

# **Review on Global Heatwaves: Drivers, Variability, and Impacts in India**

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## **Abstract**

Heatwaves are among the most severe climate extremes, exerting significant impacts on human health, agriculture, ecosystems, water resources, and infrastructure. Observational evidence demonstrates a substantial increase in the frequency, duration, and intensity of heatwaves across most global land regions since the mid twentieth century, primarily driven by anthropogenic climate change and amplified by regional land–atmosphere feedback mechanisms. Heatwaves are generally defined as prolonged periods of abnormally high temperatures relative to regional climatology; however, operational definitions vary geographically depending on background climate and societal vulnerability. Their occurrence is governed by complex interactions among atmospheric circulation anomalies, soil moisture deficits, radiative forcing, and largescale climate variability such as the El Niño–Southern Oscillation (ENSO), atmospheric blocking, and Rossby wave amplification. Heatwaves across the world—such as the devastating 2003 European heatwave, the 2010 Russian heatwave, and the recurring events in India—demonstrate the powerful influence of persistent high-pressure systems and the complex interactions between land and atmosphere. In the near future, climate models consistently project that heatwaves will become more intense as global temperatures rise, with tropical and subtropical regions expected to experience the sharpest increases in heat stress.

India represents a critical zone of vulnerability, demanding urgent attention to adaptation

strategies as heatwaves grow more frequent and severe. Eastern coastal states like Odisha face heightened risks due to the combine effect of tropical circulation shifts, monsoon variability, and land surface feedback. In this review we bring together current knowledge on the nature of heatwaves worldwide—their physical drivers, regional differences, and future trajectories—with a special focus on India, and especially eastern India, where the impacts are likely to be most severe.

### **Keywords**

Heatwaves; climate extremes; ENSO; atmospheric blocking; Rossby waves; land–atmosphere coupling; India heatwaves; Odisha climate; CMIP6 projections

### **1. Introduction**

Heatwaves rank among the most destructive and rapidly intensifying climate extremes, threatening human health, agriculture, ecosystems, and critical infrastructure in equal measure. Heatwave frequency, length, and severity have clearly and consistently increased over most continents since the middle of the 20th century, closely following rises in global temperatures. Since the 1950s, supporting statistics show significant increases in heatwave days, cumulative heat exposure, and the geographic dispersion of high heat (Perkins-Kirkpatrick & Lewis, 2020; Russo et al., 2015). Studies indicate that greenhouse gas emissions have significantly increased both the chances and severity of heatwaves, with clear evidence of human influence across regions including Europe, Asia, Australia, and North America (Stott et al., 2004; Fischer & Schär, 2010; Coumou & Rahmstorf, 2012). Research has firmly proven that the extreme heat events witnessed today are largely attributable to human-induced climate change (Otto et al., 2012; Perkins, 2015; Seneviratne et al., 2021). Evidence from both observations and climate models consistently points to the same conclusion: global warming is driving temperature extremes higher, making severe and prolonged heatwaves increasingly likely across the world (IPCC, 2021; Perkins-Kirkpatrick & Lewis, 2020).

Heatwaves can be defined as extended intervals of abnormally high temperatures relative to the prevailing climate of a region, at least persisting for several consecutive days. Because

baseline climatic conditions vary widely across the globe, the criteria used to identify heatwaves differ accordingly. In tropical countries such as India, absolute temperature thresholds are frequently employed—for example, designating a heatwave when maximum daytime temperatures in the plains reach 40 °C or above. By contrast, temperate regions tend to adopt relative measures, classifying heatwaves on the basis of percentile thresholds derived from long-term historical temperature records (Perkins & Alexander, 2013; Perkins, 2015; Seneviratne et al., 2021). The India Meteorological Department (IMD) has established an operational framework for identifying heatwaves in India, grounded in absolute temperature thresholds and statistically defined departures from long-term climatic norms (Pai et al., 2013; Rohini et al., 2016).

Heatwaves develop through complex interactions between atmospheric circulation, land surface processes, and ocean–atmosphere variability. Persistent high-pressure systems suppress cloud formation and precipitation, allowing increased solar radiation and subsidence-induced warming. Soil moisture depletion further amplifies heat extremes by reducing evaporative cooling and increasing sensible heat flux. Large-scale atmospheric dynamics, including Rossby wave amplification and jet stream displacement, play a key role in maintaining prolonged heatwave conditions. In addition, oceanic climate models such as ENSO influence regional heatwave occurrence by modifying atmospheric circulation and precipitation patterns.

Major heatwave events over Europe (2003), Russia (2010), Australia (2013), and India (2015 and 2019) demonstrate the devastating societal and environmental impacts of extreme heat. Climate model projections indicate that heatwaves will continue to intensify under future warming scenarios, particularly in tropical and subtropical regions. India, especially eastern coastal regions such as Odisha, is highly vulnerable due to combined effects of tropical climate variability, monsoon dynamics, and high population exposure.

