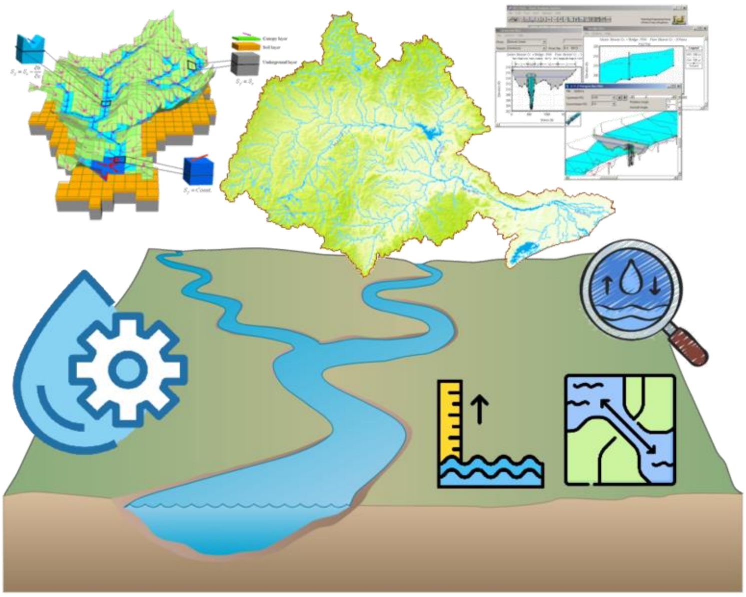
National River Conservation Directorate
Ministry of Jal Shakti,
Department of Water Resources,
River Development & Ganga Rejuvenation
Government of India

Climatological/Meteorological Data

Mahanadi River Basin



July 2025

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National River Conservation Directorate (NRCD)

The National River Conservation Directorate, functioning under the Department of Water Resources, River Development & Ganga Rejuvenation, and Ministry of Jal Shakti providing financial assistance to the State Government for conservation of rivers under the Centrally Sponsored Schemes of 'National River Conservation Plan (NRCP)'. National River Conservation Plan to the State Governments/ local bodies to set up infrastructure for pollution abatement of rivers in identified polluted river stretches based on proposals received from the State Governments/ local bodies.

www.nrcd.nic.in

Centres for Mahanadi River Basin Management Studies (cMahanadi)

The Centres for Mahanadi River Basin Management Studies (cMahanadi) is a Brain Trust dedicated to River Science and River Basin Management. Established in 2024 by NIT Raipur and NIT Rourkela, under the supervision of cGanga at IIT Kanpur, the centre serves as a knowledge wing of the National River Conservation Directorate (NRCD). cMahanadi is committed to restoring and conserving the Mahanadi River and its resources through the collation of information and knowledge, research and development, planning, monitoring, education, advocacy, and stakeholder engagement.

www.cmahanadi.org

Centre for Ganga River Basin Management and Studies (cGanga)

cGanga is a think tank formed under the aegis of NMCG, and one of its stated objectives is to make India a world leader in river and water science. The Centre is headquartered at IIT Kanpur and has representation from most leading science and technological institutes of the country. cGanga's mandate is to serve as think-tank in implementation and dynamic evolution of Ganga River Basin Management Plan (GRBMP) prepared by the Consortium of 7 IITs. In addition to this, it is also responsible for introducing new technologies, innovations, and solutions into India.

www.cganga.org

Acknowledgment

This report is a comprehensive outcome of the project jointly executed by NIT Raipur (Lead Institute) and NIT Rourkela (Fellow Institute) under the supervision of cGanga at IIT Kanpur. It was submitted to the National River Conservation Directorate (NRCD) in 2024. We gratefully acknowledge the individuals who provided information and photographs for this report.

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Preface

In an era of unprecedented environmental change, understanding our rivers and their ecosystems has never been more critical. This report aims to provide a comprehensive overview of our rivers, highlighting their importance, current health, and the challenges they face. As we explore the various facets of river systems, we aim to equip readers with the knowledge necessary to appreciate and protect these vital waterways.

Throughout the following pages, you will find an in-depth analysis of the principles and practices that support healthy river ecosystems. Our team of experts has meticulously compiled data, case studies, and testimonials to illustrate the significant impact of rivers on both natural environments and human communities. By sharing these insights, we hope to inspire and empower our readers to engage in river conservation efforts.

This report is not merely a collection of statistics and theories; it is a call to action. We urge all stakeholders to recognize the value of our rivers and to take proactive steps to ensure their preservation. Whether you are an environmental professional, a policy maker, or simply someone who cares about our planet, this guide is designed to support you in your efforts to protect our rivers.

We extend our heartfelt gratitude to the numerous contributors who have generously shared their stories and expertise. Their invaluable input has enriched this report, making it a beacon of knowledge and a practical resource for all who read it. It is our hope that this report will serve as a catalyst for positive environmental action, fostering a culture of stewardship that benefits both current and future generations.

As you delve into this overview of our rivers, we invite you to embrace the opportunities and challenges that lie ahead. Together, we can ensure that our rivers continue to thrive and sustain life for generations to come.

Centre for Mahanadi River Basin
Management and Studies (cMahanadi)
NIT Raipur & NIT Rourkela

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Abbreviations and Acronyms

cMahanadi	Centre for Mahanadi River Basin Management and Studies
BCM	Billion Cubic Meters
CG	Chhattisgarh
CGL	Central Gauge Line
CWC	Central Water Commission
HEC	Hydrologic Engineering Centre
IIT	Indian Institute of Technology
MCM	Million Cubic Meters
MRB	Mahanadi River Basin
NIT	National Institute of Technology
NRSC	National Remote Sensing Centre
OD	Odisha
RAS	River Analysis System
sq.km.	square kilometre
SoI	Source of Information
SWMM	Storm Water Management Model
WRIS	Water Resource Information System
IMD	India Meteorological Department
IPCC	Intergovernmental Panel on Climate Change
SPI	Standardized Precipitation Index
PDSI	Palmer Drought Severity Index
NGO	Non-Governmental Organization
NASA	National Aeronautics and Space Administration

1. Summary

Meteorological and climatological data encompass a broad spectrum of atmospheric and environmental variables that influence weather and climate patterns on local, regional, and global scales. Meteorology focuses on short-term atmospheric conditions, such as temperature, humidity, precipitation, wind speed, and pressure variations, while climatology examines long-term trends and patterns spanning decades to millennia. Temperature, one of the most critical variables, is influenced by solar radiation, latitude, altitude, and ocean currents, with fluctuations observed due to natural cycles like El Niño and La Niña, as well as anthropogenic impacts such as greenhouse gas emissions. Precipitation patterns vary significantly across different climatic zones, with regions experiencing arid, semi-arid, temperate, or tropical conditions, often dictated by monsoons, jet streams, and prevailing wind systems. Humidity levels, directly linked to temperature and atmospheric moisture content, affect weather phenomena like fog, cloud formation, and storms, while also playing a crucial role in heat index calculations. Wind patterns, driven by pressure differentials and the Earth's rotation, impact weather dynamics by influencing storm systems, ocean circulation, and even local climates through phenomena such as the foehn effect and trade winds. Atmospheric pressure, a key determinant in weather forecasting, governs storm formation and movement, with low-pressure systems generally associated with cyclones, hurricanes, and storms, while high-pressure systems bring stable, dry conditions.

Extreme weather events, including hurricanes, tornadoes, heatwaves, and blizzards, are closely monitored through meteorological data analysis to improve forecasting accuracy and disaster preparedness. Advances in remote sensing technology, such as satellite imagery and radar systems, have enhanced real-time weather monitoring, allowing for the detection of developing weather systems and their potential impact. Climate data, on the other hand, reveal broader trends such as global warming, sea-level rise, and shifting precipitation patterns, largely attributed to human-induced activities such as deforestation, industrialization, and fossil fuel combustion. The Intergovernmental Panel on Climate Change (IPCC) has documented significant increases in global average temperatures over the past century, with projections indicating further warming and increased frequency of extreme weather events if carbon emissions are not mitigated. Oceanic influences, including thermohaline circulation and sea surface temperature anomalies, contribute to climatic variations, affecting marine ecosystems and terrestrial weather systems alike.

Regional climate classification systems, such as the Köppen-Geiger system, categorize climates based on temperature and precipitation trends, distinguishing between tropical, dry, temperate, continental, and polar climates. Climate variability and change also influence agricultural productivity, water resource availability, and biodiversity, necessitating adaptation strategies such as sustainable land use, renewable energy

integration, and resilient infrastructure development. The study of past climates, or paleoclimatology, utilizes ice core samples, tree rings, and sediment analysis to reconstruct historical climate conditions, providing insight into natural climate variability and informing future climate projections. Urban climates, influenced by heat island effects, air pollution, and altered land surfaces, present unique challenges in mitigating rising temperatures and maintaining air quality.

Recent advancements in artificial intelligence and machine learning have revolutionized climate modelling and meteorological forecasting, improved predictive capabilities and enabled more accurate simulations of atmospheric dynamics. The integration of big data analytics with meteorological sensors has facilitated the development of early warning systems for extreme weather, reducing the risk of casualties and economic losses. Global initiatives, such as the Paris Agreement, emphasize the importance of reducing greenhouse gas emissions and transitioning towards climate-resilient societies. Climate adaptation and mitigation efforts include afforestation projects, carbon capture technologies, and sustainable urban planning to counteract the adverse effects of climate change.

Meteorological and climatological data play a crucial role in various sectors, including agriculture, aviation, transportation, and public health, ensuring informed decision-making and proactive disaster management. As climate change continues to impact global weather patterns, interdisciplinary research and international collaboration are essential to understanding and addressing the challenges posed by a rapidly changing climate. The synthesis of historical data, real-time observations, and predictive modelling remains fundamental in advancing climate science and developing strategies to enhance resilience against future climatic uncertainties.

The Mahanadi River Basin, located between 19°20′N to 23°35′N latitude and 80°30′E to 86°50′E longitude, spans a length of approximately 851 kilometers and encompasses a catchment area of 141,589 square kilometers (Table 1). The basin primarily covers the states of Chhattisgarh and Odisha, with smaller portions extending into Jharkhand, Maharashtra, and Madhya Pradesh.

This region falls under tropical to subtropical climatic zones and is characterized by a monsoon-driven climate. It receives an average annual rainfall ranging from 1,200 mm to 1,600 mm, with around 80–90% of the precipitation occurring during the Southwest Monsoon season (June to September). However, rainfall is highly variable, both from year to year and within the monsoon season, often leading to challenges in water resource planning and agriculture. Temperature in the basin ranges from 30–45°C during summer and 10–25°C in winter. Relative humidity peaks at 70–90% during the monsoon and drops to 30–50% in winter. The annual potential evapotranspiration is estimated to be around 1,200 to 1,400 mm, which influences water availability and crop planning.

The Mahanadi Basin is prone to both floods and droughts [1]. Frequent flooding occurs during intense monsoon rainfall, especially in the delta region, which is highly vulnerable. Conversely, western parts of the basin periodically suffer from droughts due to insufficient rainfall. Additionally, the eastern coastal areas, particularly in Odisha, are affected by cyclones originating from the Bay of Bengal.

Table 1. Salient Features of the Mahanadi River Basin.

Aspects	Details
Geographical Location	Lies between 19°20′N to 23°35′N latitude and 80°30′E to 86°50′E longitude
Length of the Mahanadi River (Km)	851
Catchment Area (Sq.km.)	141589
States Covered	Primarily Chhattisgarh and Odisha, parts of Jharkhand, Maharashtra, Madhya Pradesh
Climatic Zone	Tropical to Subtropical (Monsoon Climate)
Average Annual Rainfall	~1,200 mm to 1,600 mm
Rainfall Pattern	Highly seasonal; ~80–90% occurs during Southwest Monsoon (June–September)
Rainfall Variability	High inter-annual and intra-seasonal variability
Temperature Range	Summer: 30–45°C; Winter: 10–25°C
Relative Humidity	Monsoon: 70–90%; Winter: 30–50%
Evapotranspiration	Annual Potential Evapotranspiration ~1,200–1,400 mm
Flood-Prone Nature	Frequent flooding during heavy monsoon; delta region highly vulnerable
Drought Occurrence	Periodic droughts, especially in western basin areas
Cyclonic Influence	Eastern part (especially Odisha) affected by Bay of Bengal cyclones
Climate Change Impact	Increased intensity of rainfall, erratic monsoon, rising temperatures

2. Introduction

Meteorological and climatological data play a crucial role in understanding and predicting weather patterns, assessing climate change, and aiding various industries in planning and decision-making. These data encompass a broad range of atmospheric and environmental parameters, including rainfall, temperature, wind speed, humidity, solar radiation, evaporation, drought conditions, and both mini- and micro-level global and regional climate data [1, 2]. The collection, analysis, and interpretation of such data are essential for meteorologists, climatologists, policymakers, and researchers to mitigate risks associated with weather extremes and climate variability [15, 16].

