive agriculture. This study analyzes spatiotemporal variability of rainfall and agricultural droughts across Kumaon and Garhwal using historical records (1901–2022) and climate projections (2023–2100) under SSP2-4.5 and SSP5-8.5 moderate and high green-house gas emissions scenarios. Results reveal substantial intra-regional disparities: annual rainfall historically ranged from 1203 mm in rain-shadow zones (Almora, Tehri) to 1930 mm in Himalayan-facing districts (Pithoragarh, Chamoli). Projections suggest up to 20% rainfall increase in Pithoragarh and Chamoli, with little change in Almora and Tehri. Drought analysis shows late-season droughts in the historically dominant agricultural monsoon period Karif (spanning from June to October), particularly in Udham Singh (US) Nagar and Chamoli. Future projections indicate declining severe but more persistent moderate Kharif droughts (e.g., US Nagar 20.9%, Champawat 19%). Conversely, Rabi season (spanning from October to March) droughts are projected to intensify in high-altitude districts: Pithoragarh (20 years, ~11.5 weeks), Dehradun (16 years, ~13.5 weeks), threatening wheat and mustard yields with >40–50% losses. Late-season droughts also remain recurrent in Nainital (26 years) and Uttarkashi (27 years). Overall, Kumaon's vulnerability stems from persistent Kharif droughts, while Garhwal faces prolonged Rabi droughts (up to 14 weeks). These findings highlight the need for district- and season-specific adaptation strategies, focusing on climate-resilient crops and improved water management.

Key-words: agricultural drought, climate sensibility, historical data, projections

1. Introduction

Drought is a complex and multifaceted extreme weather event characterized by varying durations and severity levels, with far-reaching impacts on the environment, agriculture, economy, and society. The scientific understanding of drought—its origin, development, and eventual cessation—remains challenging due to its occurrence across all climatic zones in diverse forms, intensities, and time scales (*Mishra* and *Singh*, 2010). In India, droughts are known to cause substantial economic losses annually, significantly affecting GDP, with the extent of impact depending on the drought category (e.g., mild, moderate, or severe). Recent years have witnessed an upward trend in extreme climatic events, partly driven by anthropogenic activities. Land use changes, over-extraction of water resources, and other human interventions disrupt the hydrological cycle, contributing to the frequency and intensity of such events. The propagation of drought is influenced by a complex interplay of factors, including temperature, precipitation, evapotranspiration, humidity, climatic patterns, land use practices, and topography, making its prediction and comprehensive understanding difficult (*Wilhite* and *Glantz*, 1985). Drought is broadly categorized into four types: (1) *meteorological drought*, marked by prolonged periods of below-normal precipitation; (2) *agricultural drought*, characterized by insufficient soil moisture to support crop growth; (3) *hydrological drought*, indicated by reduced surface and subsurface water flows; and (4) *socio-economic drought*, which arises when water scarcity begins to affect human activities and the economy (*Das et al.*, 2022).

Ensuring food security in any region necessitates effective monitoring and prediction of natural disasters such as droughts, as they can significantly disrupt agricultural productivity (*CV et al.*, 2024). When meteorological drought advances into agricultural drought, it leads to reduced soil moisture and adversely impacts crop yields, potentially resulting in food shortages (*Hameed et al.*, 2020). As drought progresses from atmospheric conditions to the agricultural landscape, the competition for already limited water resources intensifies—particularly in developing nations, where agriculture is among the most vulnerable sectors. In India, drought poses a significant threat, increasing crop susceptibility to both biotic and abiotic stresses. This has made the country one of the most drought-prone regions globally. Studies estimate that drought affects approximately 68% of India’s agricultural land, with 33% of this area identified as “chronically drought-prone” (*Kaur et al.*, 2022; *Goel et al.*, 2025; *Goel* and *Singh*, 2025). Among the key drivers of soil moisture stress is a deficiency in precipitation, which underscores the importance of examining the transition from meteorological to agricultural drought (*Li et al.*, 2022).

The Shared Socioeconomic Pathways (SSPs) used in climate modeling to represent different future scenarios based on socioeconomic development and emission trends. SSP2-4.5, known as the "Middle of the Road" scenario, envisions a future with moderate challenges to mitigation and adaptation, featuring stable economic growth, moderate population increase, and gradual technological progress. It assumes moderately successful emission reductions, leading to a stabilization of radiative forcing at 4.5 W/m² by 2100 and a projected global temperature rise of 2.1–3.5°C above pre-industrial levels. In contrast, SSP5-8.5, or the "Fossil-fueled Development" scenario, anticipates rapid economic growth driven primarily by fossil fuels with minimal climate mitigation, resulting in extremely high emissions. This leads to a radiative forcing of 8.5 W/m² by 2100 and a potential temperature increase of 3.3–5.7°C, posing severe risks to the global climate system due to intensified warming and associated impacts.

Uttarakhand's climate is diverse, influenced by its varied topography, with the plains experiencing a subtropical climate with hot summers (up to 40°C) and mild winters (5–15°C) and heavy monsoon rains (1000–1500 mm annually). The middle Himalayas have a temperate climate with moderate summers (15–25°C), cold winters (0–10°C) and significant monsoon rainfall (1500–2000 mm), plus occasional snowfall. In the high Himalayas, the climate ranges from alpine to tundra, with cool summers (5–15°C), very cold winters (below -10°C) and moderate rainfall (500–1000 mm) with heavy snowfall. The monsoon season from June to September brings most of the annual rainfall, critical for agriculture, while higher altitudes receive substantial winter snowfall, crucial for glaciers. However, the region faces natural challenges like floods, landslides, cloudbursts, and avalanches, impacting agriculture and local livelihoods.

The purpose of this study is to analyze both historical (1901–2022) and future (2023–2100) drought scenarios to better understand the spatial and temporal dynamics of drought in the region. By using rainfall deviation, the study aims to assess meteorological drought and examine its transition into agricultural drought during both the Kharif and Rabi seasons. Future projections are evaluated under two shared socioeconomic pathways: SSP2-4.5, representing a moderate emission scenario, and SSP5-8.5, representing a high emission scenario to assess the potential impact of climate change on drought patterns. This comprehensive assessment is intended to support strategic planning for climate-resilient agriculture and effective drought risk management.

2. Materials and methods

2.1 Study area

Uttarakhand, in northern India, spans 53,483 km², situated between the 28°43' N to 31°27' N latitudes and 77°33' E to 81°02' E longitudes. It shares borders with Tibet (China) to the north, Nepal to the east, Uttar Pradesh to the south, and Himachal Pradesh to the west. As of the 2011 Census, its population was around 10 million, with recent estimates suggesting it has grown to approximately 11 million. The state is largely rural, with about 70% of the population living in rural areas and 30% in urban areas Key cities include Almora, Dehradun (the capital and most populous city), Haldwani, Haridwar, Mussoorie, and Nainital (see *Table 1*). Uttarakhand is divided into two regions: Garhwal and Kumaon, each with distinct cultural and geographic characteristics.

Table 1. Latitude, longitude, and elevation of districts in Kumaon and Garhwal regions of Uttarakhand

	Districts	Latitude	Longitude	Elevation
		Kumaon region		
1	Almora	29.59	79.65	1648.8
2	Bageshwar	29.84	79.77	972.9
3	Champawat	29.34	80.09	1653.5
4	Nainital	29.39	79.45	2084.0
5	Pithoragarh	29.58	80.22	1645.0
6	US Nagar	28.96	79.52	550.0
		Garhwal region		
1	Chamoli	30.46	79.87	1062.6
2	Dehradun	30.32	78.03	652.2
3	Haridwar	29.95	78.16	249.7
4	Pauri Garhwal	29.87	78.84	886.2
5	Rudraprayag	30.29	78.98	895.0
6	Tehri Garhwal	30.38	78.47	1750.0
7	Uttarkashi	30.73	78.44	1158.0

2.2. Global climate model selection

MIROC6 (Model for Interdisciplinary Research on Climate version 6) is a global climate model developed by the Atmosphere and Ocean Research Institute, University of Tokyo, the National Institute for Environmental Studies (NIES), and the Japan Agency for Marine-Earth Science and Technology (JAMSTEC). MIROC6 operates at a spatial resolution of approximately 1.4° latitude by 1.4° longitude. This coarse resolution means that each grid cell covers an area of about 155 kilometers by 155 kilometers near the equator. The resolution varies with latitude due to the Earth's curvature. The effective climate sensitivity (ECS) of MIROC6 is estimated to be 2.6 K (*Shiomaga et al.*, 2023). MIROC6 model had been selected for futuristic meteorological data analysis, because it performed best for the Indian conditions with correlation coefficient of 0.87 to 0.97 (*Jose et al.*, 2022; *Sardar et al.*, 2023).