## **2. Heatwave Definitions and Metrics**

### **2.1 Absolute threshold definitions**

The heatwaves are generally estimated by absolute temperature thresholds, commonly used in tropical and subtropical regions where baseline temperatures are high. In case of India, heatwaves in India are declared when daily maximum temperatures exceed 40 °C in plains

regions or when temperatures exceed 45 °C regardless of climatological anomaly. Similar absolute thresholds are used in China and parts of the Middle East.

## **2.2 Relative percentile-based definitions**

Climate research commonly defines heatwaves using percentile-based thresholds, such as daily maximum temperatures exceeding the 90th or 95th percentile for at least three consecutive days. This approach allows consistent comparison across regions with different climates.

## **2.3 Heat stress-based indices**

Indices such as the Excess Heat Factor and wet-bulb temperature incorporate both temperature intensity and human physiological stress, providing improved assessment of heatwave impacts.

# **3. Physical Mechanisms of Heatwaves**

## **3.1 Atmospheric Blocking**

Atmospheric blocking is a large-scale, quasi-stationary circulation anomaly characterized by a persistent high-pressure system in the mid-latitudes that disrupts the normal west-to-east progression of synoptic weather systems. These blocking systems can persist for several days to weeks and significantly alter regional weather patterns, often leading to prolonged heatwaves, droughts, or cold spells (Rex, 1950; Barriopedro et al., 2010; Woollings et al., 2018). Blocking is typically identified by strong positive geopotential height anomalies at the 500-hPa level and a reversal or weakening of the usual zonal flow.

### **Dynamical formation mechanism**

The fundamental mechanism responsible for atmospheric blocking involves the amplification and breaking of planetary-scale Rossby waves. Rossby waves arise due to the conservation of potential vorticity in a rotating atmosphere and are strongly influenced by meridional temperature gradients and background westerly winds (Holton & Hakim, 2013). Under favorable conditions, such as enhanced baroclinicity or upstream wave forcing, these waves can amplify significantly and slow their eastward propagation. When Rossby waves reach sufficiently large amplitudes, irreversible wave breaking occurs, resulting in the redistribution of potential vorticity and the formation of a persistent anticyclonic circulation anomaly (McIntyre & Palmer, 1983; Pelly & Hoskins, 2003). This process leads to the development of

a blocking high that disrupts the zonal jet stream and diverts storm tracks poleward or equatorward.

Blocking events are intimately linked to the structure and variability of the mid-latitude jet stream. The presence of a blocking high often causes the jet stream to split into two branches, forming a characteristic omega ( $\Omega$ -shaped) or dipole circulation pattern (Rex, 1950; Tibaldi & Molteni, 1990). This split flow prevents the normal progression of transient weather systems and results in persistent atmospheric conditions over affected regions. Numerical modelling and reanalysis studies have confirmed that blocking formation is linked to upstream wave energy propagation and convergence of wave activity flux, which reinforces the stationary high-pressure anomaly (Nakamura & Huang, 2018; Woollings et al., 2018).

### **Maintenance and feedback processes**

Several dynamical and thermodynamical feedback mechanisms contribute to the persistence of atmospheric blocking. One important factor is diabatic heating associated with cloud formation and latent heat release, which enhances upper-tropospheric ridging and strengthens the blocking circulation (Pfahl et al., 2015). Radiative processes, particularly clear-sky radiative cooling and increased solar heating under anticyclonic conditions, further reinforce subsidence and atmospheric stability, prolonging the blocking event.

Surface-atmosphere interactions also play a significant role in maintaining blocking systems. Reduced cloud cover under high-pressure conditions enhances surface warming and stabilizes the lower atmosphere, reinforcing the anticyclonic circulation (Miralles et al., 2014). In addition, ocean-atmosphere coupling and sea surface temperature anomalies can influence stationary wave patterns and promote blocking development (Hoskins & Karoly, 1981).

Changes in large-scale circulation associated with Arctic amplification and reduced meridional temperature gradients have also been linked to modifications in blocking frequency and persistence. Weaker zonal winds favor increased wave amplification and reduced wave phase speed, creating conditions conducive to blocking formation (Francis & Vavrus, 2012; Screen & Simmonds, 2014). However, the exact relationship between climate change and blocking frequency remains an active area of research.

### **Impacts and observational evidence**

Atmospheric blocking is strongly associated with extreme weather events across the Northern Hemisphere. Persistent blocking highs can produce prolonged heatwaves by suppressing cloud

formation and precipitation while enhancing solar radiation at the surface. The devastating European heatwave of 2003 and the catastrophic Russian heatwave of 2010 stand as exemplary of how persistent atmospheric blocking patterns can be prolonged and deadly heat events on densely populated regions (Barriopedro et al., 2010; Otto et al., 2012). Same way, winter blocking events can lead to severe cold outbreaks by allowing cold polar air to penetrate into mid-latitude regions (Cattiaux et al., 2010).