Meteorological data refer to short-term atmospheric conditions and are fundamental to daily weather forecasting [17], [18], [19]. Climatological data, on the other hand, involve long-term weather patterns and trends, often spanning decades or centuries [13, 14]. These datasets provide valuable insights into climate variability and change, allowing for informed decision-making across different sectors such as agriculture, water resource management, infrastructure development, and disaster risk reduction [2, 4].

2.1 Key Meteorological and Climatological Parameters

I. Rainfall

Rainfall is one of the most critical meteorological parameters, as it directly impacts agriculture, water resources, and ecosystems. Measured in millimeters (mm), rainfall data help in understanding precipitation trends, drought occurrences, and flood risks. Rain gauge stations, radar systems, and satellite observations are commonly used to collect rainfall data [3].

II. Temperature

Temperature influences various physical and biological processes in the environment. It is measured in degrees Celsius (°C) or Fahrenheit (°F) and is a key indicator of climate trends and variability. Temperature records help assess heatwaves, cold spells, and their impacts on agriculture, human health, and energy demand [15].

III. Wind Speed and Direction

Wind speed and direction are essential in meteorology, affecting weather systems, energy production, and transportation. Measured in meters per second (m/s) or kilometres per hour (km/h), wind data contribute to aviation safety, renewable energy planning (such as wind farms), and climate modelling.

IV. Humidity

Humidity refers to the amount of water vapor in the atmosphere and is expressed as relative humidity (percentage) or absolute humidity (grams per cubic meter). High humidity levels influence weather conditions, human comfort, and agricultural productivity. It also plays a vital role in cloud formation and precipitation processes.

V. Solar Radiation

Solar radiation is the energy received from the sun and is measured in watts per square meter (W/m^2). This parameter is crucial for understanding climate dynamics, solar energy generation, and photosynthesis in plants. Variability in solar radiation affects temperature patterns and atmospheric circulation.

VI. Evaporation

Evaporation is the process by which water is converted into vapor and released into the atmosphere. It is influenced by temperature, humidity, wind speed, and solar radiation. Evaporation data are crucial for hydrological studies, water resource management, and understanding the water cycle.

VII. Drought Monitoring

Droughts are prolonged periods of deficient precipitation, leading to water shortages and adverse impacts on agriculture, ecosystems, and economies. Drought indices, such as the Standardized Precipitation Index (SPI) and Palmer Drought Severity Index (PDSI), help in monitoring and predicting drought conditions.

VIII. Mini- and Micro-Level Climate Data

Mini- and micro-climate data (Table 2) focus on localized climate conditions, often at a smaller scale such as cities, agricultural fields, or forests [20-24]. These datasets are essential for urban planning, precision agriculture, and ecological studies. Factors such as land use, topography, and vegetation influence micro-climates.

Table 2. Characteristic of Mini- and Micro-Level CMIP6 Climate Data

Data Type	CMIP6 Variable Name	Spatial Resolution	Temporal Resolution	Temporal Coverage	Application
Precipitation	pr	~1° (~100 km), downscaled to ~10 km or finer using CORDEX/Statistical tools	Daily, Monthly	1850–2100	Rainfall trend analysis, flood/drought prediction
Temperature (Max)	tasmax	Same as above	Daily, Monthly	1850–2100	Heatwave risk, agriculture modeling
Temperature (Min)	tasmin	Same as above	Daily, Monthly	1850–2100	Cold spells, crop suitability analysis
Mean Temperature	tas	Same as above	Daily, Monthly	1850–2100	Long-term climate change trend
Relative Humidity	hurs	~1°; less frequently available at higher resolution	Daily, Monthly	1850–2100	Evapotranspiration, comfort indices
Surface Wind Speed	sfcWind	~1°	Daily, Monthly	1850–2100	Wind energy potential, dust transport
Evapotranspiration	evspsbl	~1°	Monthly	1850–2100	Water balance models, irrigation planning
Soil Moisture	mrso (total), mrsos (surface)	~1°	Monthly	1850–2100	Drought indices, crop water stress modeling

Radiation	rsds, rlds	~1°	Daily, Monthly	1850–2100	Solar energy potential, heat balance
Sea Level Pressure	psl	~1°	Daily, Monthly	1850–2100	Synoptic-scale pressure patterns
Cloud Cover	clt	~1°	Monthly	1850–2100	Solar radiation modeling, atmospheric stability
Snow Cover	snc	~1°	Monthly	1850–2100	Hydrological modeling, cryosphere studies

3. Purpose of the Study

The primary purpose of this study is to analyze and evaluate meteorological and climatological data to enhance the understanding and prediction of atmospheric conditions and climate variability. The study aims to:

I. **Enhance Weather Forecasting Accuracy:** By examining historical and real-time meteorological data, the study seeks to improve weather prediction models and support timely decision-making in weather-sensitive industries.

II. **Assess Climate Change and Variability:** Investigating long-term climatological trends to identify patterns, anomalies, and the impact of human activities on climate systems.

III. **Support Disaster Risk Reduction and Management:** Utilizing climate data to assess and mitigate risks associated with extreme weather events such as storms, droughts, floods, and heatwaves.

IV. **Improve Agricultural Planning and Food Security:** Providing insights into rainfall patterns, temperature variations, and drought conditions to assist farmers in crop selection, irrigation planning, and yield optimization.

V. **Facilitate Water Resource Management:** Ensuring sustainable water use by analyzing precipitation, evaporation, and humidity data to manage reservoirs, rivers, and irrigation systems effectively.

VI. **Promote Renewable Energy Development:** Supporting solar and wind energy projects by analyzing solar radiation and wind speed data for optimal energy generation and efficiency.

VII. **Advance Scientific Research and Policy Formulation:** Offering valuable datasets to researchers and policymakers for informed decision-making regarding environmental conservation and sustainable development.

4. Data Sources

In the context of climatological and meteorological data for the entire Mahanadi River Basin, multiple reputable data sources have been utilized. The India Meteorological Department (IMD) [5, 6] provides long-term gridded datasets on rainfall, temperature, and humidity, which are crucial for trend and variability analysis. POWER NASA (Prediction of Worldwide Energy Resource) offers satellite-derived climate parameters such as solar radiation, wind speed, and surface temperature (Table 2). Climate projection data are sourced from CMIP6 (Coupled Model Intercomparison Project Phase 6), (Annexture I) which supports future climate scenario analysis under various Representative Concentration Pathways (RCPs). Central Water Commission (CWC) [8-10] supplies hydro-meteorological and river gauge data essential for water resource assessments and flood analysis. Drought-related information is obtained from IMD's Standardized Precipitation Index (SPI) records and other indices published by national drought monitoring agencies (Table 3). Together, these datasets provide a comprehensive foundation for assessing the climatological and meteorological characteristics of the Mahanadi River Basin [7-11].

Table 3. Dataset Used

S. No.	Agency / Source	Type of Data	Relevance to the Mahanadi River Basin
1	India Meteorological Department (IMD) [12]	Historical rainfall, temperature, humidity, wind speed, and solar radiation.	Primary source for long-term observed climate data across stations in the basin.
2	POWER NASA (Prediction of Worldwide Energy Resources)	Satellite-based daily global meteorological data, including temperature, rainfall, and wind.	Supplementary data for regions with sparse ground observations, useful for modelling.
3	CMIP6 (Coupled Model Intercomparison Project Phase 6)	Future climate projections under different emission scenarios (RCPs/SSPs).	Used for climate change impact assessments in the basin.
4	Central Water Commission (CWC) [11]	River discharge, reservoir levels, hydro-	Key source for stream flow, flood data, and

		meteorological observations.	hydrological calibration in the basin.
5	National Drought Management Centre / IMD Drought Atlas	Drought indices, SPI, severity maps.	Used to assess historical and current drought conditions across the basin.
6	India-WRIS (Water Resources Information System)	Integrated data portal combining rainfall, flow, water bodies, land use.	Basin-wide datasets helpful for spatial mapping and correlation with climate.

5. Historical Rainfall Data (1901–1930)

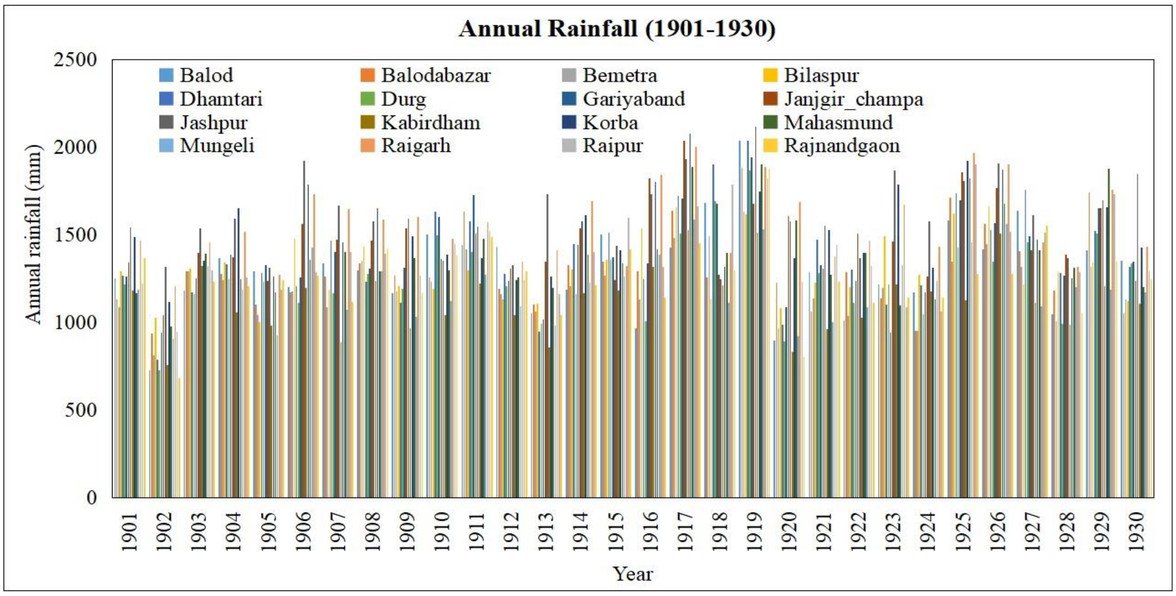


Figure 1. Annual Rainfall (1901-1930)

➢ **Variations in Rainfall**

I. The data set shows significant inter-annual variations in rainfall across all districts. Some years experienced extreme highs, while others saw drought-like conditions (Figure 1).

II. For example, in **1919**, rainfall peaked in many districts (e.g., Jashpur: **2116.33 mm**, Mahasamund: **1903.96 mm**, Raigarh: **1886.33 mm**), while **1920** saw a drastic drop in multiple regions.

➢ **Districts with Highest Rainfall**

I. **Jashpur** consistently records the highest rainfall, with multiple years exceeding **2000 mm** (notably in **1919 and 1925**).