2.3. Softwares used

2.3.1. Weather Cock

It is a software developed by the AICRPAM Unit of CRIDA, Hyderabad for agroclimatic analysis, thus, different agroclimatic analyses, converting daily rainfall data into weekly and annual data, as well as meteorological and agricultural drought analyses are possible using this software. This particular software is based on Visual Basic (VB) and easy to operate even for beginners. Doing agroclimatic analysis with MS Excel for individual stations is drudgery and may lead to wrong results. The weathercock software reduces this drudgery and eliminates any mistakes associated with MS-Excel. Moreover, batch processing a special provision in the weathercock to facilitate analysis for hundreds of stations at a moment if input files are prepared in the said format as doing agroclimatic analysis at localized scale have hundreds / thousands of stations (*Sikdar et al.*, 2020).

2.3.2. Spyder

All preprocessing and statistical downscaling of IMD historical (rainfall and maximum/minimum temperature) and MIROC6 (CMIP6) future climate scenarios under SSP2-4.5 and SSP5-8.5 were performed in Python (v3.11) using the Spyder IDE (v5.x, Anaconda distribution) on Windows 10/Ubuntu 22.04 with ≥16 GB RAM. Spyder's integrated workspace facilitated efficient handling of large NetCDF datasets, supported by scientific libraries such as xarray, netCDF4, dask, xclim, xesmf, scikit-learn, matplotlib, cartopy and others.

2.4. Climate data collection

2.4.1. Historical data

The historical climate data for India were obtained from the India Meteorological Department (IMD) Gridded Data Portal (https://www.imdpune.gov.in/), which provides quality-controlled, homogenized, and spatially interpolated datasets in NetCDF(.nc), Binary(.grd), and Text (.txt) formats for research and analysis. The portal offers daily gridded rainfall data at a spatial resolution of 0.25° × 0.25° covering the period 1901–2022. For this study, daily rainfall datasets corresponding to the study region (Uttarakhand) were extracted and processed for further analysis and downscaling.

2.4.2. Future data

The future climate projections, along with the corresponding historical simulations, were obtained from the Copernicus Climate Data Store (CDS) of the European Centre for Medium-Range Weather Forecasts (ECMWF), accessible at https://climate.copernicus.eu/. The CDS provides free, quality-controlled, and standardized climate datasets from multiple sources, including reanalysis products (e.g., ERA5), satellite observations, and climate model outputs from the Coupled Model Intercomparison Project Phase 6 (CMIP6) under various SSP scenarios. Users can access daily, monthly, and seasonal variables, such as precipitation, temperature, humidity, wind speed, and pressure, at different spatial resolutions and time periods, in NetCDF format.

For this study, daily precipitation data simulated by the MIROC6 global climate model at a horizontal resolution of 1.4° × 1.4° were downloaded for both the historical baseline period (1985–2014) and the projected future period (2015–2100) under SSP2-4.5 and SSP5-8.5 scenarios. The common observed and simulated data period (2015–2022) was used for calibration, and the performance was evaluated by calculating bias, Nash-Sutcliffe efficiency (NSE) and root mean square error (RMSE) for maximum temperature (Tmax), minimum temperature (Tmin), and rainfall. These datasets were used to evaluate the model skill in reproducing historical climate patterns over Uttarakhand and to assess projected changes for the future periods (2023–2100) in comparison with observed IMD gridded data.

2.5. Climate data conversion and analysis

The rainfall data, sourced from IMD (historical data spanning 1901-2022) and the Copernicus Climate Data Store (simulated data from 2015-2100), were converted from NetCDF (network common data form) files to CSV (comma separated values) format. These data were then downscaled using the Spyder software (a Python package) for the 13 districts of Uttarakhand. This process ensured the data was in a usable format for detailed analysis and application in regional climate studies.

MIROC6 model predict the meteorological data based on the shared socio-economic pathway (SSP) emission scenarios SSP2-4.5 and SSP5-8.5.

2.6. Calibration of the meteorological data

The accuracy of the bias-corrected monthly mean data for maximum and minimum temperatures, as well as average rainfall, across 13 districts, was assessed by comparing it with observed data from the period 2015-2022, which is consistent for both datasets. There are different measures used to verify and to have the agreement between observed and predicted value.

2.6.1. Bias

Bias indicates the average difference between the observed values and the calculated (modeled) values. It shows whether the model tends to overestimate (if the value is negative) or underestimate (if the value is positive) the observations. To obtain the average bias over a period:

$$Bias = 1/N \sum_{i=1}^{N} (Oi - Si),$$

where *N* is the number of observations, *Oi* is the observed value, and *Si* is the modeled value

2.6.2. Root mean square error (RMSE)

RMSE is the square root of the MSE. It provides a measure of the magnitude of the error, giving more weight to larger errors:

$$RMSE = \sqrt{1/N \sum_{i=1}^{N} (Oi - Si)^2}\,.$$

2.6.3. Nash-Sutcliffe efficiency (NSE)

The Nash-Sutcliffe efficiency is used to assess the predictive power of hydrological models, but it can be applied to other types of models as well. The NSE is defined as:

$$NSE = 1 - \frac{\sum_{i=1}^{N} (Oi - Si)^2}{\sum_{i=1}^{N} (Oi - \bar{O})^2}\,.$$

- $NSE = 1$ means perfect match between observed and predicted values,
- $0 < NSE < 1$ means acceptable model performance. The closer the NSE to 1, the better the model is,
- $NSE=0$ means that the model predictions are as accurate as the mean of the observed data, and
- $NSE<0$ means that he model is worse than using the mean of the observed data.

Table 2. Statistical parameters for monthly mean meteorological data under the two SSP scenarios of Uttarakhand

Statistical parameters	**Max. temperature (°C)**		**Min. temperature (°C)**		**Rainfall (mm)**	
	SSP 2-4.5	**SSP 5-8.5**	**SSP 2-4.5**	**SSP 5-8.5**	**SSP 2-4.5**	**SSP 5-8.5**
Bias	-1.18	-0.87	-0.06	0.00	-6.36	0.31
RMSE	1.38	1.22	0.62	0.52	17.40	17.13
NSE	0.93	0.95	0.99	0.99	0.98	0.98

The statistical evaluation of MIROC6 model outputs against observed IMD data for 13 districts of Uttarakhand during 2015–2022 indicates good model performance for monthly Tmax, Tmin, and rainfall (*Table 2*). Bias values were close to zero for Tmin and rainfall, while Tmax showed a slight underestimation (–1.18 to –0.87 °C). The RMSE values were relatively low (≤1.38 °C for temperature and ~17 mm for rainfall), suggesting small deviations from observations. High NSE values (>0.90 across all variables) further confirm the strong predictive capability of MIROC6. Overall, the model effectively captures the monthly variability of temperature and rainfall, making it suitable for climate projection studies in Uttarakhand.

2.7. Bias correction of modeled data

To mitigate the biases in the modeled data, various bias correction methods have been developed, all dependent on the quality of observational datasets used. Effective bias correction relies on robust observation data, especially crucial for correcting extreme precipitation events, necessitating long-term datasets. The Delta Change method, widely used in climate impact research, adjusts observations based on GCM or RCM projections. Rainfall adjustments typically involve calculating percentage changes: a 20% increase in modeled rainfall would mean multiplying historical data by 1.2 for future projections, with different adjustments for various seasons or months. Notably, this method does not address changes in climate variability, such as increased extreme rainfall frequency or prolonged dry spells.

In the initial phase of the study, future meteorological data on rainfall projected by MIROC6 was downscaled for 13 districts of Uttarakhand. This simulated baseline data was compared against observed baseline meteorological data from IMD gridded datasets to establish correction factors. These correction factors were then applied to the futuristic data to refine and derive the correction factors. Subsequently, the expected changes in rainfall were analyzed during the 21st century across various locations in the state.

The deviation percentage method for bias correcting rainfall involves adjusting historical rainfall data by a percentage deviation calculated from climate model projections. Here's a step-by-step outline of how this method is typically applied:

a. *Calculate the deviation percentage*: The method determines the percentage of deviation of simulated future rainfall projections from historical observations. This is often calculated as:

$$\text{deviation percentage} = (R_{model} - R_{historical})/R_{historical}) \times 100\%,$$

where R_{model} is the rainfall projected by the climate model and $R_{historical}$ is the simulated historical rainfall data.

b. *Apply the deviation percentage:* In this step, the method adjusts the historical rainfall data by adding or subtracting the calculated deviation percentage to obtain bias-corrected future rainfall data:

For an increase in rainfall: corrected rainfall = $R_{observed} \times (1+\text{deviation } \%)$

For a decrease in rainfall: corrected rainfall = $R_{observed} \times (1-\text{deviation } \%)$

The agroclimatic analysis viz., converting daily rainfall data into weekly and annual data, meteorological and agricultural drought analysis was possible using the WeatherCock software.