Blocking also contributes to drought development by diverting storm tracks away from affected regions, reducing precipitation over extended periods (Schubert et al., 2014). Observational analyses using reanalysis datasets such as ERA-Interim and ERA5 have confirmed that blocking events are associated with significant geopotential height anomalies, reduced zonal wind speeds, and persistent circulation patterns lasting several days to weeks (Tibaldi & Molteni, 1990; Woollings et al., 2018).

### **3.2 Rossby Wave Amplification and Jet Stream Dynamics**

Rossby waves are large-scale planetary waves that arise from the conservation of potential vorticity in a rotating atmosphere and the meridional gradient of the Coriolis parameter (Rossby, 1939; Holton & Hakim, 2013). These waves propagate along the mid-latitude jet stream, which acts as a dynamical waveguide due to strong potential vorticity gradients near the tropopause (Hoskins & Ambrizzi, 1993). The phase speed and amplitude of Rossby waves are strongly controlled by the background zonal wind; weaker jet conditions favor slower propagation and larger wave amplitudes, increasing the likelihood of persistent circulation anomalies (Held, 1993; Woollings et al., 2010).

Amplification of Rossby waves occurs through several dynamical processes, including upstream wave energy propagation, nonlinear wave breaking, and quasi-resonant amplification (Petoukhov et al., 2013; Nakamura & Huang, 2018). When Rossby waves reach large amplitudes, potential vorticity contours overturn, producing persistent anticyclonic ridges and atmospheric blocking patterns (McIntyre & Palmer, 1983). These upper-tropospheric ridges induce subsidence, adiabatic warming, and reduced cloud cover, enhancing surface solar radiation and promoting heatwave development (Seneviratne et al., 2010; Miralles et al., 2014).

Jet stream variability plays a critical role in modulating these processes. A weakened or highly meandering jet stream allows Rossby waves to become quasi-stationary, resulting in prolonged

ridging over continental regions and persistent heat extremes (Francis & Vavrus, 2012; Screen & Simmonds, 2014). Such quasi-stationary wave patterns have been linked to major heatwaves, including the European heatwave of 2003 and the Russian heatwave of 2010, both associated with amplified upper-level ridges and disrupted zonal flow (Barriopedro et al., 2010; Otto et al., 2012). Recent studies have further shown that quasi-resonant Rossby waves can synchronize heatwaves across multiple mid-latitude regions, significantly increasing their duration and intensity (Kornhuber et al., 2019).

Climate change may influence Rossby wave dynamics through Arctic amplification, which reduces the equator-to-pole temperature gradient and weakens zonal winds, thereby favoring increased wave amplification and persistence (Francis & Vavrus, 2012; IPCC, 2021). Although uncertainties remain, observational and modeling evidence indicates that interactions between Rossby wave amplification, jet stream variability, and thermodynamic warming will continue to play a central role in the increasing frequency and severity of heatwaves under future climate conditions (Coumou et al., 2015; IPCC, 2021).

### **3.3 Land–Atmosphere Feedbacks**

Land–atmosphere feedbacks are a key thermodynamic mechanism controlling the intensity and persistence of heatwaves, particularly over continental and monsoon regions. Soil moisture availability regulates the partitioning of surface energy into latent and sensible heat fluxes. Under moist conditions, evapotranspiration dissipates a large fraction of net radiation, limiting surface warming. However, during dry conditions, reduced soil moisture suppresses evapotranspiration and increases sensible heat flux, leading to rapid warming of the land surface and lower atmosphere (Seneviratne et al., 2010; Miralles et al., 2014).

This soil moisture–temperature coupling creates a positive feedback, whereby elevated temperatures enhance evaporative demand and further deplete soil moisture, reinforcing heatwave intensity and duration (Fischer et al., 2007; Hirschi et al., 2011). Enhanced sensible heating also deepens the planetary boundary layer and promotes subsidence and atmospheric stability, suppressing cloud formation and increasing solar radiation at the surface (Findell & Eltahir, 2003; Vogel et al., 2017). These processes contribute to the persistence of anticyclonic circulation and atmospheric blocking associated with major heatwave events, such as those observed in Europe (2003) and Russia (2010) (Barriopedro et al., 2010).

Land–atmosphere coupling is particularly strong in transitional and monsoon climates, including India, where pre-monsoon soil moisture depletion and intense solar heating enhance

sensible heat flux and favor the development of thermal lows and heatwaves (Ratnam et al., 2016; Rohini et al., 2016). Climate model projections indicate that increasing temperatures and soil drying under global warming will further strengthen these feedbacks, increasing heatwave frequency and severity in many regions (IPCC, 2021).