II. Other high-rainfall districts include **Raigarh, Korba, and Mahasamund** (Figure 2).

- **Drought Years & Districts**

I. **1902** and **1920** stand out as drought-prone years, with many districts recording rainfall below **1000 mm**.

II. **Balodabazar, Bemetra, and Durg** tend to have lower rainfall compared to other regions (Figure 2).

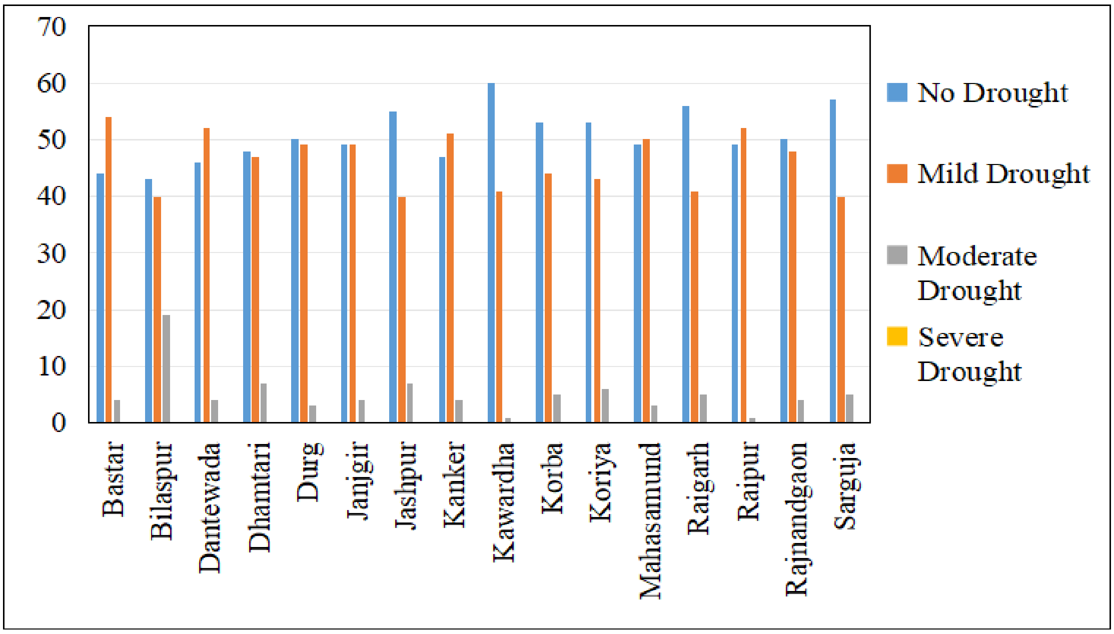


Figure 2. Frequency and Intensity of Drought as per the IMD during the Period of 102 Years (1901-2002)

- **Long-Term Trends**

I. There is no clear increasing or decreasing trend in rainfall over the years, indicating natural variability.

II. However, extreme fluctuations suggest the possibility of periodic climate influences affecting rainfall.

- **Significant Findings**

- **1919 was the wettest year**, with many districts recording their highest rainfall in this data set.
- **1920 was one of the driest years**, with several districts experiencing a drastic drop in precipitation.
- **Jashpur consistently receives the highest rainfall**, making it a crucial region for water resource planning.

6. Previous Rainfall Trend (1994-2023)

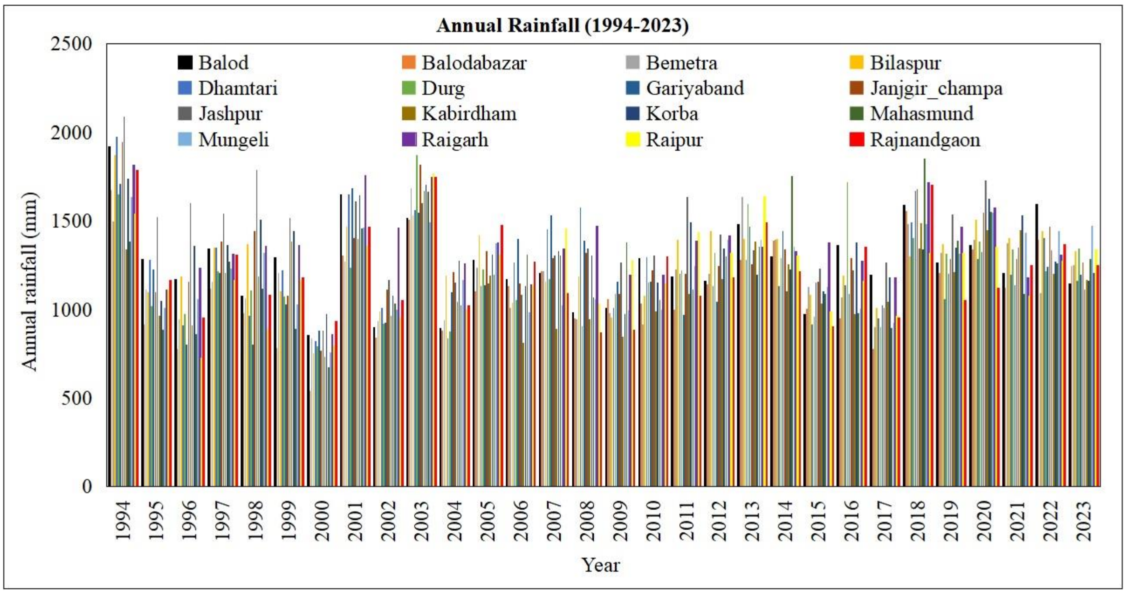


Figure 3. Annual Rainfall (1994-2023)

6.1 Variation in Rainfall Patterns

I. Rainfall levels vary significantly from year to year across all districts.

II. Certain years exhibit extreme highs and lows, indicating periods of heavy monsoon and drought (Figure 3).

6.2 Wettest Years

I. The years **2003, 2011, 2016, 2019, and 2020** show **higher rainfall peaks**, suggesting exceptionally wet monsoon seasons.

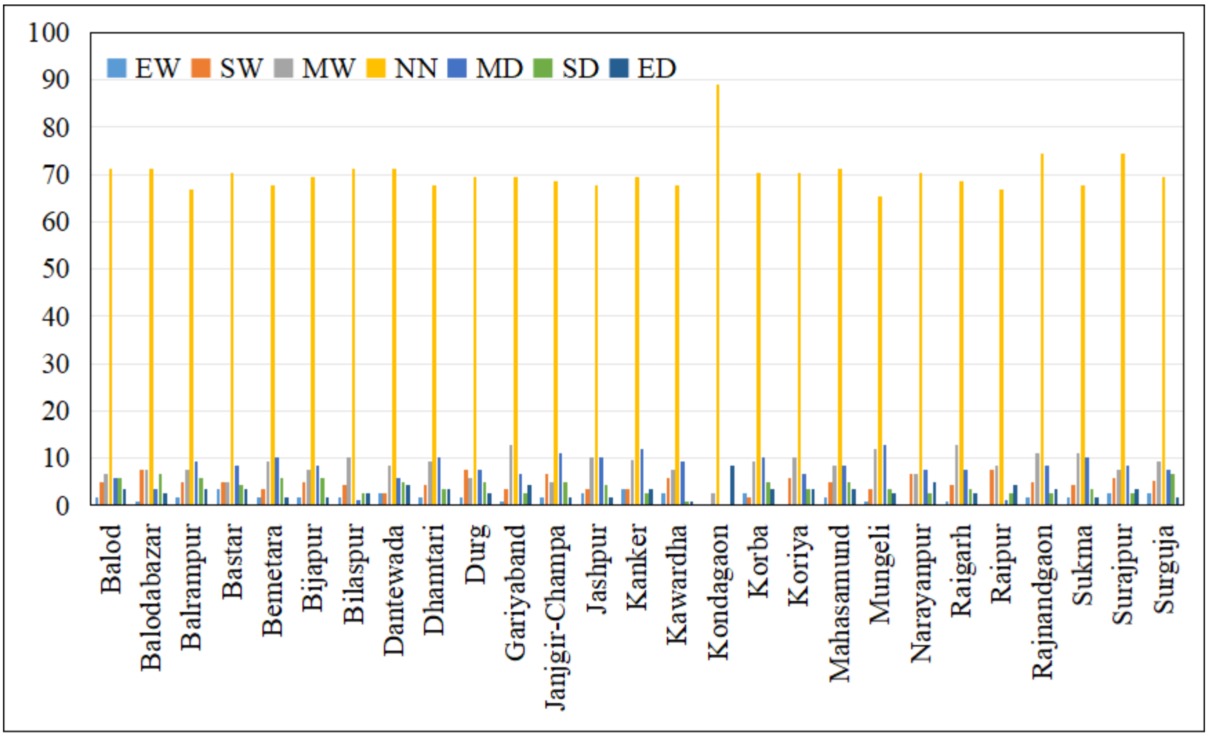
6.3 Drought Years

I. The period between **1999-2002, 2005-2007, and 2014-2015** appears to have **lower rainfall**, indicating dry or drought-prone years (Figure 4).

6.4 District Variability

I. **Jashpur, Raigarh, and Korba** tend to receive consistently higher rainfall.

II. **Balod, Bemetra, and Durg** often record lower rainfall compared to other districts.



(EW: Extremely Wet, SW: Severely Wet, MW: Moderately Wet, NN: Near Normal, MD: Moderately Dry, SD: Severely Dry, ED: Extremely Dry)

Figure 4. Frequencies (in %) of drought/wet events on 12 month or annual time scale for the Chhattisgarh state during 1901-2018

7. Significant Changes in Historical Rainfall (1901-1930 vs. 1994-2023)

The historical rainfall data from 1901-1930 and 1994-2023 reveal significant inter-annual variability, with both periods experiencing extreme wet and dry years. While no clear long-term increasing or decreasing trend is observed, the recent decades exhibit more frequent drought cycles compared to the early 20th century (Table 4). However, Jashpur consistently records the highest rainfall, making it a crucial region for water resource management, while Balod, Bemetra, and Durg continue to receive lower precipitation, indicating potential water scarcity issues. The wettest years in both periods, such as 1919 and 2019, highlight the presence of heavy monsoon seasons, whereas prolonged dry spells in 1920 and 2001-2002 suggest increasing climate variability. The modern data suggests that extreme rainfall variations have become more pronounced, with prolonged dry periods interspersed with years of heavy precipitation.

Table 4. Rainfall parameters and its observation. (1901-1930 vs. 1994-2023)

Parameters	1901-1930	1994-2023	Key observations
Inter-Annual Variability	High fluctuations with extreme wet and dry years	High fluctuations with distinct drought and wet periods	Both periods exhibit variability, but recent years show more frequent drought cycles.
Wettest Years	1919 (Jashpur: 2116.33 mm, Mahasamund: 1903.96 mm)	2019, 2016, 2011, 2003	More frequent wet years in the modern period.
Driest Years	1902, 1920 (rainfall below 1000 mm in many regions)	2001-2002, 2015, 1999-2002	Recent decades have experienced longer dry spells.
Districts with Highest Rainfall	Jashpur, Raigarh, Korba, Mahasamund	Jashpur, Raigarh, Korba	Jashpur consistently receives the highest rainfall in both periods.
Drought-Prone Districts	Balodabazar, Bemetra, Durg	Balod, Bemetra, Durg	Same districts remain drought-prone over the century.
Long-Term Trend	No clear increasing or decreasing trend	Slightly stable but with more extreme fluctuations	Natural variability dominates, but modern data suggests more erratic changes.
Recent Trends	No noticeable change	2020-2023 shows stable but slightly lower rainfall than peak years	Climate stability seen in recent years, but periodic extremes are common.
Significant Findings	1919 was the wettest year, 1920 was among the driest	2019 was the wettest, 2001-2002 among the driest	Both periods show extreme rainfall years, but modern drought cycles appear longer.

8. Recent Trends (2020-2023)

I. Rainfall has remained **relatively stable but slightly lower** than peak years like 2019.

II. No drastic decline or increase is observed in the last few years.

➢ **Significant Findings**

I. **2019 appears to be one of the wettest years**, with multiple districts experiencing heavy rainfall.

II. **2001-2002 and 2015 are among the driest years**, indicating possible drought conditions.

III. **Jashpur, Raigarh, and Korba are the highest rainfall-receiving districts**, making them critical for water resources (Figure 5).

IV. **Balod and Bemetra frequently record lower rainfall**, potentially requiring better water conservation strategies.

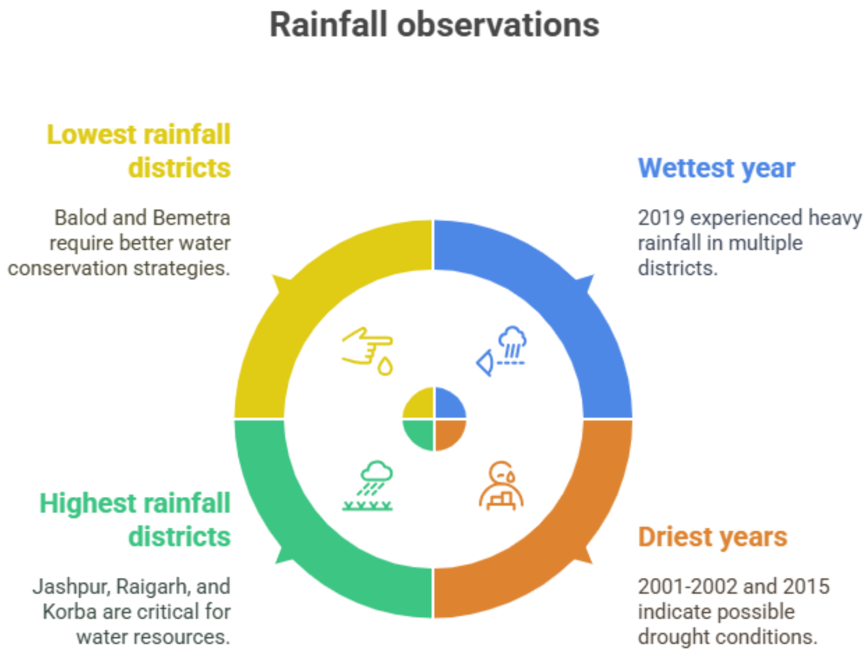


Figure 5. Rainfall Observation (2020-2023)

9. Historical Rainfall Data for Odisha

➢ **Variations in Rainfall Across Time**

- **Rainfall across Odisha** shows **significant inter annual and inter decadal variability** from 1901 to 2023.
- While the **average annual rainfall** remained mostly between **1200 mm to 2000 mm**, certain years recorded **sharp extremes**, both high and low.
- The earlier period (1901–1930) shows **more consistent rainfall** patterns, whereas **greater fluctuations** are visible in the recent decades (1990–2023), hinting at **increased variability due to climate change** (Figure 6).