2.8. Drought and its classification

Drought is a normal, recurrent climatic feature that occurs around the world causing huge loss to the farming community. Drought is universally acknowledged as a phenomenon associated with deficiency of rainfall. Droughts occur at random and there is no periodicity in its occurrence thus, it cannot be predicted in advance. In semiarid stations, the occurrence of rainfall is seasonal and is known more for its variability with respect to space and time. Drought is characterized by moisture deficit resulting either from i) below normal rainfall, ii) erratic rainfall distribution, iii) higher water need, or iv) a combination of all the three factors.

2.8.1. Meteorological drought

A period of prolonged dry weather condition due to below normal rainfall. According to the India Meteorological Department, there are two types of meteorological drought based on rainfall deficit from normal. Based on the daily rainfall data as input file in the Weathercock software, it gives the output in % deviation of rainfall of the particular year. The criteria for the meteorological drought have been presented in the *Table 3*.

Table 3. Criteria of meteorological drought condition (IMD)

Deviation (%)	Drought condition
-25 and above	no drought
-25 to -50	moderate drought
< -50	severe drought

2.8.2. Agricultural drought

Agricultural impacts due to short-term precipitation shortages, temperature anomaly causes increased evapotranspiration and soil water deficits that could adversely affect crop production. According to the National Commission on

Agriculture, 1976, at least four consecutive weeks receiving less than half of the normal rainfall during the Kharif season and six such consecutive weeks during the Rabi season is considered as agricultural drought period based on weekly rainfall as input file. Normal rainfall: Average rainfall for a location/region over a period of years (preferable 30years) (https://www.ipcc.ch/report/ar6/syr/resources/spm-headline-statements/).

In agroclimatic analysis, meteorological and agricultural drought study is important. The frequencies of occurrence of different type of meteorological droughts (moderate and severe) over a period of year would give insight for vulnerability of a particular location/region to drought on annual basis. Agricultural drought analysis would give idea about susceptibility of a region to drought on seasonal basis, i.e., main crop growing season. India is a monsoon-dependent nation for agriculture, with most of its precipitation occurring during the south-west monsoon season.

The drought classification was carried out on the basis of standard meteorological weeks (SMWs), which represent fixed weekly intervals used in agroclimatic analyses. For the Kharif season, agricultural droughts were categorized into three critical periods based on the crop growth stages (*Gupta et al.*, 2022): early-season drought (SMW 22–28: germination to early vegetative stage), mid-season drought (SMW 29–35: active vegetative to flowering stage), and late-season drought (SMW 36–42: grain filling to maturity stage). This classification enables differentiation between drought events that impact crop establishment, vegetative growth, and yield formation phases.

For historical analysis (1901–2022), drought occurrence was evaluated for the Kharif season in all districts of the Kumaon and Garhwal regions. For future projections (2023–2100) under SSP2-4.5 and SSP5-8.5 scenarios, the drought analysis included both the Kharif season (SMW 22–42) and the Rabi season (SMW 44–60) to assess potential impacts across the region's major cropping periods.

2.8.3. Duration of weeks

The duration of agricultural drought was calculated using the Weathercock software, wherein the standard meteorological weeks (SMWs) indicating drought occurrence were identified. Drought events for Kharif or Rabi season could last for 1, 2, 3, or 4 consecutive weeks. For each year, the range of drought weeks was determined based on the observed minimum and maximum durations. Subsequently, the average duration was computed for all 13 districts of Uttarakhand, both for the historical period and under future scenarios, using weekly rainfall data.

3. *Results*

3.1. Kumaon region of Uttarakhand

3.1.1. Historical rainfall trend

During the historical period (1901–2022), Kumaon's annual rainfall ranged from 1203 mm in Almora to nearly 1930 mm in Pithoragarh. Pithoragarh (1930 mm) and Bageshwar (around 1780 mm) consistently received the highest rainfall due to orographic uplift, ensuring adequate water availability for paddy and maize during the Kharif season. Nainital, with ~1700 mm, showed high intra-district variation linked to altitudinal gradients, often influencing apple and horticultural crop production in upper elevations versus paddy in the lower valleys. Almora (1203 mm) and Champawat (around 1260 mm), both in partial rain-shadow zones, received comparatively less rainfall, frequently causing stress in unirrigated maize and pulses. US Nagar (Tarai plains) maintained relatively stable rainfall (~1400–1500 mm), sufficient for rice–wheat cropping systems under irrigated conditions (*Fig. 1*).

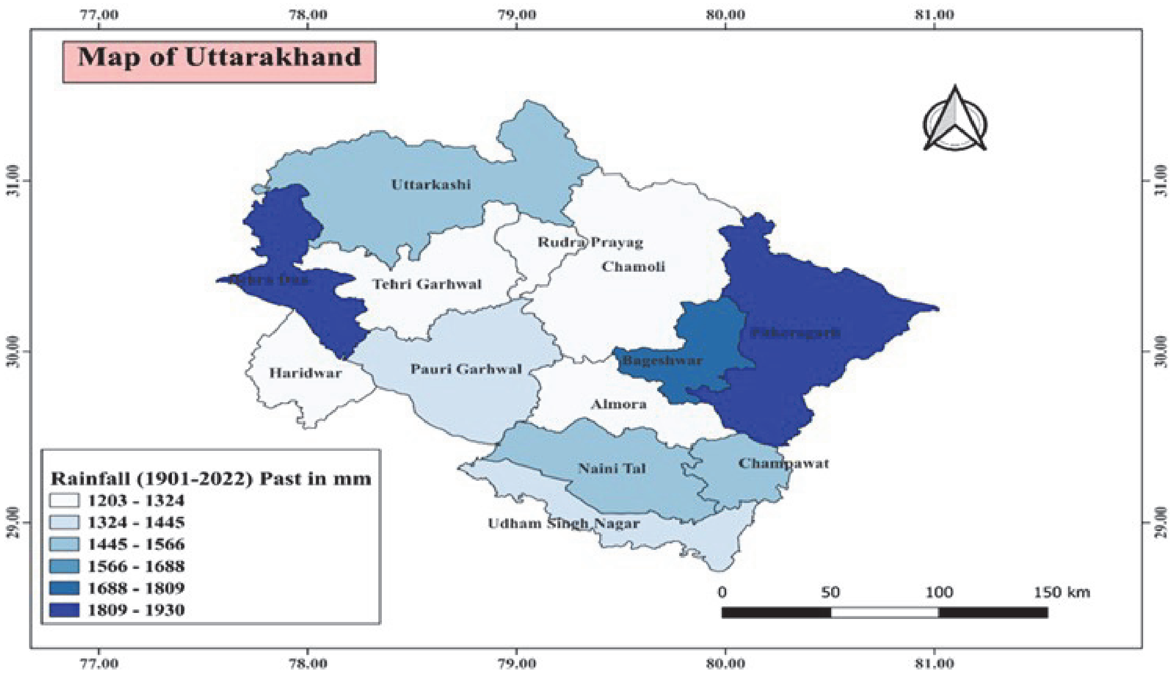

Fig. 1. The rainfall map for both the Kumaon and Garhwal region of Uttarakhand in the historical periods (1901–2022).

3.1.2. Historical drought trend

During the 1901–2022 period, Kumaon experienced several meteorological droughts, with moderate drought years dominating. US Nagar and Champawat each recorded 19 years of moderate droughts (~15.6% of total years), significantly impacting rice and maize yields. Severe droughts were rare but still notable in Almora and Pithoragarh (4 years each, ~3.3%). Almora, despite 111 no-drought years (91%), faced yield variability in rainfed maize due to its exposure to short but impactful droughts (*Table 4*; *Fig. 2*).

Table 4. Frequency and intensity of meteorological and agricultural droughts in Kumaon region of Uttarakhand for Historical periods (1901–2022)

Districts	Meteorological Drought				Agricultural Drought					
	No Drought (years)	Moderate Drought (years)	Severe Drought (years)	Total Drought (years)	Early Drought (22-28)		Mid Drought (29-35)		Late Drought (36-42)	
					Freq.#	Dur.#	Freq.	Dur.	Freq.	Dur.
Almora	111	07	04	11	15	4-7 (4.83)	10	4-8 (5.55)	35	4-9 (5.22)
Bageshwar	103	16	03	19	15	4-7 (4.56)	08	4-9 (4.83)	25	4-7 (4.83)
Champawat	99	19	04	23	13	4-10 (5.07)	06	4-7 (4.67)	40	4-9 (5.38)
Nainital	105	16	01	17	15	4-6 (4.53)	04	4-5 (4.40)	42	4-9 (5.20)
Pithoragarh	105	13	04	17	12	4-7 (4.58)	04	4-10 (5.88)	25	4-7 (4.79)
US Nagar	99	19	04	23	28	4-7 (4.90)	12	4-9 (4.86)	13	4-9 (5.32)

Freq. = Frequency of the drought in years, Dur. = Duration of the weeks in the form of range and value in parathesis represents the average number of weeks (Standard Meteorological Week no.)