### **3.4 Radiative Feedbacks**

Radiative feedbacks significantly amplify heatwaves by increasing net surface energy input under persistent clear-sky and high-pressure conditions. Subsidence associated with anticyclonic circulation suppresses cloud formation, enhancing incoming shortwave solar radiation and increasing surface heating (Seneviratne et al., 2010; Miralles et al., 2014). At the same time, elevated atmospheric temperature and water vapor increase downward longwave radiation, reducing nocturnal cooling and contributing to sustained high daytime and nighttime temperatures (Trenberth & Fasullo, 2012; Perkins-Kirkpatrick Kirkpatrick & Lewis, 2020).

Surface characteristics further modulate radiative feedbacks. Dry soils and vegetation stress reduce evaporative cooling and increase net radiative heating, while urban surfaces with low albedo and high heat storage intensify local warming through the urban heat island effect (Oke, 1982; Zhao et al., 2014). Observational and modeling studies, including analyses of the 2003 European heatwave, show that enhanced solar radiation and reduced cloud cover substantially increased surface heat fluxes and heatwave intensity (Fischer et al., 2007). Under continued greenhouse warming, increased longwave radiative forcing is expected to further increase heatwave frequency and severity (IPCC, 2021).

## **4. Role of Ocean–Atmosphere Variability**

### **4.1 ENSO Influence**

The El Niño–Southern Oscillation (ENSO) is the dominant mode of interannual climate variability and significantly influences global heatwave occurrence through coupled ocean–atmosphere interactions in the tropical Pacific (Philander, 1990; McPhaden et al., 2006). During El Niño events, anomalously warm sea surface temperatures weaken the Walker circulation and shift convection eastward, inducing subsidence and reduced cloud cover over many continental regions. These circulation changes enhance solar radiation, suppress precipitation, and increase surface temperatures, thereby favoring heatwave development (Trenberth et al., 1998; IPCC, 2021).

In India and South Asia, El Niño weakens the summer monsoon circulation and reduces pre-monsoon and monsoon rainfall, leading to soil moisture deficits and enhanced land–atmosphere feedbacks that intensify heatwaves (Ratnam et al., 2016; Rohini et al., 2016). Several major Indian heatwave years, including 1998, 2010, and 2015, coincided with El Niño conditions (Pai et al., 2013). ENSO also modulates heat extremes in Australia, Africa, and Southeast Asia through large-scale atmospheric teleconnections and subsidence-induced warming (Perkins et al., 2012; Mueller & Seneviratne, 2012).

Overall, ENSO influences heatwaves by altering atmospheric circulation, suppressing precipitation, and enhancing radiative and land–atmosphere feedbacks, thereby increasing the likelihood and severity of extreme heat events, particularly during El Niño phases (IPCC, 2021).

#### **4.2 Indian Ocean Dipole (IOD) Influence**

The Indian Ocean Dipole (IOD) is a key mode of ocean–atmosphere variability characterized by anomalous sea surface temperature gradients between the western and eastern Indian Ocean (Saji et al., 1999; Webster et al., 1999). During positive IOD events, cooler SSTs in the eastern Indian Ocean suppress convection and rainfall over South and Southeast Asia, enhancing subsidence, reducing cloud cover, and increasing surface solar radiation, which favors heatwave development over the Indian subcontinent (Ashok et al., 2001; IPCC, 2021).

Positive IOD phases are associated with reduced rainfall and soil moisture deficits over central and eastern India, strengthening land–atmosphere feedbacks and increasing heatwave likelihood, whereas negative IOD phases generally enhance convection and suppress extreme heat (Behera et al., 2005; Ratnam et al., 2016). The IOD can also interact with ENSO, and concurrent El Niño and positive IOD events can significantly intensify drought and heatwave conditions over India (Meyers et al., 2007; IPCC, 2021).

#### **4.3 Other Climate Modes**

In addition to ENSO and the Indian Ocean Dipole, several other large-scale climate modes influence heatwave variability by modulating atmospheric circulation, sea surface temperatures, and land–atmosphere interactions. The Madden–Julian Oscillation (MJO), a dominant mode of tropical intraseasonal variability, affects convection and atmospheric circulation over the Indian Ocean and western Pacific. Suppressed convective phases of the MJO enhance subsidence and clear-sky conditions over South Asia, increasing solar radiation

and favoring heatwave development, particularly during the pre-monsoon season (Zhang, 2005; Ratnam et al., 2016).