➢ **Districts with Highest Rainfall**

- **Kandhamal, and Sundargarh** frequently recorded **high annual rainfall**, often exceeding **2000 mm/year**.
- **Jagatsinghpur, and Kendrapara** (not shown but commonly high-rainfall districts in Odisha) may also show similar trends in full datasets.
- **Kandhamal district** stands out as a **high-precipitation zone**, consistently ranking among the top rain-receiving regions.

➢ **Drought Years & Low Rainfall Events**

- Multiple districts show rainfall **below 1000 mm/year**, particularly in: **1911, 1920, 1965, 1987, 2001, 2015, and 2018** historically associated with droughts in India.
- In 1990–2023, **more frequent low-rainfall years** are observed, especially in **2001, 2015, and 2018**, aligning with **documented meteorological droughts**.
- Districts such as **Jharsuguda, Nuapada, and Boudh** frequently dipped below the **1000 mm threshold**, indicating **higher drought vulnerability**.
- These areas are showing a **trend towards increasing drought susceptibility.**

The drought-prone districts in Odisha that significantly affect the Mahanadi water availability include Nabarangpur, Kalahandi, Bolangir, Boudh, and Kandhamal. These areas have been identified as drought hotspots due to their susceptibility to agricultural droughts, which are influenced by various factors such as rainfall patterns and soil characteristics.

➢ **Drought Hotspot Identification**

Nabarangpur: Noted for frequent drought occurrences, particularly affecting agricultural productivity (Patel, n.d.).
Kalahandi: Experiences severe drought conditions, impacting water availability for irrigation (Atul et al., 2024).

Bolangir: Identified as a region with a high frequency of mild to moderate droughts (Patel, n.d.).
Boudh: This district faces significant drought risks, particularly in the upper regions of the Mahanadi basin (Nayak & Manjunatha, 2019).
Kandhamal: Similar to the others, it is prone to drought, affecting local agriculture and water resources (Patel, n.d.).

➢ **Impact on Water Availability**

Drought conditions in these districts lead to reduced surface water levels in the Mahanadi River, exacerbating water scarcity for both drinking and agricultural purposes (Das, 2024).
The cumulative effect of these droughts can lead to long-term water stress, impacting the socio-economic conditions of the local population (Atul et al., 2024). While these districts are primarily affected by drought, it is essential to consider that other regions along the Mahanadi River may also experience varying degrees of drought risk, influenced by different climatic and anthropogenic factors. This highlights the need for comprehensive drought management strategies across the entire basin.

➢ **Long-Term Trends**

- The rainfall distribution over time suggests a **shift from stable patterns (1901–1930)** to **erratic rainfall patterns (1990–2023)**.
- While total average rainfall may not show a steep decline, the **distribution, intensity, and frequency of rainfall events have changed**.
- This aligns with regional climate change literature indicating:

    a. **Shorter rainy seasons**
    b. **Higher intensity storms**
    c. **More dry spells between events**

➢ **Significant Observations and Changes**

As observed in Table 5, a comparative analysis of rainfall parameters between the periods 1901–1930 and 1990–2023 highlights a clear shift in regional climate behaviour. While the earlier period experienced relatively stable rainfall in the range of ~1200–1800 mm with uniform spatial distribution, the recent decade's exhibit increased variability, both in magnitude and spatial extent (~1000–2500 mm). The frequency of extreme rainfall events has become more prominent in recent years, with multiple districts experiencing either excess rainfall or deficits below 1000 mm in more than five years. This intensification of extremes points toward the influence of anthropogenic climate change, deviating from historical patterns driven largely by natural variability. The increase in drought frequency and erratic rainfall patterns pose significant risks to agriculture, water resources, and disaster preparedness, especially in vulnerable regions like Chhattisgarh and Odisha. Strengthened climate adaptation and mitigation strategies are essential to address these growing challenges.

Table 5. Significant Observations and Changes from (1901 -1930 to 1990 – 2023)

Parameter	1901–1930	1990–2023
Average Rainfall Range	~1200 mm – 1800 mm	~1000 mm – 2500 mm
Rainfall Extremes	Less frequent	More frequent heavy rainfall & lows
Drought Frequency	2–3 significant drought years	>5 years with <1000 mm in multiple districts
Spatial Distribution	More uniform	Highly variable across districts
Climate Influence	Natural variability	Anthropogenic climate change impacts

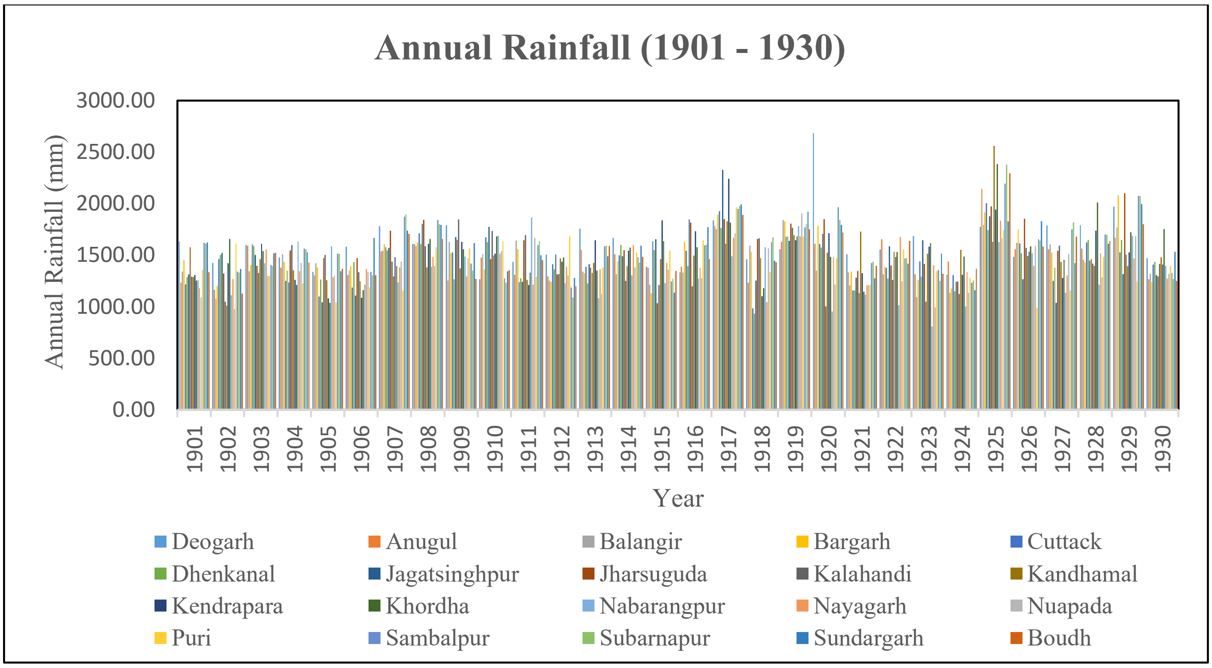


Figure 6. Annual Rainfall (1901-1930)

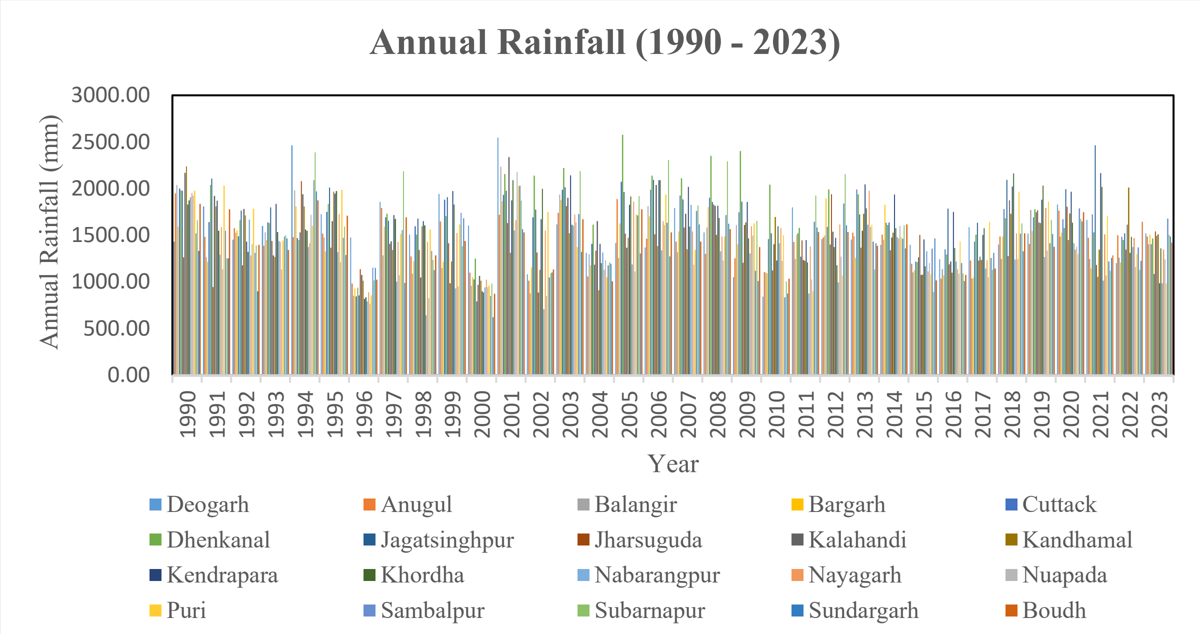


Figure 7. Annual Rainfall (1990-2023)

- **Significant Findings**

I. The state is witnessing **intensifying hydro-climatic extremes**, with **more frequent heavy rainfall events**, yet also **more years of district-scale droughts** (Figure 7).

II. Districts like **Kandhamal, and Sambalpur** continue to receive **high rainfall**, while **Nuapada, Jharsuguda, and Boudh** show tendencies toward **deficit rainfall**

10. Maximum Temperature Data – Chhattisgarh

10.1 Historical Maximum Temperature Data (1951-1980)

- **Key Findings**

i. **Temperature Fluctuations:**

1. The maximum temperature fluctuates between **30.5°C and 33.8°C** across the years.
2. Recurring peaks every **4-5 years**, likely indicating periodic climatic effects.

ii. **Increasing Peaks Over Time:**

1. Early peaks (1951-1960) reached around **32.5°C**, while later peaks (1970-1980) frequently exceeded **33.5°C**.

2. This suggests a gradual warming trend over the decades.

iii. **Lowest and Highest Temperatures:**

1. The lowest temperatures, around **30.5°C**, occurred in the mid-1950s.
2. The highest recorded temperatures (~33.8°C) appear in the late 1970s.

iv. **Regional Variability**

1. Different locations show slight variations, but the overall trend remains consistent.
2. Some regions, like **Jashpur and Rajnandgaon**, appear to have higher temperature peaks compared to others (Figure 8).