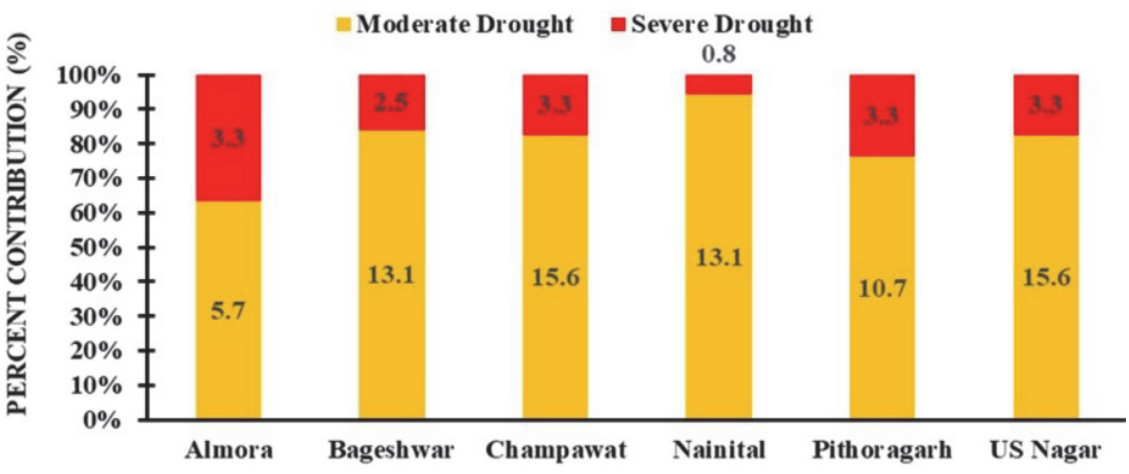

Fig. 2. Percentage share of moderate and severe meteorological droughts in Kumaon region of Uttarakhand for historical periods (1901–2022)

Agricultural droughts were most frequent during the late Kharif season (SMW 36–42). Nainital and Champawat were the worst affected with 42 and 40 late-season drought years, respectively, often coinciding with maize grain filling and rice maturity stages—critical periods for yield. US Nagar faced 28 early drought years, affecting rice transplanting and maize germination. Almora reported 15 early droughts and 10 mid-season droughts, frequently affecting rainfed pulses and millets (*Table 4; Fig. 3*).

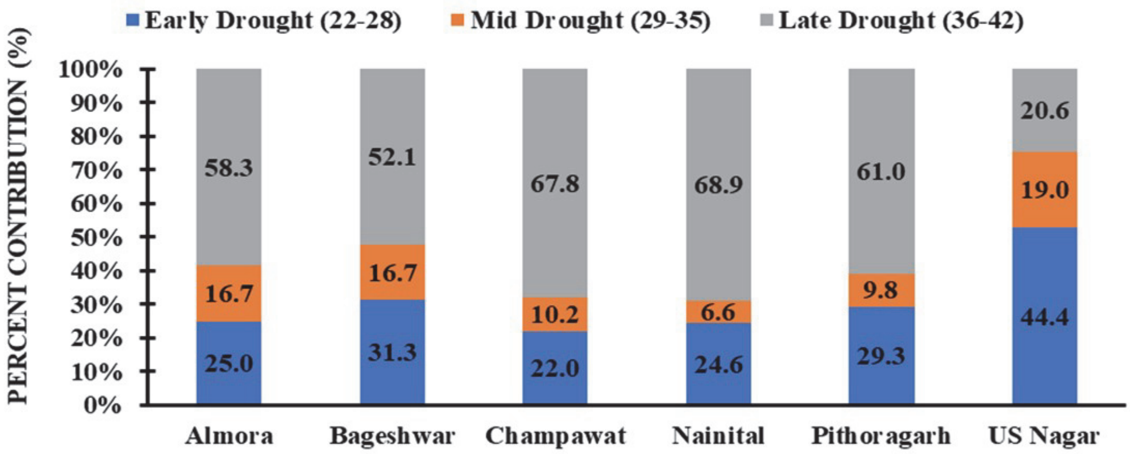

Fig. 3. Percentage share of early, mid and late monsoon season agricultural drought in Kumaon region of Uttarakhand for historical periods (1901–2022)

Drought duration in Kumaon ranged between 4–10 weeks. On average, early-season droughts lasted ~4.5 weeks, mid-season droughts ~5 weeks, and late-season droughts stretched up to ~5.5 weeks, often extending into September. These longer late-season droughts coincided with the reproductive phases of maize and rice, leading to significant yield losses in unirrigated fields. For instance, yield losses of 20–30% were reported in drought-prone upland maize areas of Almora and Champawat during prolonged late-season dry spells (*Table 4; Fig. 4*).

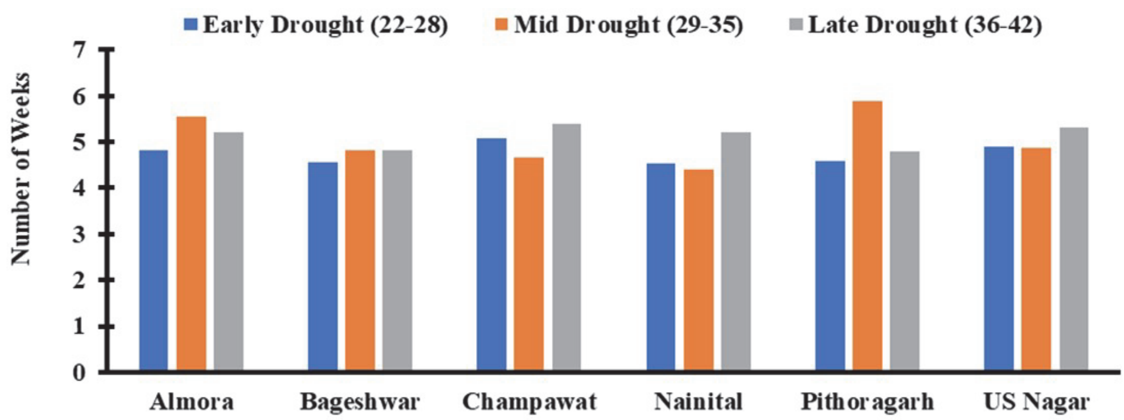

Fig. 4. Duration of early, mid and late monsoon season agricultural drought in Kumaon region of Uttarakhand for historical periods (1901–2022)

3.1.3. Future rainfall trend

Under SSP 2-4.5, rainfall in Kumaon increases significantly, with Pithoragarh projected at ~2382 mm (+23% increase from baseline). Bageshwar and Nainital also show increases of ~15–20%, improving prospects for paddy and maize but raising risks of excess rainfall and lodging. Almora and Champawat show modest gains (~8–10%). Under SSP 5-8.5, wetter conditions intensify, with US Nagar expected to reach ~2241 mm, which may benefit double-cropping but also increase flooding in the Tarai plains (*Figs. 5* and *6*).

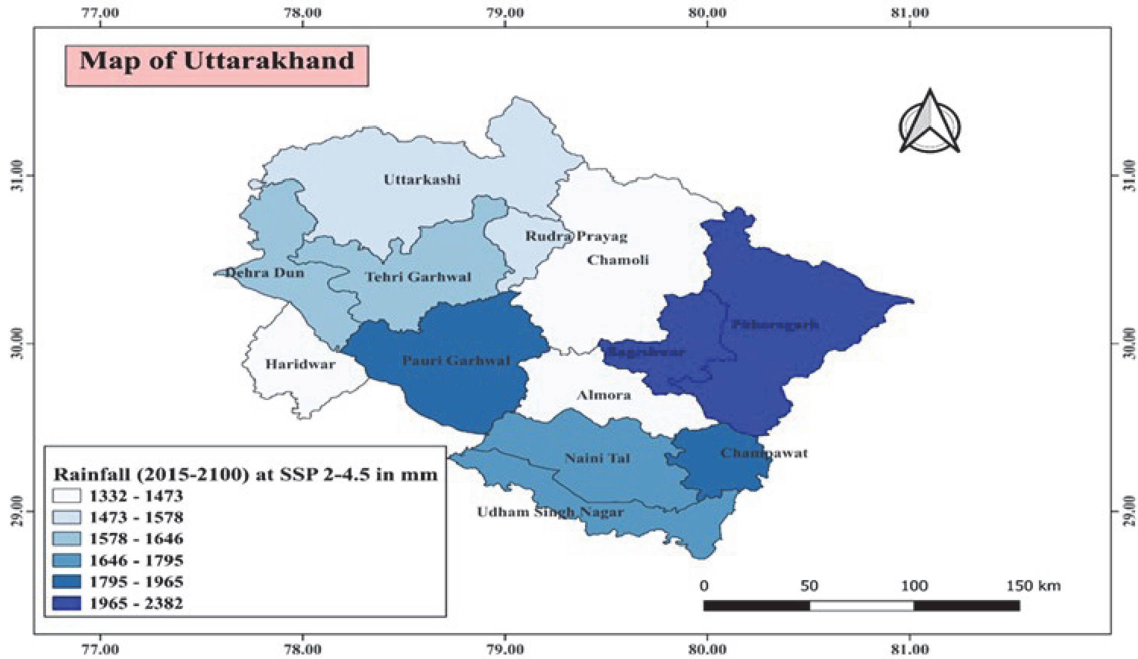

Fig. 5. The rainfall map for both the Kumaon and Garhwal region of Uttarakhand in the future periods (2023–2100) at SSP 2-4.5