The Pacific Decadal Oscillation (PDO) and the Atlantic Multidecadal Oscillation (AMO) shape heatwave occurrence through their long-term modulation of sea surface temperatures and planetary wave patterns. Positive phases of these oscillations are associated with increased continental warming and changes in atmospheric circulation that can enhance heatwave frequency and persistence (Knight et al., 2006; Dong et al., 2017). These modes can also modulate ENSO teleconnections, altering regional heatwave risk.

In the Northern Hemisphere mid-latitudes, the North Atlantic Oscillation (NAO) and the Arctic Oscillation (AO) play a fundamental role in governing jet stream positioning and the frequency of atmospheric blocking events. Depending on their phase, these modes can promote persistent anticyclonic circulation and suppressed cloud cover, substantially raising the likelihood of extreme heat events, particularly across Europe and Asia (Cassou et al., 2005; Woollings et al., 2010).

Overall, these climate modes influence heatwaves by modifying large-scale circulation, subsidence, and precipitation patterns, often interacting with ENSO and regional land-atmosphere feedbacks to determine the timing and severity of extreme heat events (IPCC, 2021).

## **5. Global Heatwave Case Studies**

### **5.1 European Heatwave (2003)**

The European heatwave of summer 2003 is one of the most severe and well-documented extreme heat events in modern history, characterized by exceptionally high temperatures, prolonged duration, and widespread societal and ecological impacts (Fischer et al., 2007). During June–August 2003, large parts of Western and Central Europe experienced temperature anomalies exceeding +3–5 °C above the climatological mean, with daily maximum temperatures surpassing 40 °C in France, Spain, Italy, and Germany (Schär et al., 2004; Fischer et al., 2007). The event resulted in more than 70,000 excess deaths and caused major agricultural losses and ecosystem stress (Robine et al., 2008).

The primary dynamical driver of the event was a persistent upper-tropospheric anticyclonic circulation associated with strong atmospheric blocking over Western Europe. This blocking system suppressed cloud formation, enhanced subsidence, and increased incoming solar

radiation, leading to sustained surface heating (Cassou et al., 2005; Black et al., 2004). Amplified Rossby wave patterns and weakened zonal flow contributed to the persistence of the blocking high, allowing extreme temperatures to continue for several weeks (Schär et al., 2004).

Land–atmosphere feedbacks played a critical role in intensifying the heatwave. Preceding spring and early summer drought conditions significantly reduced soil moisture across Europe, limiting evapotranspiration and increasing sensible heat flux. This soil moisture deficit amplified surface warming and contributed substantially to the magnitude of temperature extremes (Fischer et al., 2007; Seneviratne et al., 2010). Observational and modeling studies estimate that soil moisture feedbacks accounted for a large fraction of the observed temperature anomalies.

Radiative feedbacks further strengthened the event, as clear-sky conditions increased net shortwave radiation and reduced nighttime cooling due to enhanced longwave trapping (Trenberth & Fasullo, 2012). Furthermore, sea surface temperature anomalies in the North Atlantic and Mediterranean played a significant role in modulating atmospheric circulation and regional heat transport, thereby reinforcing the persistence and intensity of the heatwave (Feudale & Shukla, 2011).

Climate attribution studies indicate that anthropogenic climate change significantly increased the likelihood and intensity of the 2003 heatwave. Climate model simulations suggest that human-induced warming at least doubled the probability of such an event, and similar extremes are projected to become more frequent under future warming scenarios (Stott et al., 2004; IPCC, 2021). The 2003 European heatwave is therefore widely regarded as a benchmark event demonstrating the combined influence of atmospheric blocking, land–atmosphere feedbacks, and anthropogenic warming on extreme heat.

## **5.2 Russian Heatwave (2010)**

The 2010 Russian heatwave was an example of driven by a quasi-stationary blocking high over western Russia; it is further amplified by Rossby wave patterns which suppressed synoptic variability. Temperature anomalies exceeded +5–10 °C, which scaled record-breaking extremes observed in Moscow. Persistent subsidence, reduced precipitation, and strong soil moisture deficits reinforced land–atmosphere feedbacks, intensifying surface heating [Barriopedro et al., 2011; Rasmijn et al., 2018]. Although atmospheric circulation anomalies played a dominant dynamical role, background anthropogenic warming significantly increased

the likelihood of extreme temperature thresholds being exceeded [Coumou & Rahmstorf, 2011].

### **5.3 Australian Heatwaves**

Australian heatwaves are strongly modulated by large-scale ocean–atmosphere variability and land-surface processes. El Niño phases of the El Niño–Southern Oscillation (ENSO) suppress rainfall over eastern and southeastern Australia, leading to soil moisture depletion and enhanced sensible heat flux. Persistent subtropical ridging and reduced frontal activity promote multi-day heat extremes [Perkins et al., 2012; Perkins & Alexander, 2013]. The 2012–2013 “Angry Summer” exemplified the combined influence of anomalous circulation and land–atmosphere coupling. Climate projections indicate substantial increases in heatwave frequency and duration under continued greenhouse forcing [Cowan et al., 2014].