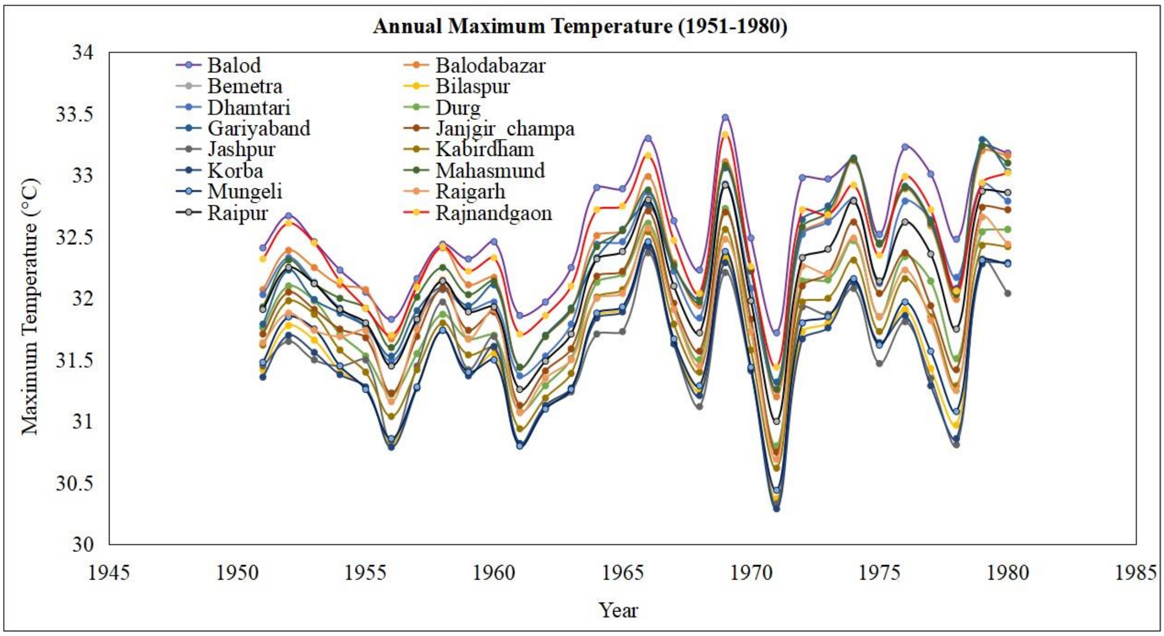


Figure 8. Maximum Temperature Trend (1951-1980)

➤ **Significance**

- The data reveals a **gradual rise in peak temperatures** over the years, hinting at early indicators of climate change.
- Understanding these trends is crucial for **climate research, agricultural planning, and policymaking** to mitigate future temperature extremes.
- The periodic nature of temperature peaks suggests **potential links to climatic cycles**, such as El Niño or monsoon variations (Figure 9).

10.2 Previous Maximum Temperature Data (1994-2023)

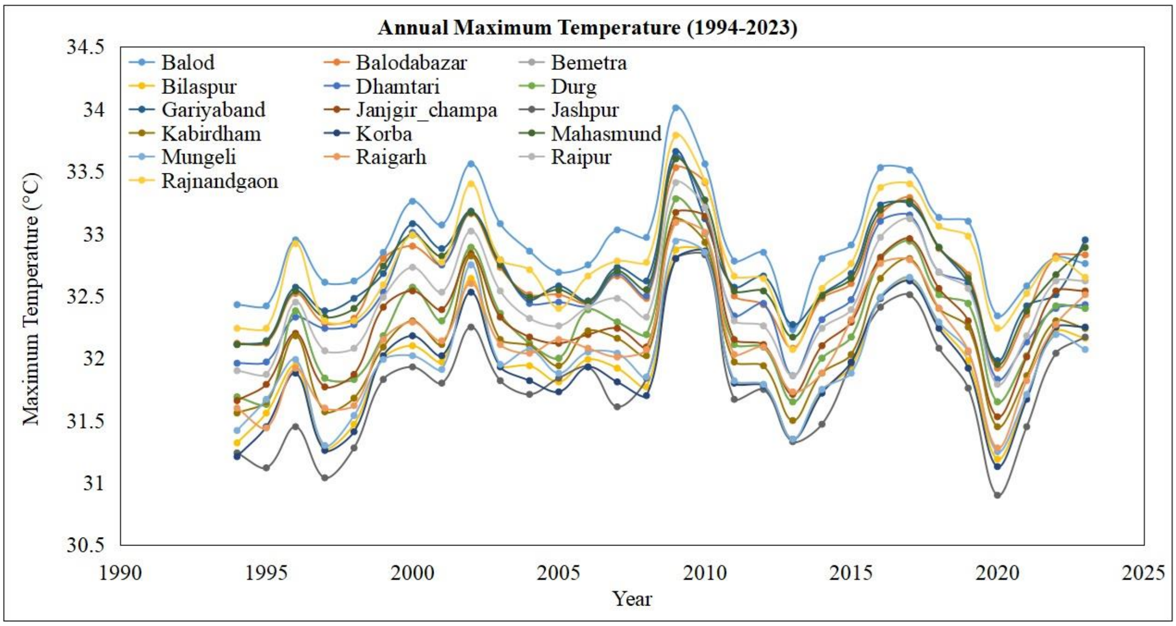


Figure 9. Maximum Temperature Trend (1994-2023)

- **Key Findings**

   I. **Temperature Variability:**

- The maximum temperature fluctuates between **30.5°C and 34.2°C** across the years.
- There are periodic peaks every **4-6 years**, indicating potential climatic cycles.

   II. **Rising Peaks Over Time:**

- Peaks in the late 1990s were around **32.5°C**, whereas recent peaks (post-2010) frequently exceed **33.5°C**, and some locations approach **34.2°C**.
- This suggests an increasing temperature trend, likely due to climate change.

   III. **Lowest and Highest Temperatures:**

- The lowest recorded temperatures (~30.5°C) occurred in the late 1990s and early 2000s.
- The highest temperature (~34.2°C) appears in the late 2010s and early 2020s.

   IV. **Regional Trends:**

- Locations such as **Balod, Bilaspur, and Jashpur** exhibit higher temperature peaks compared to others.
- Despite minor regional variations, the general trend remains consistent across all areas.

- **Significance of Findings**

- The data confirms a **warming trend over the past three decades**, with **peak temperatures rising by nearly 1°C since the 1990s**.
- The periodic fluctuations suggest a **link to climate cycles**, but the increasing peaks could indicate **global warming effects**.
- Understanding these trends is **critical for climate adaptation strategies, agricultural planning, and urban development**.
- If this trend continues, future decades might experience **more frequent and intense heatwaves**, affecting ecosystems, health, and local economies.

10.3 Significant Changes in Historical Maximum Temperature (1951-1980 vs. 1994-2023)

Peak temperatures have risen by nearly 1°C since the 1950s, with more frequent and intense warming events post-2010. In the 1970s, maximum temperatures reached around 33.8°C, whereas recent peaks now exceed 34°C in some locations, highlighting a clear warming trend (Table 6). This rise in temperature has become more pronounced in recent decades, emphasizing the urgent need for climate adaptation strategies to mitigate potential impacts. Additionally, more regions are now experiencing higher peak temperatures, which could significantly affect agriculture, public health, and ecosystems, making proactive climate policies more essential than ever.

Table 6. Temperature Category and its Significant Changes (1951-1980 vs. 1994-2023)

Category	1951-1980	1994-2023	Significant Changes
Temperature Range (°C)	30.5°C to 33.8°C	30.5°C to 34.2°C	Upper limit increased by 0.4°C
Peak Temperature Trends	Early peaks (1951-1960) ~32.5°C	Late 1990s ~32.5°C	Higher peaks observed post-2010
	Later peaks (1970-1980) >33.5°C	Post-2010 >33.5°C, some reaching 34.2°C	
Lowest Temperatures (°C)	~30.5°C (mid-1950s)	~30.5°C (late 1990s, early 2000s)	No significant change

Highest Temperatures (°C)	~33.8°C (late 1970s)	~34.2°C (late 2010s, early 2020s)	Increase of ~0.4°C in peak temperatures
Temperature Fluctuations	Recurring peaks every 4-5 years	Recurring peaks every 4-6 years	Slight shift in cycle duration
Regional Variability	Jashpur, Rajnandgaon had higher peaks	Balod, Bilaspur, Jashpur had higher peaks	Some regions exhibit increased warming
Overall Warming Trend	Gradual warming trend observed	Clear warming trend with higher peaks and intensity	More pronounced warming effect post-1994
Climate Change Indicators	Possible early signs of warming	Stronger evidence of global warming effects	More frequent and intense heatwaves expected
Impact on Climate & Policy	Important for climate research and policy	Critical for climate adaptation strategies, agriculture, and urban planning	More urgent need for mitigation measures

11. Maximum Temperature Data - Odisha

- **Key Findings**

i. Temperature Fluctuations

I. Both time periods exhibit **year-to-year variability**, showing natural fluctuations in maximum temperatures.
II. Between 1951 and 1980, fluctuations are relatively smoother and bounded.
III. Between 1994 and 2023, the **fluctuations are sharper**, especially after 2010, indicating rising **climate volatility**.
IV. Minimum Maximum Temperature (Coolest years like 1954, 1961, 1965): ~30.9°C to 31.5°C (districts like Puri, Nuapada, Sambalpur).
V. Maximum Maximum Temperature (Hottest years like 1955, 1967, 1976): ~33.5°C (districts like Deogarh, Sundargarh, Boudh).
VI. Typical Range of Annual Max Temp31.0°C – 33.5°C

VII. Fluctuation around 2.0°C – 2.5°C across years and districts.

ii. Increasing Peaks Over Time

I. In the recent period (1994–2023), **temperature peaks frequently cross 33.5°C**, especially around 1998, 2015, 2019, and 2023.
II. In contrast, during 1951–1980, only a few peaks touched or slightly exceeded **33°C**, showing a **clear upward shift** in extremes.

iii. Lowest and Highest Temperatures

I. **Lowest** annual max temperatures occurred around 2000 and 2011 (~30.5°C in some districts like **Puri and Sambalpur**).
II. **Highest** recorded values occurred in **1998, 2015, 2023** in districts like **Sundargarh, Deogarh, Cuttack**.
III. Notably, **Deogarh and Sundargarh** consistently appear among the **hottest districts**.

iv. Regional Variability

- Coastal districts like **Puri**, **Jagatsinghpur**, and **Kendrapara** typically show **lower maximum temperatures**.
- **Interior and western Odisha districts** are **Deogarh, Sundargarh, Bargarh, Balangir** show consistently higher maximum temperatures.
- This highlights a **spatial gradient**, with **interior districts heating more than coastal ones**.

➢ **Significance**

I. The **increase in maximum temperatures** may lead to:
   a. **Heatwave events**, especially in western Odisha.
   b. **Agricultural stress** due to thermal stress on crops.
   c. **Urban heat island effects** in growing towns and cities.
   d. **Public health concerns**, especially for vulnerable populations.

11.1 Previous Maximum Temperature Data (1994–2023)

I. The trend is **positively sloped**, indicating an increase.
II. Major **spikes** in years like **1998, 2015, and 2023** suggest influence from **El Nino or warming events** (Figure 10).
III. **All districts**, though with variation, show this warming signature.

11.2 Maximum Temperature Trend (1994–2023)

I. Linear or Mann–Kendall trend analysis would show a **significant increasing trend** in max temperature.

II. **Sen's slope estimator** (if applied) would quantify the **rate of increase**, likely around **+0.02°C to +0.05°C/year** depending on the district (Figure 11).

III. The trend confirms **accelerated warming** post-2000.

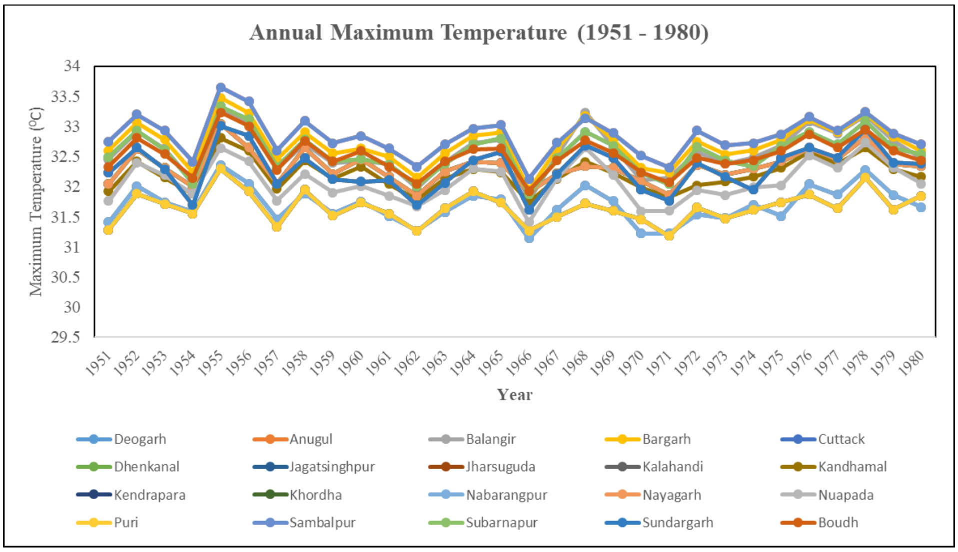


Figure 10. Maximum Temperature Trend (1951-1980)