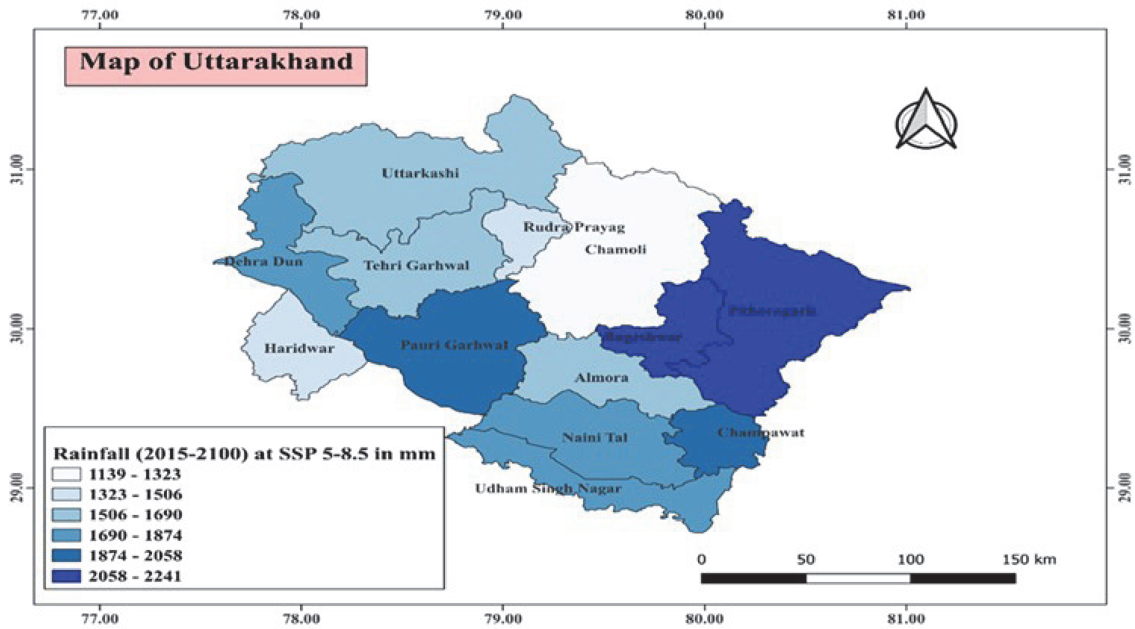

Fig. 6. The rainfall map for both the Kumaon and Garhwal region of Uttarakhand in the future periods (2023–2100) at SSP 5-8.5

3.1.4. Future drought trend

Future projections (2023–2100) show zero severe drought years across Kumaon districts, suggesting improved resilience. However, moderate droughts persist, especially in US Nagar and Champawat (16 years each, ~19% of total years), which may intermittently reduce Kharif crop productivity despite overall wetter conditions (*Table 5*; *Fig. 7*).

Table 5. Frequency and intensity of meteorological and agricultural drought in Kumaon region of Uttarakhand for Future Scenarios (2023–2100)

Districts	Meteorological Drought				Agricultural Drought							
					Kharif Drought						Rabi Drought	
	No Drought (years)	Moderate Drought (years)	Severe Drought (years)	Total Drought (years)	Early Drought (22-28)		Mid Drought (29-35)		Late Drought (36-42)			
					Freq.#	Dur.#	Freq.	Dur.	Freq.	Dur.	Freq.	Dur.
Almora	74	04	0	04	11	4-5 (4.45)	04	4-6 (5.25)	21	4-6 (4.82)	-	-
Bageshwar	62	14	2	16	12	4-7 (5.64)	05	4-8 (6.25)	13	4-7 (5.23)	11	6-17 (8.67)
Champawat	62	16	0	16	10	4-5 (4.25)	05	4-5 (4.57)	20	4-6 (4.75)	-	-
Nainital	66	12	0	12	11	4-6 (4.91)	03	8(8)	26	4-8 (5.18)	-	-
Pithoragarh	65	13	0	13	05	5-7 (6.20)	10	4-9 (6.69)	11	4-7 (5.05)	20	6-21 (11.45)
US Nagar	62	16	0	16	10	4-6 (4.73)	04	4(4)	20	4-8 (5.22)	-	-

Freq. = Frequency of the Drought in years, Dur. = Duration of the weeks in the form of range and value in parathesis represents the average number of weeks (Standard Meteorological Week no.)

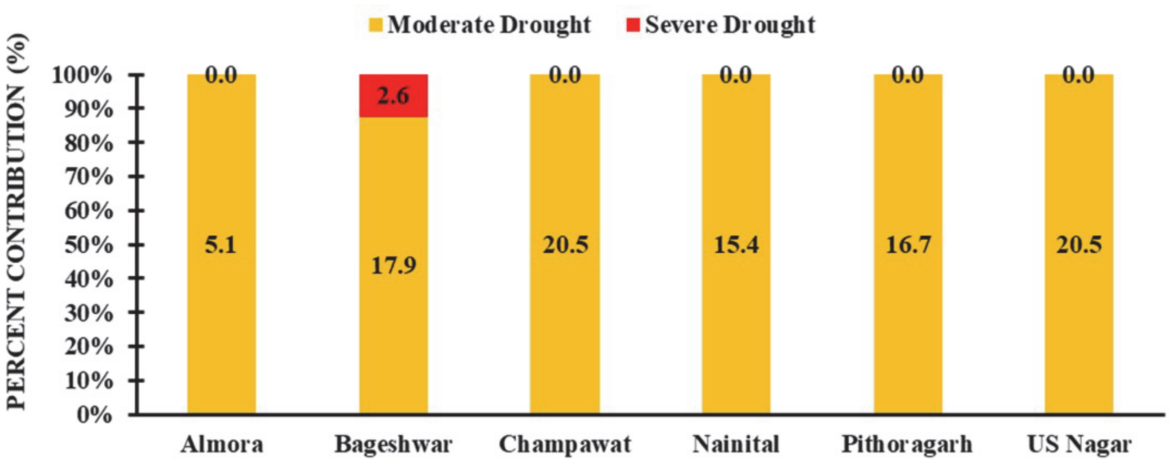

Fig. 7. Percentage share of moderate and severe meteorological droughts in Kumaon region of Uttarakhand for future scenarios (2023–2100)

Agricultural droughts remain concentrated in the late Kharif season, with Nainital projected for 26 late-season drought years (~30% of study years) and Champawat for 20 years. Such droughts directly coincide with rice maturity and maize cob formation. Importantly, Rabi droughts emerge in the future, particularly in Pithoragarh (20 years, avg. duration 11.5 weeks) and Bageshwar (11 years), potentially threatening wheat and mustard yields (*Table 5; Fig. 8*).

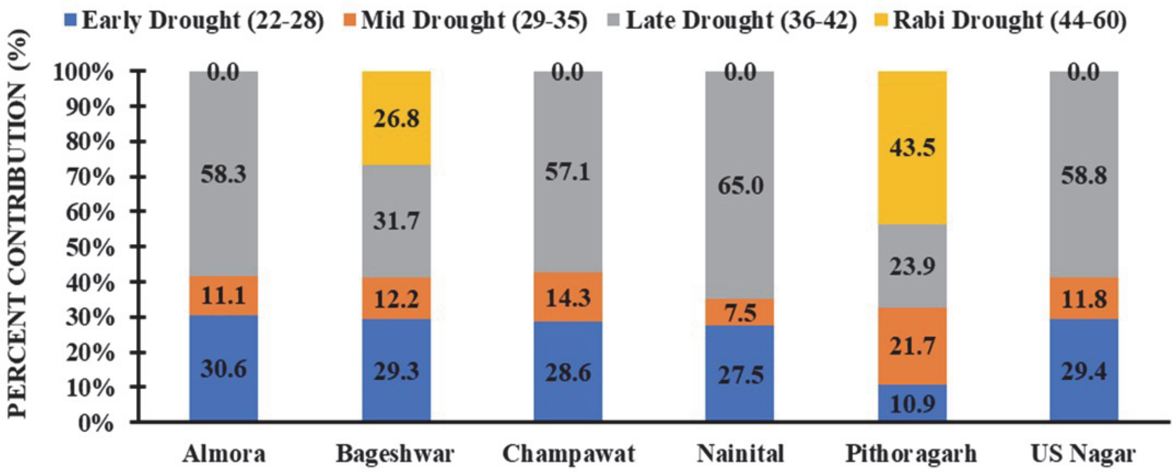

Fig. 8. Percentage share of early, mid, late monsoon and Rabi season agricultural drought in Kumaon region of Uttarakhand for future scenarios (2023–2100)

Future drought durations vary widely from 4–21 weeks. Kharif droughts remain moderate in length (4–8 weeks), but Rabi droughts extend much longer. Pithoragarh reports an average Rabi drought length of ~11.5 weeks, long enough to disrupt the entire wheat growth cycle, potentially reducing yields by >40% in unirrigated areas (*Table 5; Fig. 9*).