### **5.4 Heatwaves in China: *Observed Trends and Recent Extremes (1961–2024)***

Since last six decades China has also been experiencing the higher temperature with increasing the frequency, duration, and intensity. The regional circulation dynamics and anthropogenic warming trigger the extreme weather phenomenon. The long-term analyses show that heatwave days and extreme temperature anomalies have risen significantly since the late 1980s, with increasing spatial variability across climatic zones (Chen & Li, 2017; Liu & Li, 2025).

As for as the eastern China is concerned, including the Yangtze River Delta and central plains, the heatwave frequency and duration exhibited upward trends during the period of 1961 to 2010. The hotspot regions recording progressively longer and more intense events (Climate Change Research, 2013). Urban clusters in the middle and lower Yangtze Basin also show pronounced increases due to both climate warming and urban heat island effects (NHES, 2020).

### **Major Heatwave Events (Post-1960)**

- **1988 Heatwaves:** Early large-scale anomalies across North China linked to persistent ridging and reduced rainfall.

- **1998, 2003:** Part of broader Asian and European extremes; elevated temperatures across eastern China.
- **2013 “Early Summer Heat”:** Record early onset of extreme temperatures, with durations of 10+ days in multiple provinces.
- **2022 Record Heatwave:** Eastern China, particularly the Yangtze River Basin, experienced anomalies of +4–6 °C, coinciding with a strong South Asian high and Western Pacific subtropical high circulation that produced prolonged subsidence and clear skies, leading to extreme surface heating (Zhang et al., 2025).
- **2023 North China Heatwave:** Persistent high pressure in the mid-latitudes, combined with drought conditions, produced daily maxima exceeding regional records and highlighted the role of soil moisture deficits in amplifying heat intensity (Jiang et al., 2023).
- **2024 Events:** Early indications confirm continued high frequency of extreme heat episodes, consistent with ongoing warming trends and enhanced land–atmosphere feedbacks.

### **Physical Drivers for China Heatwave**

Heatwave occurrence in China is linked to both **large-scale circulation patterns** and **local feedback processes**:

- **Subtropical High Systems** – The main reason of this weather condition is driven by Western Pacific subtropical high and South Asian high often expand and intensify during summer. This condition promotes by subsiding the upper-level circulation, reduced the cloud cover, and enhanced solar radiation over eastern and southern China (Atmospheric Research, 2025).
- **Rossby Wave Patterns and Blocking** – Mid-latitude circulation anomalies can produce wave patterns that reinforce heat-favorable ridges, particularly in northern China.
- **Soil Moisture Feedback** – Soil Moisture Feedback – The dry soil is also a factor contributing to the heatwave intensity because of the due to low evaporative cooling and increasing sensible heat flux, particularly in northern and central regions (Chinese Academy of Sciences, 2025).

- **Urban Heat Islands** – Urbanization intensifies local heat extremes, especially in megacities in the Yangtze River Basin.

### **Trends and Climate Change Context**

Multiple observational studies confirm a **significant upward trend in heatwave metrics** across China since the 1980s, characterized by:

- Increased heatwave frequency and number of heatwave days
- Longer event durations
- Elevated nighttime temperatures (warm nights)
- Greater spatial coherence of extreme heat

These trends align with global anthropogenic warming, which shifts the baseline temperature distribution upward and increases the likelihood of extreme events (Perkins-Kirkpatrick & Lewis, 2020).

<b>Mechanism</b>	<b>India</b>	<b>Russia</b>	<b>Australia</b>	<b>Europe</b>
ENSO influence	Strong	Weak/Indirect	Strong	Weak
IOD influence	Moderate	None	Strong	None
North Atlantic variability	Weak	Moderate	None	Strong
Atmospheric blocking	Episodic	Dominant	Episodic	Dominant
Rosby wave amplification	Secondary	Major	Secondary	Major
Monsoon interaction	Critical	NA	NA	NA
Land–atmosphere feedback	Strong	Strong	Strong	Strong
Anthropogenic amplification	Increasing	Increasing	Increasing	Increasing

## 6. Heatwaves in India

In India, heatwaves conditions generally prevail during the pre-monsoon season (April–June). During this period the maximum temperatures frequently exceed 40–45 °C across the Indo-Gangetic Plain, central plateau, and eastern regions. The India Meteorological Department operationally defines heatwave conditions based on absolute and anomaly-based thresholds (IMD, 2020).