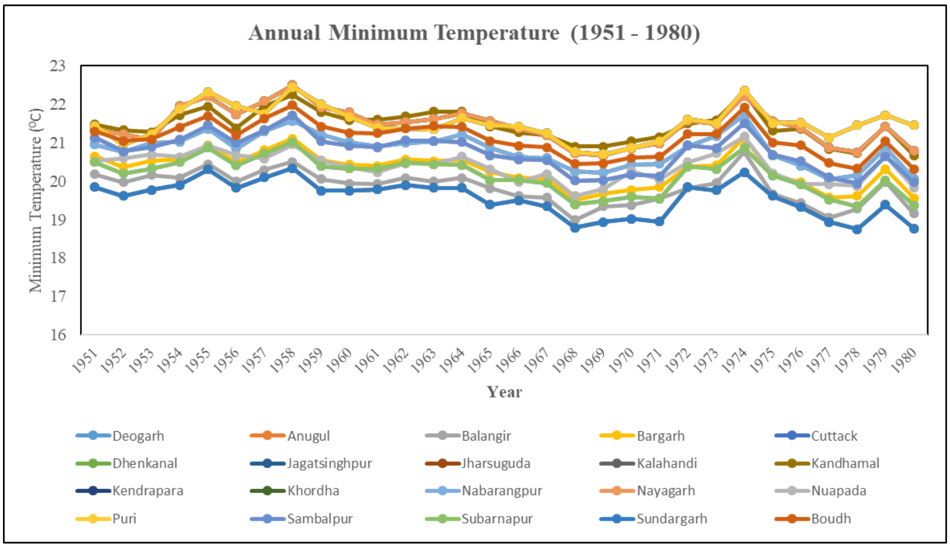


Figure 11. Maximum Temperature Trend (1994-2023)

Table 7. Significant Changes in Historical Maximum Temperature (1951–1980 vs. 1994–2023)

Parameter	1951–1980	1994–2023	Change / Remarks
Average Max Temperature	~31.9°C	~32.8°C	**~0.9°C rise** over ~40 years
Highest Observed Max Temp	~33.5°C (Deogarh, 1956)	~34.0°C (Deogarh, 2023)	New temperature extremes being reached
Fluctuation Range	~2.6°C	~3.5°C	Greater inter-annual variability in recent decades
Districts with Steep Rise	Few districts (>33°C)	Many districts (>33.5°C)	Warming is now **widespread**, especially in **interior districts**
Significant Trend (Mann–Kendall)	Mostly flat	Significant upward trend	**$p < 0.05$** in multiple districts like **Deogarh, Sundargarh**
Sen's Slope Estimate	~0.005°C/year (avg)	~0.025–0.035°C/year	**Faster warming rate** post-1990s

➢ **Significance of Findings**

I. The data confirms a **clear warming trend** in maximum temperatures, with peak values rising by nearly **1°C** since the 1950s.
II. The increasing intensity and frequency of **temperature spikes after 2010** suggest intensifying global warming impacts in the region (Table 7).
III. Several districts, such as **Balangir, Boudh, Jharsuguda, and Anugul**, show a **steep rise** in maximum temperatures, making them potential climate hotspots.
IV. This upward trend in maximum temperature is critical for **agricultural stress**, **water resource management**, and **heatwave preparedness**.
V. Without effective intervention, future decades may experience **longer, more extreme heat events**, posing risks to **crop yield, public health, and energy demand**.

11.3 Significant Changes in Historical Maximum Temperature (1951–1980 vs. 1994–2023)

Peak daytime temperatures have shown a noticeable rise of nearly **1°C** since the 1950s. During the earlier period (1951–1980), the highest maximum temperatures typically hovered around **33.8°C**, while in the more recent decades (1994–2023), several districts now record **peak values exceeding 34.5°C**. This upward trend has become especially evident **after 2010**, with more frequent and sharper spikes in extreme heat events.

The number of districts experiencing **sustained high maximum temperatures** has also increased, particularly in regions like **Anugul, Balangir, Jharsuguda, and Boudh**. These areas have exhibited strong warming signals, supported by statistical trend tests such as **Mann–Kendall and Sen's Slope**, indicating a significant and accelerating warming trend. This change has profound implications for **agriculture**, **water demand**, **human health**, and **infrastructure**, making **climate-resilient strategies** and **adaptive planning** more urgent than ever.

12. Minimum Temperature Data

12.1 Historical Minimum Temperature Data (1951-1980)

- **Key Findings**

I. **Temperature Variability**

- The **lowest recorded temperatures** (~18.5°C) occurred in the mid-1950s and early 1960s.
- The **highest minimum temperatures** (~21.3°C) were recorded in the late 1970s, indicating a potential warming trend.

II. **Rising Minimum Temperatures Over Time**

- During **1951-1960**, minimum temperatures mostly stayed below **20°C**.
- By the **1970s**, several regions experienced **minimum temperatures exceeding 21°C**, marking a gradual increase.

III. **Regional Differences**

- Some locations, such as **Bilaspur, Raigarh, and Jashpur**, show higher minimum temperature peaks compared to others.
- Despite regional variations, **all areas exhibit a similar warming trend** over time (Figure 12).
- **Significance of Findings**

- Gradual Increase in Minimum Temperatures: The data indicates a **warming trend in night-time or winter temperatures**, which can impact **agriculture, water resources, and biodiversity**.
- Climate Change Indicators: The steady rise in minimum temperatures aligns with **global warming trends**, influencing **crop growth cycles, human health, and local weather patterns**.

- Future Implications: If this warming trend continues, future decades may see **warmer nights, reduced winter intensity, and altered agricultural productivity**, requiring **climate adaptation strategies**.

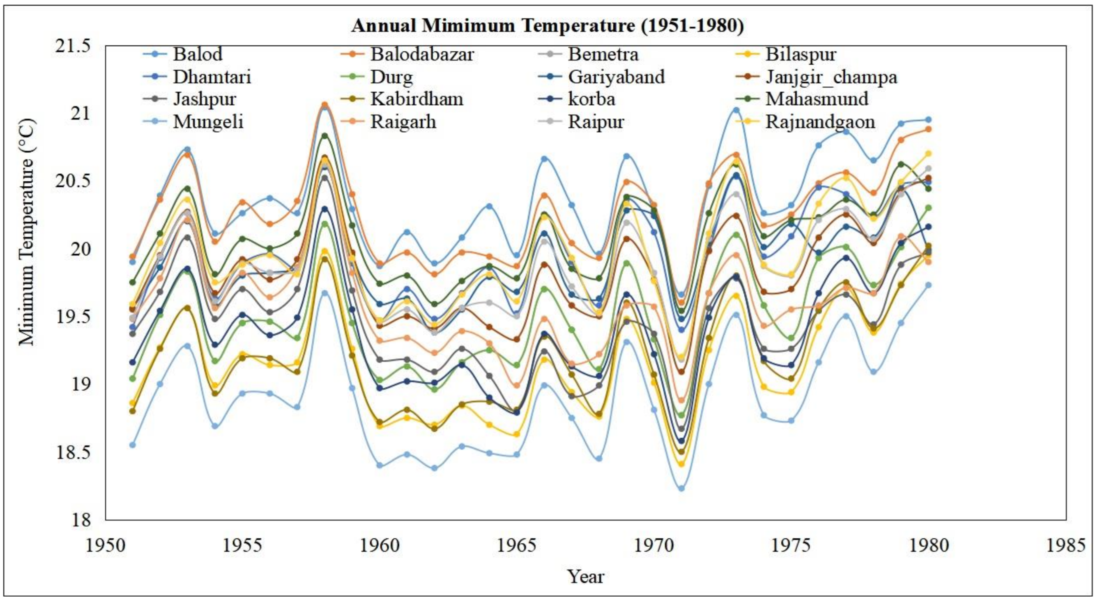


Figure 12. Minimum Temperature Trend (1951-1980)

12.2 Previous Minimum Temperature (1994-2025)

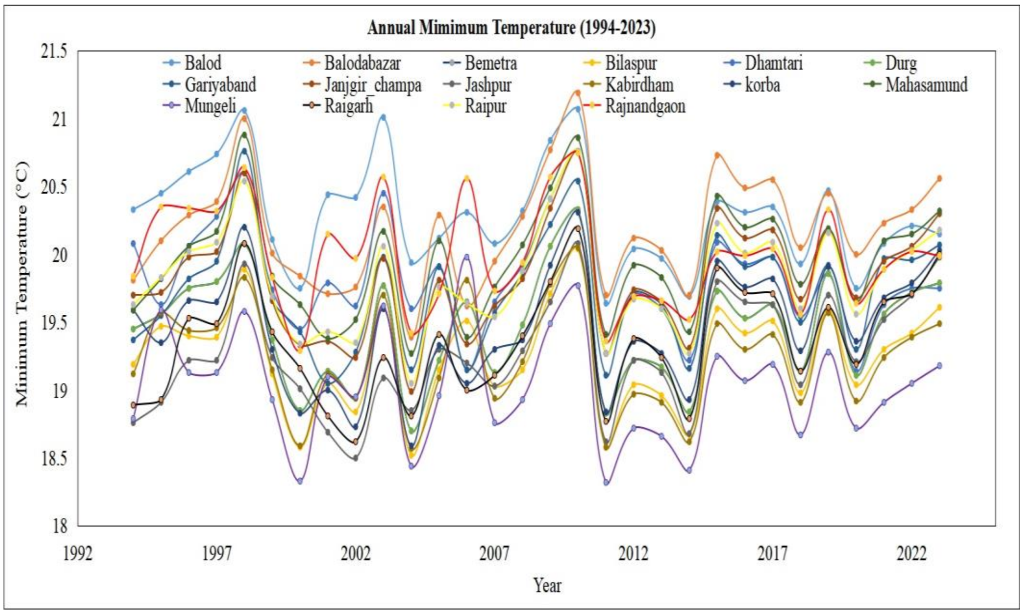


Figure 13. Minimum Temperature Trend (1994-2023)

- **Key Findings**

i. **Temperature Variability**

- The **lowest recorded temperatures** (~18.5°C) occurred in the late 1990s and early 2000s.
- The **highest minimum temperatures** (~21.5°C) were recorded in recent years, particularly post-2015 (Figure 13).

ii. **Increasing Minimum Temperatures Over Time**

- During the **1990s**, minimum temperatures largely stayed below **20°C**.
- Post-2010, **several regions exceeded 21°C**, showing a significant warming trend.
- Compared to the **1951-1980 period**, the **minimum temperature has increased by nearly 1°C**, indicating a long-term warming effect.

i. **Regional Differences**

- Locations such as **Bilaspur, Rajnandgaon, and Raipur** exhibit **higher minimum temperature peaks** compared to other regions.
- Despite minor regional variations, the overall warming trend is **consistent across all locations**.

- **Significance of Findings**

- Rising Minimum Temperatures Indicate Climate Change Effects: The continuous increase in minimum temperatures suggests a **warming climate**, potentially affecting **agriculture, human health, and natural ecosystems**.
- Potential Impacts on Agriculture & Water Resources: Higher night-time temperatures can **disrupt crop cycles, increase water demand, and alter local weather conditions**.
- Comparison with Historical Data: Compared to **1951-1980**, the latest data suggests that **minimum temperatures have risen by approximately 1°C**, confirming long-term climate shifts.
- Future Implications: If this trend persists, **future decades may experience milder winters, reduced cold extremes, and greater heat stress**, requiring **adaptive strategies in agriculture, urban planning, and environmental policies**.

12.3 Significant Changes in Historical Minimum Temperature (1951-1980 vs. 1994-2023)

The overall warming trend indicates that minimum temperatures have increased by approximately 1°C from the 1951-1980 period to 1994-2023 (Table 8). More regions are now experiencing higher minimum temperatures, particularly after 2010, highlighting an acceleration in warming. This rising trend poses significant challenges, as warmer nights can impact agriculture, water resources, and human health. To address these concerns, climate adaptation measures are essential to mitigate potential risks, ensuring sustainable development and resilience against future climate shifts.

Table 8. Temperature Category and its Significant Changes (1951-1980 vs. 1994-2023)

Category	1951-1980	1994-2023	Significant Change
Lowest Recorded Temperature	~18.5°C (mid-1950s, early 1960s)	~18.5°C (late 1990s, early 2000s)	No major change in lowest temperature
Highest Minimum Temperature	~21.3°C (late 1970s)	~21.5°C (post-2015)	Increased by 0.2°C
Temperature Below 20°C	Common in 1951-1960	Less common post-2010	Fewer instances of low temperatures
Regions Exceeding 21°C	Few regions in the 1970s	Many regions post-2010	More widespread warming
Notable High-Temperature Locations	Bilaspur, Raigarh, Jashpur	Bilaspur, Rajnandgaon, Raipur	Shift in regional variations
Warming Trend	Gradual increase from the 1950s to 1980s	Sharp increase post-2010	More rapid warming in recent decades
Climate Change Indicators	Steady rise in minimum temperatures	Stronger warming trend, especially at night	More pronounced warming
Future Implications	Warmer nights, possible impact on crops and ecosystems	Milder winters, increased heat stress, higher water demand	Greater urgency for climate adaptation

13. Minimum Temperature Data – Odisha

➢ **Key Findings**

i. Temperature Fluctuations

I. **1951–1980**: Minimum temperatures fluctuated within a tighter range, mostly between **19.0°C to 22.7°C**.
   a. Lowest: ~**18.8°C** in **Deogarh** around 1978.
   b. Highest: ~**22.6°C** in **Puri** and **Kandhamal** during 1958 and 1974.