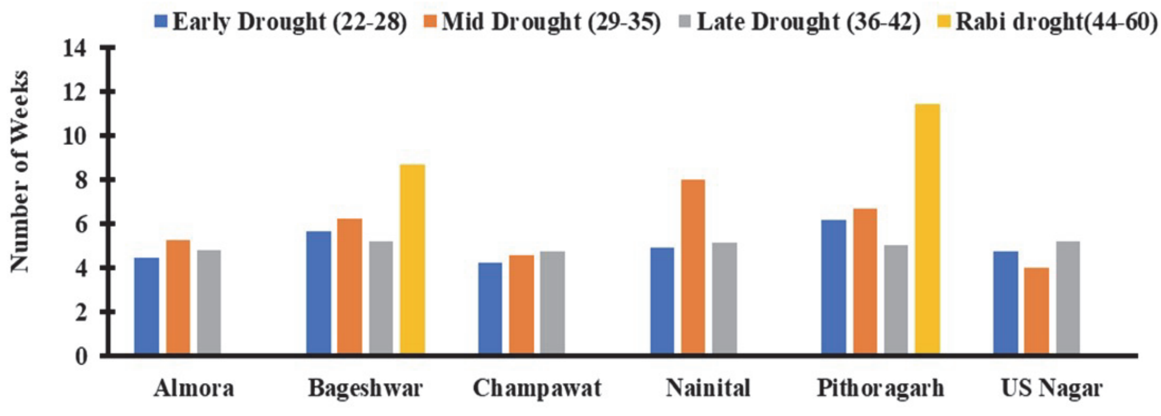

Fig. 9. Duration of early, mid, late monsoon and Rabi season agricultural drought in Kumaon region of Uttarakhand for future scenarios (2023–2100)

3.2. Gharwal region of Uttarakhand

3.2.1. Historical rainfall trend

Garhwal's rainfall during 1901–2022 varied from 1203 mm (Tehri) to 1930 mm (Chamoli, Uttarkashi). Chamoli and Uttarkashi, with their high-altitude locations, benefitted from heavy monsoonal rains, ensuring sufficient water for paddy and finger millet. Dehradun (~1500 mm) and Haridwar (~1450 mm) maintained stable rainfall for rice–wheat systems. Tehri and Pauri Garhwal, with <1300 mm, frequently faced dry spells, often reducing maize and pulse yields in upland regions (*Fig. 1*).

3.2.2. Historical drought trend

Rudraprayag reported the highest meteorological drought frequency (16 years, 13.1%), while Chamoli had the lowest (9 years, 7.4%). Severe droughts were rare, with Pauri Garhwal reporting the maximum (5 years, 4.1%), often coinciding with maize tasseling and paddy reproductive stages, leading to substantial yield deficits (*Table 6; Fig. 10*).

Table 6 Frequency and intensity of meteorological and agricultural drought in Garhwal region of Uttarakhand for Historical periods (1901–2022)

Districts	Meteorological Drought				Agricultural Drought					
	No Drought (years)	Moderate Drought (years)	Severe Drought (years)	Total Drought (years)	Early Drought (22-28)		Mid Drought (29-35)		Late Drought (36-42)	
					Freq.[#]	Dur.[#]	Freq.	Dur.	Freq.	Dur.
Chamoli	113	09	0	09	11	4-6 (4.57)	03	4-7 (5.75)	39	4-8 (5.00)
Dehradun	103	17	02	19	16	4-7 (4.44)	09	4-5 (4.33)	33	4-9 (5.16)
Haridwar	107	15	0	15	24	4-7 (4.62)	04	4-5 (4.25)	27	4-8 (5.11)
Pauri Garhwal	101	16	05	21	18	4-8 (5.06)	09	4-6 (4.60)	34	4-8 (5.36)
Rudraprayag	106	14	02	16	23	4-7 (4.76)	04	4-9 (5.18)	38	4-9 (5.29)
Tehri Garhwal	103	15	04	19	15	4-7 (4.74)	09	4-9 (5.33)	37	4-9 (5.30)
Uttarkashi	103	17	02	19	09	4-7 (4.71)	10	4-7(4.75)	32	4-7 (5.13)

[#] Freq. = Frequency of the Drought in years, Dur. = Duration of the weeks in the form of range and value in parathesis represents the average number of weeks (Standard Meteorological Week no.)

Agricultural droughts were heavily late-season dominated. Chamoli, Tehri, and Rudraprayag reported 39, 37, and 38 late-season drought years, respectively, affecting maize and rice at maturity. Early droughts were frequent in Haridwar (24 years) and Rudraprayag (23 years), often disrupting rice transplanting. Such frequent early droughts in Haridwar forced farmers to delay rice sowing, reducing yields by 15–20% (*Table 6; Fig. 11*). Droughts lasted 4–9 weeks, with late-season droughts averaging ~5.3 weeks. Early and mid-season droughts were shorter (~4–6 weeks). The shorter but frequent early droughts coincided with germination and transplanting, leading to crop failure in rainfed maize fields (*Table 6; Fig. 12*).

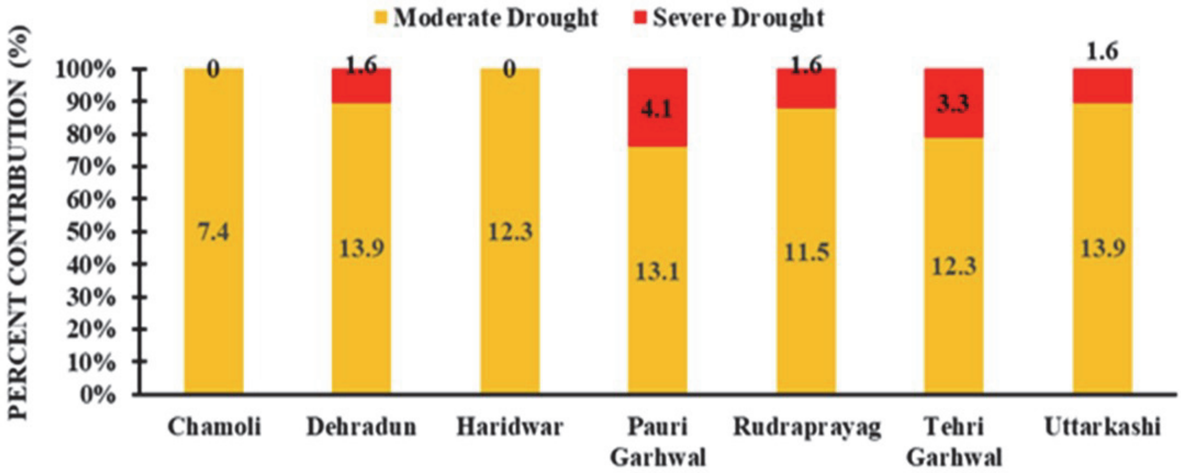

Fig. 10. Percentage share of moderate and severe meteorological droughts in Garhwal region of Uttarakhand for historical periods (1901–2022).