The Figure 1. Shows the presence of persistent subtropical anticyclone makes the Central and eastern India constitute a major hotspot by advection of hot continental air masses (Ratnam et al., 2016). Interannual variability is strongly influenced by ENSO, with El Niño phases reducing pre-monsoon rainfall and intensifying soil moisture deficits [Ratnam et al., 2016; Rohini et al., 2016]. The moisture transport and thermal anomaly also get amplified during the positive phases of the Indian Ocean Dipole. Land–atmosphere coupling amplifies extremes through reduced evapotranspiration and increased boundary-layer heating [Seneviratne et al., 2010]. Observational records indicate a significant upward trend in heatwave frequency and spatial extent since the 1980s, consistent with anthropogenic warming (Pai et al., 2013; Perkins-Kirkpatrick & Lewis, 2020).

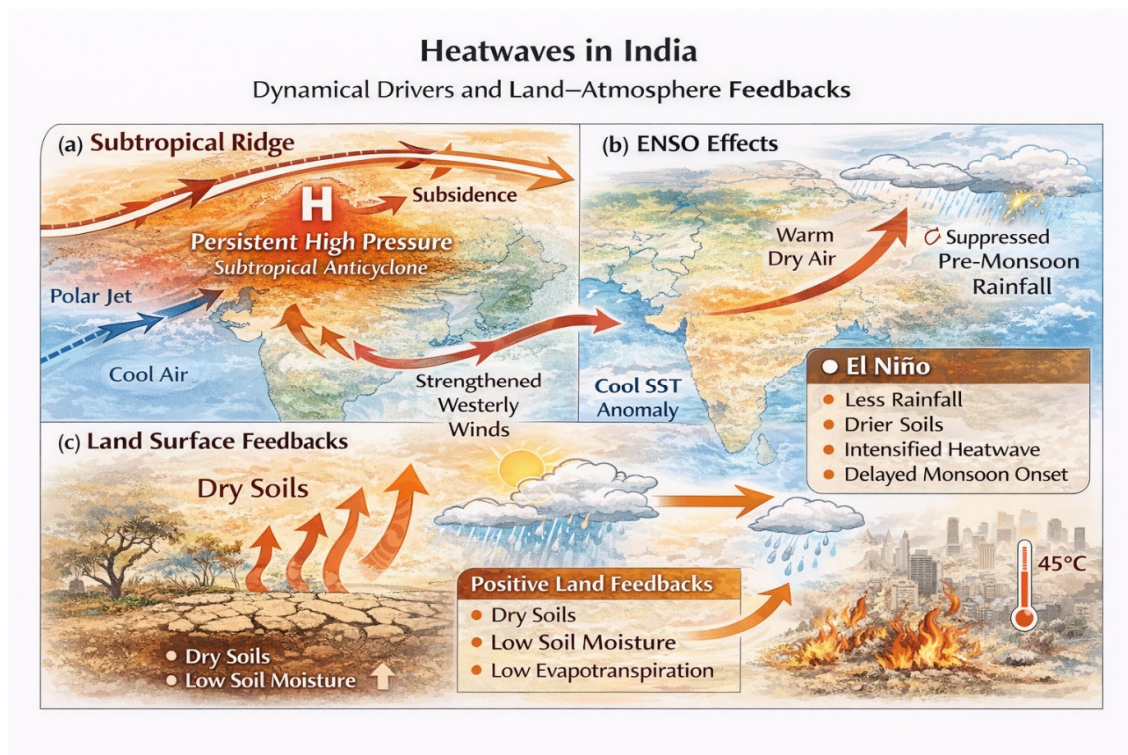


Figure 1. Schematic explanation of the dynamical drives while heatwaves prevail in India.

## 7. Heatwaves over Odisha: Climatology, Drivers, and Recent Extremes

Odisha, located along the eastern coast of India beside the Bay of Bengal, represents one of the most heatwave-prone regions of eastern India. The state frequently experiences extreme pre-monsoon heat during April–June, when synoptic subsidence, continental heating, and monsoon onset variability combine to produce prolonged high-temperature episodes. Major heatwave years — including 1998, 2010, 2015, 2019, and 2024 — frequently coincide with prevailing large-scale ocean–atmosphere anomalies and regional land–atmosphere feedback processes.

### 1. Climatological Characteristics

#### 1.1 Seasonal Cycle

Heatwaves in Odisha primarily occur during the **pre-monsoon season (April–June)**, when: strong solar insolation maximizes net radiation, the continental heat low develops over

northwest and central India, the delayed southwest monsoon onset and the coastal humidity can exacerbate heat stress.

Interior districts such as Sambalpur, Titlagarh, and Jharsuguda frequently record  $T_{max} > 45$  °C during severe events.

## **2.2 Long-Term Trends**

Observational analyses over eastern India indicate: Increasing frequency of heatwave days since the 1980s, rising nighttime temperatures (warm nights), increasing thermal stress and enhanced persistence of pre-monsoon dry spells.