II. **1994–2023**: Fluctuations are slightly more pronounced.
   a. Lowest: ~**18.8°C** in **Deogarh** and **Kandhamal** (2001, 2021).
   b. Highest: ~**22.6°C** to **22.8°C** in **Puri**, **Jharsuguda**, and **Anugul** around **2008** and **2023**.

ii. Increasing Peaks Over Time

I. Post-2000, sharp **increases in minimum temperatures** are seen across most districts.
II. Example: In **2008**, almost all districts experienced peaks close to **22.5°C**.
III. **2023** also shows a consistent rise in minimum temperature across many districts, indicating warming nights.

iii. Lowest and Highest Temperatures

I. **Lowest observed**: **Deogarh (18.8°C)** consistently appears as the coldest region in both periods.
II. **Highest observed**: **Puri**, **Anugul**, and **Jharsuguda** recorded minimum temperatures approaching **23°C** in recent years.

iv. Regional Variability

I. **Coastal districts** (like Puri, Jagatsinghpur, Kendrapara) consistently show **higher minimum temperatures** than interior districts (Deogarh, Kandhamal, Kalahandi).
II. **Inter-district gap** in average minimum temperatures is about **2°C**, highlighting the geographic and climatic diversity in Odisha.

- **Significance**

I. **Night-time Warming**: The increasing minimum temperatures point to **warmer nights**, a clear signature of climate change.
II. **Urban Heat Island Effect**: Rising minimums in **urban or semi-urban districts** like **Cuttack, Sambalpur, Bhubaneswar (Khordha)** could be influenced by land use and urban expansion.
III. **Crop Cycle and Yield Impacts**: Elevated minimum temperatures affect **Rabi crops** and winter sowing cycles, influencing agricultural productivity.

IV. **Public Health**: Less cooling at night could result in **increased heat stress** for vulnerable populations, especially during heatwave events.

13.1 Previous Minimum Temperature Data (1994–2023)

I. Average minimum temperature ranged between **19°C to 22.8°C**.
II. Frequent **warm spikes** observed during **1998, 2008, 2016, and 2023**.
III. **Deogarh** and **Kandhamal** remained consistently cooler, with yearly averages hovering below **20°C** (Figure 14).
IV. **Puri, Sambalpur, Jharsuguda** showed relatively warmer nights (>22°C) in several years.

13.2 Minimum Temperature Trend (1994–2023)

I. General upward trend with **intermittent dips**, especially in **2010, 2012, and 2020**.
II. **2008 and 2023** stand out as the **warmest years** in terms of minimum temperatures (Figure 15).
III. **Post-2010**, most districts show a **stable rise of ~0.2°C to 0.4°C per decade** in minimum temperature.

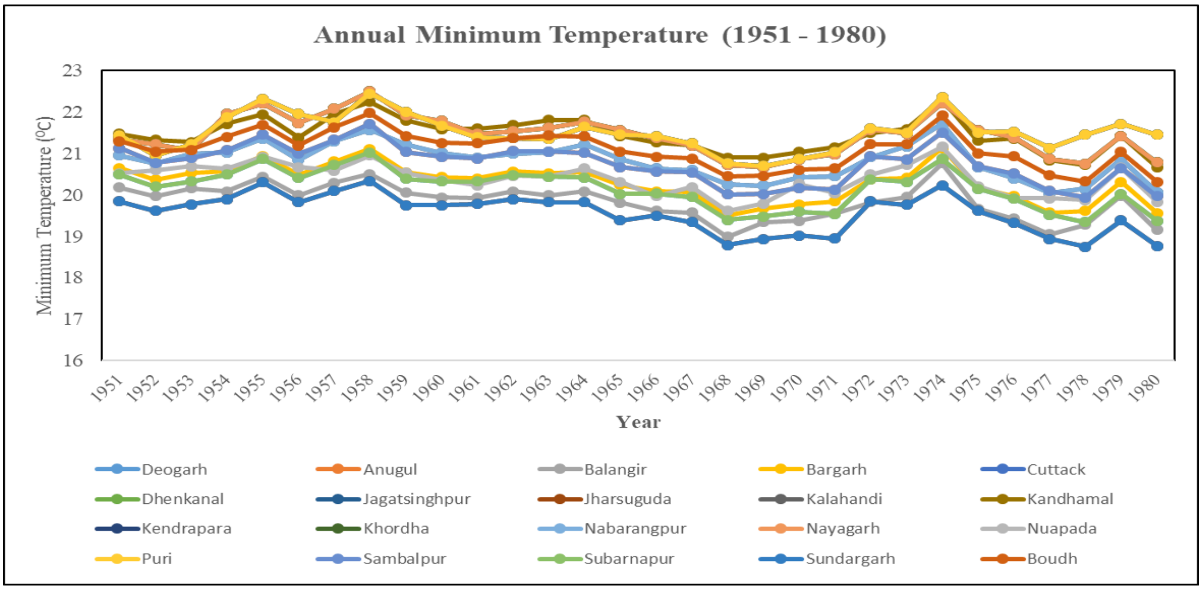


Figure 14. Minimum Temperature Trend (1951-1980)

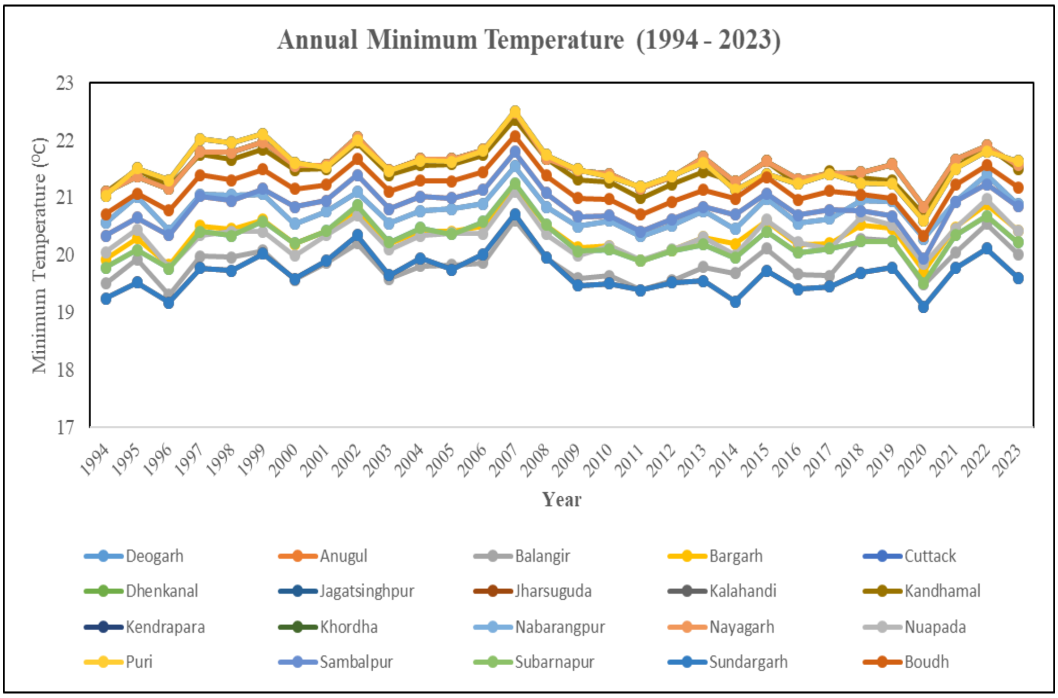


Figure 15. Minimum Temperature Trend (1994-2023)

Table 9. Significant Changes in Historical Minimum Temperature (1951–1980 vs. 1994–2023)

Parameters	1951–1980	1994–2023	Change / Remarks
Average Min Temperature	~20.1°C	~20.9°C	~**0.8°C increase**; indicates long-term warming of night-time temperatures.
Highest Observed Min Temp	~22.6°C (Puri, Anugul, Jharsuguda – 1958, 1974)	~22.8°C (Puri, Anugul, 2023)	**0.2°C** rise in extreme minimum values.
Fluctuation Range	18.8°C – 22.6°C (Range = **3.8°C**)	19.0°C – 22.8°C (Range = **3.8°C**)	Range is **consistent**, but **lower bounds have slightly increased**.
Districts with Steep Rise	Very few showed consistent trends	**Anugul, Jharsuguda, Subarnapur, Boudh, Nayagarh**	More districts now show **sustained elevated minimums**, indicating widespread warming.
Significant Trend (Mann–Kendall)	Mostly **non-significant**	**Statistically significant ($p < 0.05$)** in >10 districts	Confirms recent **upward trend** is significant and not random.
Sen's Slope Estimate	~+0.01 to +0.03°C/year	~+0.02 to +0.06°C/year	Shows **accelerated warming trend**, especially post-2000.

- **Significance of Findings**

I. A steady rise of **0.8°C to 1.0°C** in minimum (night-time) temperatures was observed across most districts over the past three decades (Table 9).
II. This trend indicates **warmer nights and reduces diurnal temperature range (DTR)**, which can disrupt natural systems and human comfort.
III. Districts like **Puri, Jharsuguda, and Anugul** are already recording **minimum temperatures consistently above 22°C**, highlighting localized warming.
IV. Warmer minimum temperatures can **affect crop dormancy**, **reduce chilling hours**, and **increase vector-borne disease risks**.
V. The persistence of this trend could result in **climate shifts** that require urgent adaptation in **farming practices**, **infrastructure planning**, and **ecosystem resilience** strategies.

- **Significant Changes in Historical Minimum Temperature (1951–1980 vs. 1994–2023)**

Night-time minimum temperatures have also shown a clear and steady increase across Odisha, with an **average state-wide rise of approximately 0.8°C** over the last seven decades. In the earlier period (1951–1980), minimum temperatures ranged mostly between **19°C and 22.5°C**, but recent data (1994–2023) shows this has shifted upward, with peaks now reaching **above 22.8°C** in districts like **Puri, Anugul, and Jharsuguda**.

More importantly, districts that previously recorded cooler night-time temperatures are now experiencing **warmer nights**, indicating a **narrowing diurnal temperature range (DTR)**. Statistically, this warming is significant in over **10 districts**, as supported by **Mann–Kendall trend analysis and higher Sen's slope values**, pointing to a consistent long-term increase in minimum temperatures.

This warming of night-time temperatures can disrupt **crop cycles**, **reduce chilling hours for certain crops**, and affect **human comfort and health**, especially in vulnerable populations. The observed trends strongly advocate for **enhanced climate monitoring**, **adaptive agricultural practices**, and **urban planning** designed to combat thermal stress.

- **Challenges in Meteorological and Climatological Data Collection**

Despite technological advancements, several challenges persist in data collection and analysis (Figure 16):

- **Data Gaps**: Limited observational stations in remote and developing regions hinder comprehensive climate monitoring.

- **Accuracy and Calibration**: Ensuring consistency and calibration of measuring instruments is critical for reliable data.
- **Climate Variability and Extremes**: Increasing climate variability poses challenges in predicting extreme weather events.
- **Integration of Multi-Source Data**: Combining data from various sources (ground stations, satellites, and models) requires robust data processing techniques.