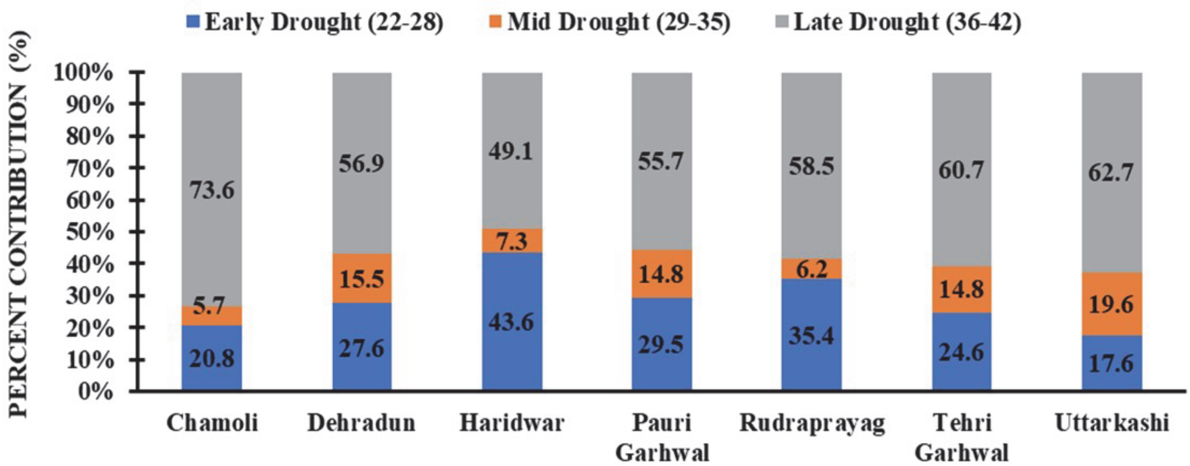

Fig. 11. Percentage share of early, mid and late monsoon season agricultural drought in Garhwal region of Uttarakhand for historical periods (1901–2022).

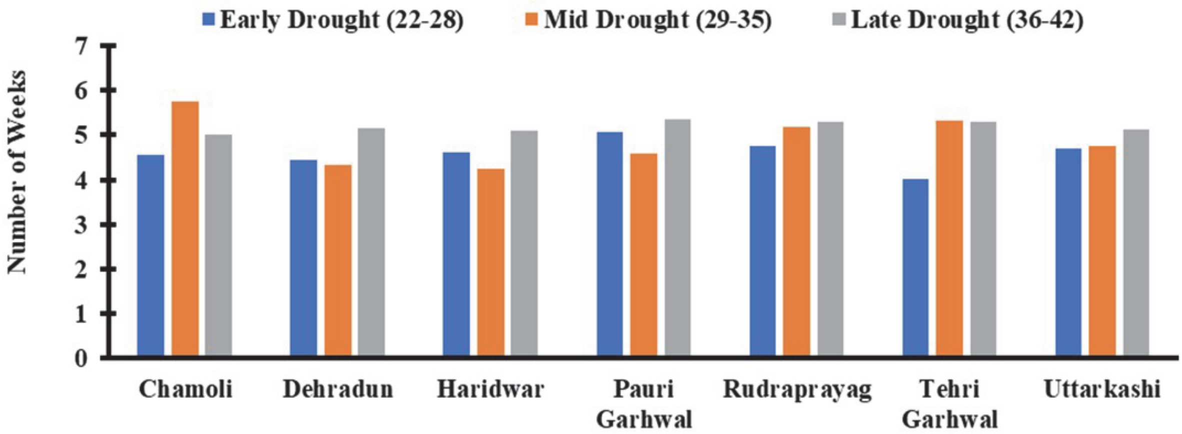

Fig. 12. Duration of early, mid and late monsoon season agricultural drought in Garhwal region of Uttarakhand for historical periods (1901–2022).

3.2.3. Future rainfall trend

Projections under SSP 2-4.5 indicate rainfall increases across Garhwal, with Chamoli projected to exceed 2200 mm (+15%). Rudraprayag also shows gains, supporting maize–paddy systems. Dehradun and Haridwar show ~10% increases, beneficial for rice–wheat cropping. However, Tehri and Pauri continue to lag behind with smaller increments, leaving some areas vulnerable to moisture stress. Under SSP 5-8.5, rainfall intensifies, particularly in Chamoli, Uttarkashi, and Dehradun, raising risks of localized flooding during Kharif (*Figs. 5* and *6*).

3.2.4. Future drought trend

Severe droughts nearly disappear, except in Uttarkashi (3 years, ~3.5%). Moderate droughts persist, especially in Haridwar (13 years, ~15%) and Tehri Garhwal (10 years). These may disrupt rice transplanting and reduce maize yields intermittently (*Table 7; Fig. 13*). Late-season droughts remain the most prominent, with Uttarkashi (27 years) and Tehri Garhwal (24 years) showing the highest frequency. Early and mid-season droughts are less common but notable in Chamoli and Rudraprayag. Importantly, Rabi droughts emerge in Dehradun (16 years, ~19%) and Uttarkashi (6 years), directly threatening wheat and mustard production (*Table 7; Fig. 14*). Future droughts last 4–15 weeks. Kharif droughts average 4–7 weeks, while Rabi droughts extend much longer—Dehradun (~13.5 weeks) and Uttarkashi (~14 weeks). Such prolonged dry spells overlap with critical wheat growth phases (tillering–grain filling), risking >50% yield loss in unirrigated regions (*Table 7; Fig. 15*).

Table 7. Frequency and intensity of meteorological and agricultural drought in Garhwal region of Uttarakhand for Future Scenarios (2023–2100)

Districts	Meteorological Drought				Agricultural Drought							
					Kharif Drought						Rabi Drought	
	No Drought (years)	Moderate Drought (years)	Severe Drought (years)	Total Drought (years)	Early Drought (22-28)		Mid Drought (29-35)		Late Drought (36-42)			
					Freq.#	Dur.#	Freq.	Dur.	Freq.	Dur.	Freq.	Dur.
Chamoli	75	03	0	03	13	4-5 (4.36)	03	6(6)	21	4-7 (4.82)	-	-
Dehradun	73	05	0	05	05	4-5 (4.56)	04	5(5)	18	4-7 (4.82)	16	6-15 (13.45)
Haridwar	65	13	0	13	12	4-5 (4.55)	03	5(5)	24	4-7 (4.91)	-	-
Pauri Garhwal	69	09	0	09	12	4-7 (4.67)	09	4-5 (4.43)	19	4-7 (5.29)	-	-
Rudraprayag	69	09	0	09	12	4-6 (4.50)	08	4-6 (4.40)	20	4-7 (5.06)	-	-
Tehri Garhwal	68	10	0	10	11	4-5 (4.27)	06	4-5 (4.50)	24	4-7 (5.06)	-	-
Uttarkashi	73	02	03	05	04	4-6 (4.85)	11	4-6 (5.00)	27	4-7 (4.86)	06	14(14)

Freq. = Frequency of the Drought in years, Dur. = Duration of the weeks in the form of range and value in parathesis represents the average number of weeks (Standard Meteorological Week no.)

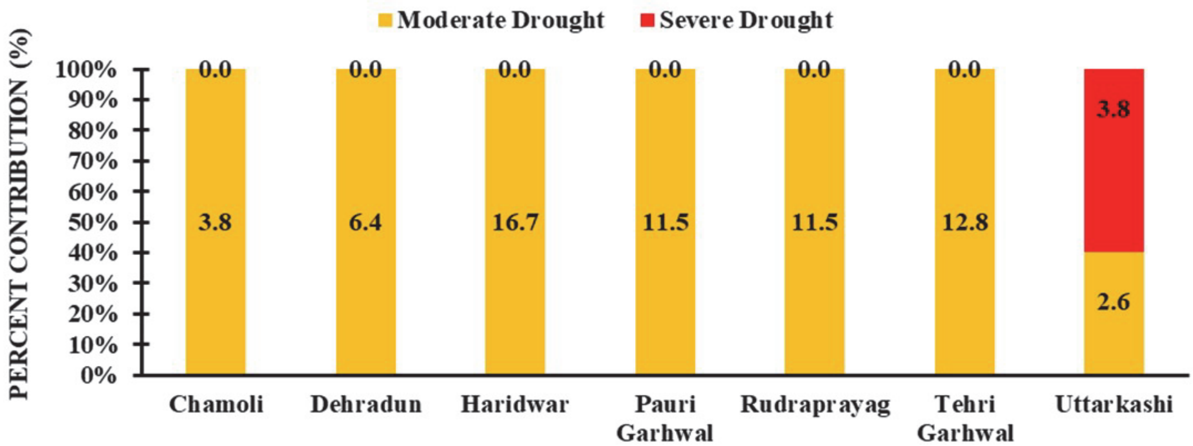

Fig. 13. Percentage share of moderate and severe meteorological droughts in Garhwal region of Uttarakhand for future scenarios (2023–2100).

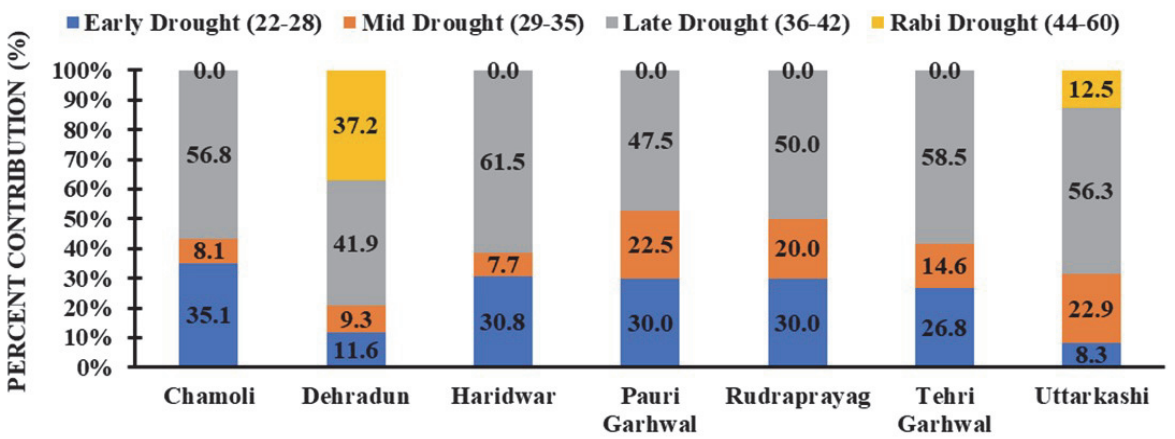

Fig. 14. Percentage share of early, mid, late monsoon and Rabi season agricultural drought in Garhwal region of Uttarakhand for future scenarios (2023–2100).

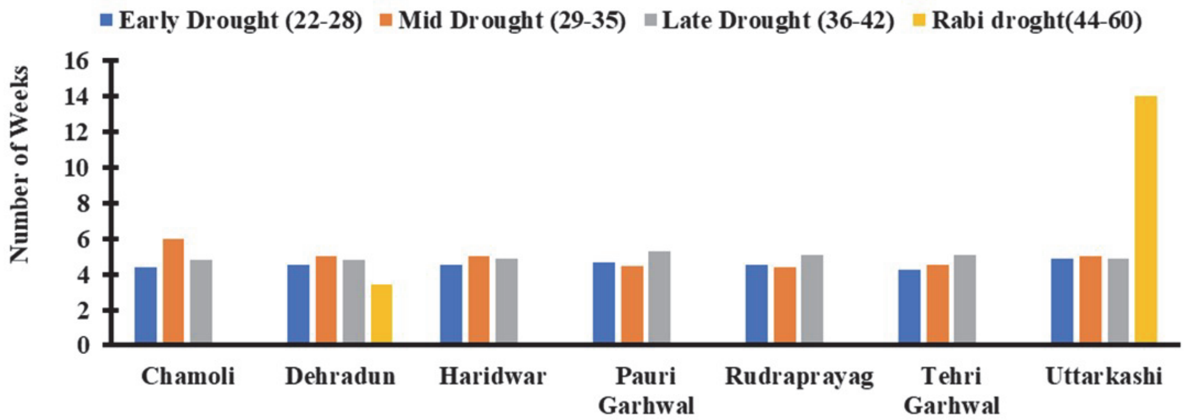

Fig. 15. Duration of early, mid, late monsoon and Rabi season agricultural drought in Garhwal region of Uttarakhand for future scenarios (2023–2100).

3.3. A comparative analysis from historical and future perspective of drought in Kumaon and Gharwal regions

3.3.1. Historical perspective

Historically, Kumaon had fewer no-drought years compared to Garhwal. Almora and Bageshwar reported 91.0% and 84.4% no-drought years, whereas Chamoli and Haridwar recorded 92.6% and 87.7%, respectively. Severe droughts were more frequent in Pauri Garhwal (4.1%), whereas Kumaon districts rarely exceeded 3%. Agricultural droughts were consistently late-season dominated in both regions, but Garhwal had higher frequency and persistence. For example, Chamoli had 39 late-season droughts vs. Nainital's 42, yet also suffered more early droughts (11) compared to Nainital (15), amplifying stress on maize and rice systems. Overall, Garhwal displayed slightly greater vulnerability due to multi-season drought exposure (*Tables 4* and *6*).

3.3.2. Future perspective

In the future, severe droughts decline significantly, with Kumaon reporting none and Garhwal only Uttarkashi at 3.5%. However, moderate droughts persist, more in Kumaon (US Nagar 20.9%, Bageshwar 19.8%) than Garhwal (Chamoli 3.5%, Uttarkashi 3.5%). The emergence of Rabi droughts is a key shift, more severe in Garhwal (Dehradun 16 years, Uttarkashi 6 years) than Kumaon (Pithoragarh 20 years, Bageshwar 11 years), threatening wheat-based systems. Duration of droughts is projected to be longer in Garhwal (up to 14 weeks) than Kumaon (up to 11.5 weeks), raising risks of prolonged stress during crop critical stages. This suggests that Kumaon will face moderate drought persistence in Kharif crops, while Garhwal will be more vulnerable in Rabi crops, requiring region-specific adaptation strategies for rice–maize and wheat–mustard systems (*Tables 5* and *7*; *Figs. 9* and *15*).

4. Discussion

This spatiotemporal assessment of rainfall and drought patterns across Kumaon and Garhwal (1901–2022 historical; 2015–2100 projected) reveals distinct climatic trends and regional contrasts. Historically, annual rainfall varied from 1203 mm in Almora to 1930 mm in Pithoragarh, driven largely by orographic effects. Himalayan-facing districts like Pithoragarh, Bageshwar, Chamoli, and Uttarkashi consistently received higher precipitation, whereas interior and leeward districts such as Almora, Champawat, Tehri Garhwal, and Pauri Garhwal faced rain-shadow effects. Under future climate scenarios (SSP 2-4.5 and SSP 5-8.5), rainfall is expected to increase across most districts up to 15–20% in high-altitude regions such as Pithoragarh and Chamoli—signaling intensified monsoonal activity. However, this increase will not be uniform; marginal gains of only 5–8% are projected for Almora, Tehri Garhwal, and Champawat, indicating that spatial heterogeneity in rainfall will persist. The study on meteorological and agricultural drought conditions and their dynamic relationships during the pre-monsoon season (March–May) in northwest Bangladesh was conducted by *Al Shoumik et al.* (2023). A similar study was carried out by *Verma et al.* (2023), which examined the severity and frequency of meteorological drought under two climate change scenarios—Shared Socioeconomic Pathway (SSP2-4.5 and SSP5-8.5) over Indian conditions. *Sivan* and *Pramada* (2024) investigated the spatiotemporal characteristics of historic and future droughts over a monsoon-dominated humid region (Kerala) in India. *Gupta et al.* (2022) carried out a block-level characterization of agricultural and meteorological drought in Hazaribagh district using 35 years (1983–2017) of daily rainfall data based on IMD criteria. The study revealed considerable spatial variability in the intensity and frequency of drought across different blocks of the district. The drought trends in the state give similar results where the results reveal a historical predominance of late-season Kharif droughts (SMW 36–42), especially in US Nagar, Nainital, Rudraprayag, and Chamoli. Between 1901 and 2022, these districts experienced 10–15 years of severe or moderate late-season droughts. Future projections indicate a decline in the frequency of severe drought years (from an average of 7–10 per district in the 20th century to 2–4 in the 21st century), with a corresponding rise in moderate drought episodes. Meanwhile, Rabi season droughts historically negligible are projected to increase, particularly in high-altitude districts like Pithoragarh and Uttarkashi, where 6–9 Rabi drought years are anticipated under SSP 5-8.5. This emerging seasonal shift poses a challenge to conventional crop calendars and water allocation practices. The aim is to provide actionable advisories to farmers regarding optimal sowing dates and cropping patterns in response to projected climate variability.

5. *Conclusion*

Historically, Kumaon and Garhwal have shown distinct spatial and temporal rainfall–drought dynamics. Orographically favored districts such as Pithoragarh, Bageshwar, Chamoli, and Uttarkashi consistently received higher precipitation, while in leeward districts like Almora, Champawat, Tehri, and Pauri, the rainfall-deficit persisted. Droughts were predominantly late in the Kharif season in both regions, adversely affecting maize and rice at reproductive stages, with Garhwal displaying slightly greater vulnerability due to its exposure to multi-season droughts. Moderate droughts occurred frequently in US Nagar, Champawat, and Rudraprayag, while severe droughts, though infrequent, occasionally disrupted agricultural productivity in rainfed areas. Future projections indicate an overall increase in rainfall, more pronounced in Himalayan-facing districts (15–20%) compared to modest increments in rain-shadow areas (5–10%). Severe droughts are projected to decline; however, moderate droughts will continue to occur, particularly in Kumaon's US Nagar and Champawat. Importantly, the historically negligible Rabi droughts are expected to emerge, with Garhwal (Dehradun, Uttarkashi) facing longer and more severe episodes than Kumaon (Pithoragarh, Bageshwar). Extended drought durations, up to 14 weeks in Garhwal and 11.5 weeks in Kumaon, will pose significant threats to wheat–mustard and rice–maize systems. Consequently, Kumaon is likely to remain more vulnerable during the Kharif season, while Garhwal may face heightened risks in the Rabi season, necessitating region-specific adaptation strategies in crop planning, irrigation scheduling, and water resource management.

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