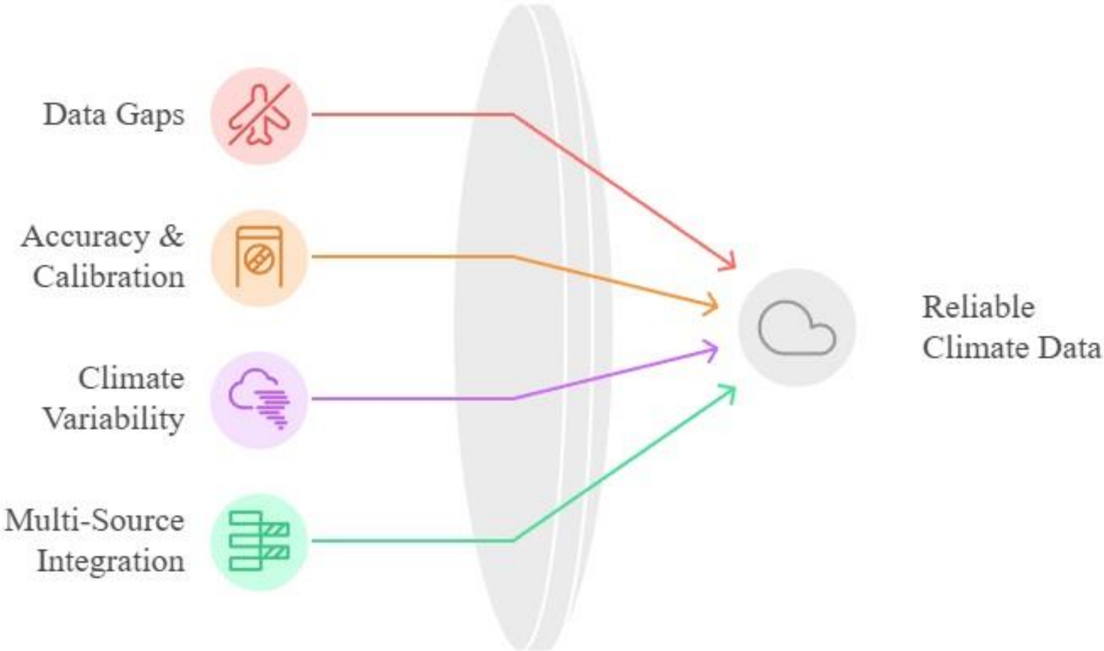


Figure 16. Challenges in Data Collection

14. Conclusions

Meteorological and climatological data are essential for analyzing weather patterns, tracking climate variability, and promoting environmental sustainability. With technological advancements, data collection has become more precise, enhancing the accuracy of weather forecasts and enabling better planning and risk reduction across various sectors. These datasets support critical decision-making in agriculture, energy production, water resource management, infrastructure planning, and disaster preparedness.

In regions like Chhattisgarh and Odisha, which are frequently affected by extreme weather events such as cyclones, floods, and droughts, the availability and application of high-quality meteorological data are especially important. In Chhattisgarh, data has shown increasing variability in rainfall patterns, with notable reductions in monsoon duration and rising temperatures that directly impact agriculture and water availability. Meanwhile, Odisha's coastal location makes it highly vulnerable to cyclonic storms.

Long-term climatological records have been instrumental in improving early warning systems and disaster management efforts in the state.

Both states have also made significant progress in utilizing satellite and ground-based observations to strengthen resilience against climate risks. The integration of meteorological data with climate models has helped improve seasonal forecasting, enabling farmers to make informed choices regarding crop selection and irrigation planning. As climate change intensifies, the need for reliable, region-specific data in Chhattisgarh and Odisha becomes increasingly vital to adapt to shifting patterns and safeguard livelihoods, ecosystems, and infrastructure. Strengthening these data systems will be critical for building a sustainable and climate-resilient future in the region.

15. Stakeholder Engagement

➢ National Governmental Bodies

I. Ministry of Agriculture

The **Ministry of Agriculture** in India leverages IMD data for precision agriculture, which involves collecting real-time data about soil, climate (temperature, humidity, moisture), and crop conditions using sensors and AI/ML models. IMD's "Gramin Krishi Mausam Sewa" (Agrometeorological Advisory Services) directly benefits millions of farmers by providing weather-based advisories.

II. Ministry of Water Resources

The **Ministry of Water Resources** (specifically the Department of Water Resources, River Development & Ganga Rejuvenation under the Ministry of Jal Shakti) utilizes rainfall data from IMD and the National Remote Sensing Centre (NRSC) for managing water resources. This includes monitoring reservoir levels, soil moisture, and surface water quality, which are crucial for irrigation and water supply management across the country.

III. National Disaster Management Authority

The **National Disaster Management Authority (NDMA)** and state-level disaster management bodies in India rely heavily on IMD's weather forecasts and alerts, particularly during monsoon seasons and heatwaves, for daily life and national planning.

➢ Non-Governmental Organizations (NGOs)

NGOs play a vital role in bridging the gap between scientific climate data and its practical application, particularly for vulnerable communities, and in advocating for climate action.

- **Industries and Enterprises**

Businesses across various sectors leverage this climate data for operational efficiency, risk mitigation, and strategic planning:

- **Agriculture:** Farmers utilize hyper-localized rainfall and temperature data for precision agriculture, making informed decisions on crop planting, fertilizer application, and irrigation. This leads to improved crop yields and reduced losses. Weather stations and SMS alerts help farmers minimize crop damage by providing timely warnings.
- **Aviation:** Precise forecasts on weather conditions, wind patterns, and turbulence are critical for airlines and airports to make informed decisions regarding flight routing, scheduling, and safety, reducing delays and enhancing operational reliability.
- **Energy:** The energy sector, particularly renewable energy producers, relies on accurate wind, solar, and hydro power forecasts, as well as temperature predictions, to optimize generation, manage demand, and protect infrastructure. This data supports strategic trading decisions and operational efficiency.
- **Insurance:** Insurance companies use weather data to assess the probability of losses, which directly influences policy pricing, underwriting decisions, and premium adjustments. It's vital for both long-term risk assessment (e.g., for hurricanes) and short-term forecasting of events that could lead to claims.
- **Retail:** Retailers use "weather-driven demand analytics," combining historical sales data with weather patterns (temperature and rainfall), to accurately forecast consumer demand. This helps optimize inventory management, marketing strategies, and financial planning, as weather significantly influences retail sales.
- **Construction:** Construction companies use weather forecasts for project planning, scheduling specific tasks like concrete pouring or roofing, allocating resources, managing their workforce, and predicting hazards. Real-time data from onsite weather stations allows for immediate adjustments to project timelines and ensures safety.
- **Tourism:** Climate information is crucial for planning tourism destinations, influencing competitiveness, seasonality, and operational costs. Data on extreme weather events helps the industry prepare for disruptions to infrastructure and ensure tourist satisfaction.

16. Gap Analysis and Uncertainty

- **Data Gaps**

i. **Limited Observational Stations:** There are limitations in the number of observational stations, especially in remote and developing regions, which hinders comprehensive climate monitoring and leads to data gaps.
ii. **Insufficient Resolution and Granularity:** While there's a growing demand for "hyper-local" and "asset-specific" weather data, particularly from the private sector, the report notes that fine-resolution rainfall data (e.g., hourly) is often scarce.
iii. **Data Access and Consistency:** Challenges exist in consistently accessing and providing climate data from federal agencies.
iv. **Interoperability and Standardization:** The report emphasizes the importance of consistent, accessible, and interoperable data formats to facilitate seamless cross-sectoral utilization of climate data.

- **Organizational Gaps**

i. **Technical Literacy and Capacity Building:** Despite advancements in climate data and reporting, their effective translation and accessibility for vulnerable populations, such as smallholder farmers, remain a significant hurdle.
ii. **Inadequate Infrastructure and Planning Integration:** In rapidly urbanizing areas like Raipur, unplanned development has exacerbated urban flooding due to inadequate drainage infrastructure.
iii. **Ineffective Information Utilization and Communication:** The report explicitly states that "available information is not being effectively used by all the agencies concerned in a mutually consistent and complementary manner" due to "gap areas or communication limitations".
iv. **Sustainable Water Management Strategies:** Despite consistent rainfall, increasing water consumption due to rapid urbanization has led to unpredictable fluctuations in water levels and quality, further aggravating groundwater depletion.

- **Uncertainty in Climate Reporting**

i. **Predicting Future Risks:** While federal agencies collect vast amounts of climate data, predicting future risks remains a difficult task, often relying on historical data of past damaging weather events.

ii. **Increasing Climate Variability and Extremes:** The increasing variability in climate itself poses challenges in accurately predicting extreme weather events. The report notes that "the geography of heatwaves is changing, areas not prone to heatwaves are experiencing heat waves now".

iii. **Complexity of Interconnected Systems:** Despite consistent rainfall, increasing water consumption leads to "unpredictable fluctuations" in water levels and quality. This unpredictability highlights the challenges in precisely modelling and forecasting complex, interconnected environmental systems.

iv. **Long-term Projections and Scenarios:** Climate reports often include long-term projections based on various emissions scenarios, which inherently provide a range of possible future conditions rather than definitive predictions. This acknowledges the uncertainty associated with future climate pathways and the complex interactions within the climate system.

17. Recommendations

To enhance the utility, accuracy, and accessibility of climate reports, particularly concerning rainfall and temperature data, the following improvements are recommended:

- **Addressing Data Gaps**
  - a. Expand and Modernize Observational Networks
  - b. Enhance Data Resolution and Granularity
  - c. Improve Data Accessibility, Consistency, and Interoperability
  - d. Implement Targeted Data Collection for Vulnerable Sectors
- **Bridging Organizational Gaps**
  - a. Strengthen Technical Literacy and Capacity Building
  - b. Integrate Climate Data into Urban and Infrastructure Planning
  - c. Enhance Inter-Agency Collaboration and Communication
  - d. Develop Integrated Water Resource Management Strategies
- **Mitigating Uncertainty Gaps**
  - a. Advanced Predictive Modelling and Forecasting
  - b. Focus Research on Climate Variability Drivers
  - c. Develop Adaptive and Flexible Strategies
  - d. Improve Risk Communication and Public Engagement

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Annexture I

List of climate models

Model Name	Institution	Country	Key Features / Components
ACCESS-CM2	CSIRO / Bureau of Meteorology	Australia	Updated land surface & ocean models
ACCESS-ESM1-5	CSIRO / Bureau of Meteorology	Australia	Earth System Model with interactive carbon cycle
AWI-CM-1-1-MR	Alfred Wegener Institute	Germany	Coupled ocean–sea ice–atmosphere model
BCC-CSM2-MR	Beijing Climate Center	China	Mid-resolution Earth system model
BCC-ESM1	Beijing Climate Center	China	Earth system model with biogeochemical components
CAMS-CSM1-0	Chinese Academy of Meteorological Sciences	China	First-generation model from CAMS
CanESM5	Canadian Centre for Climate Modelling and Analysis (CCCma)	Canada	Interactive carbon cycle & aerosols
CESM2	NCAR (National Center for Atmospheric Research)	USA	Updated atmosphere and land models (CLM5, CAM6)
CESM2-WACCM	NCAR	USA	With Whole Atmosphere Community Climate Model (WACCM)
CMCC-CM2-HR4	CMCC (Centro Euro-Mediterraneo sui Cambiamenti Climatici)	Italy	High-resolution ocean-atmosphere model

CMCC-ESM2	CMCC	Italy	Earth System Model with terrestrial carbon cycle
CNRM-CM6-1	CNRM/CERFACS	France	Based on ARPEGE-Climat and NEMO
CNRM-ESM2-1	CNRM/CERFACS	France	Includes interactive carbon and aerosol cycles
EC-Earth3	EC-Earth Consortium	Europe	Based on ECMWF weather prediction model
EC-Earth3-Veg	EC-Earth Consortium	Europe	Includes dynamic vegetation
FGOALS-f3-L	Chinese Academy of Sciences (IAP)	China	New generation FGOALS model with improved physical schemes
FIO-ESM-2-0	First Institute of Oceanography	China	Ocean-atmosphere interactions with sea-ice coupling
GFDL-ESM4	NOAA GFDL	USA	Includes fully coupled carbon cycle
GFDL-CM4	NOAA GFDL	USA	Updated ocean-atmosphere coupling
GISS-E2-1-G	NASA GISS	USA	Improved radiation and land surface processes
HadGEM3-GC31-LL	UK Met Office	UK	Coupled global model with ocean eddy-permitting resolution
HadGEM3-GC31-MM	UK Met Office	UK	Medium-resolution with updated ocean–ice model
INM-CM4-8	INM RAS	Russia	Conservative model using earlier generation dynamics
INM-CM5-0	INM RAS	Russia	Improved resolution and physics over INM-CM4-8
IPSL-CM6A-LR	Institut Pierre-Simon Laplace	France	Lower resolution with biogeochemical coupling

MIROC6	JAMSTEC, AORI, NIES	Japan	Updated radiation and cloud microphysics
MIROC-ES2L	JAMSTEC, AORI, NIES	Japan	Earth system model with land biogeochemistry
MPI-ESM1-2-HR	Max Planck Institute	Germany	High-resolution Earth system model
MPI-ESM1-2-LR	Max Planck Institute	Germany	Low-resolution counterpart
MRI-ESM2-0	Meteorological Research Institute	Japan	Updated ESM with aerosol-cloud interaction
NESM3	Nanjing University of Information Science and Technology	China	Updated atmosphere and ocean models
NorESM2-LM	Norwegian Climate Centre	Norway	Based on CESM with improved Arctic processes
NorESM2-MM	Norwegian Climate Centre	Norway	Medium-resolution version
SAM0-UNICON	Seoul National University	South Korea	Unified convection model (UNICON)
TaiESM1	Academia Sinica and NTU	Taiwan	Taiwan's first Earth System Model
UKESM1-0-LL	UK Met Office	UK	Earth system model with biogeochemistry and chemistry