These trends are consistent with broader Indian heatwave intensification linked to anthropogenic warming and land–atmosphere coupling (Pai et al., 2013; Rohini et al., 2016).

## **3. Major Heatwave Years**

### **3.1 1998**

The 1998 event coincided with a strong El Niño. Reduced pre-monsoon rainfall and enhanced subsidence over eastern India led to prolonged extreme temperatures across Odisha (Ratnam et al., 2016; Rohini et al., 2016).

### **3.2 2010**

Although globally associated with the Russian blocking event, eastern India experienced significant pre-monsoon warming under continental subsidence and regional circulation anomalies (Pai et al., 2013; Ratnam et al., 2016).

### **3.3 2015**

The 2015 heatwave was one of the deadliest in eastern India, including Odisha. It occurred during a strong El Niño event and was associated with: delayed monsoon onset, persistent clear-sky conditions and severe soil moisture depletion. Large positive  $T_{max}$  anomalies (4–7 °C above normal) were recorded regionally (Ratnam et al., 2016; Im et al., 2017).

### **3.4 2019**

The 2019 heatwave featured prolonged pre-monsoon dryness and late monsoon onset.  $T_{max}$  exceeded 45 °C in multiple districts, and warm night conditions increased heat stress.

### **3.5 2024**

The 2024 event has been exhibited an extended duration more than 10 consecutive heatwave days in some districts with high nighttime temperatures enhanced boundary-layer heating. Preliminary assessments suggest strong coupling between land surface drying and atmospheric subsidence (Perkins-Kirkpatrick & Lewis, 2020; Rohini et al., 2016).

## **4. Physical Mechanisms Driving Odisha Heatwaves**

### **4.1 ENSO Teleconnection**

Heatwaves over Odisha are strongly influenced by the El Niño–Southern Oscillation. El Niño years suppress convection over South Asia by weakening the Walker circulation, leading to:

- Reduced cloud cover
- Suppressed rainfall
- Increased net shortwave radiation

Ratnam et al. (2016) demonstrated enhanced subsidence over central–eastern India during El Niño years, increasing the probability of heat extremes (World Weather Attribution, 2024; IMD, 2024).

## **8. Future Projections of Heatwaves under CMIP6 Scenarios**

Climate projections from the Coupled Model Intercomparison Project (CMIP 6) indicate a substantial increase in the frequency, duration, and intensity of heatwaves during the twenty-first century under continued global warming (Intergovernmental Panel on Climate Change, 2021; Mishra et al., 2020).

Different models CMIP6 simulations show that South Asia, including India, will experience a strong amplification of heat extremes due to increasing greenhouse gas forcing and land–atmosphere feedback (Intergovernmental Panel on Climate Change, 2021).

### **8.1 Increasing Heatwave Frequency and Duration**

Future projections also possess that the number of heatwave days across India is going to increase significantly under all Shared Socioeconomic Pathways (SSPs), with the most pronounced increases occurring under high-emission scenarios such as SSP3-7.0 and SSP5-8.5 (Mishra et al., 2020; Kumar et al., 2023). Model results suggest that long-duration heatwaves exceeding 10–12 consecutive days could become more frequent in northern and central India by the late twenty-first century (Chathu & Ramesh, 2023).

Additionally, these simulations also possess that the number of heatwave days are likely to increase to double in northwest Indian, and three-to-four times in coastal and eastern region in coming years (Kumar et al., 2023).

The maximum temperature anomalies are also projected to shift toward higher sides, with late-century warming under SSP5-8.5 producing significant positive temperature anomalies relative to the historical baseline (Intergovernmental Panel on Climate Change, 2021).

## **8.2 Intensification of Human Heat Stress**

Moreover, the increasing temperatures are likely to intensify the human thermal stress indices across India during the twenty-first century (Kumar et al., 2023).

Based on these studies the thermal discomfort is expected to increase at a rate of approximately 0.09 °C per decade under SSP1-2.6, 0.26 °C per decade under SSP2-4.5, and 0.56 °C per decade under SSP5-8.5 (Kumar et al., 2023).

Consequently, densely populated regions of South Asia are projected to experience a substantial increase in days of very strong heat stress (UTCI > 38 °C) (Kumar et al., 2023).

## **8.3 Increasing Risk of Humid Heatwaves**

Present studies show a growing risk of humid heatwaves, where extreme temperatures combine with high humidity to produce dangerous wet-bulb conditions (Singh et al., 2025). The climate projections argue that in the future harsh heatwave days are going up to five times in of 1.5 °C global warming case and till 8 times in case of 2 °C warming leading to significant health risk across South Asia (Singh et al., 2025).

Such events are especially dangerous as elevated humidity impairs the body's evaporative cooling capacity, raising the risk of heat-related illness and death (Intergovernmental Panel on Climate Change, 2021).

#### **8.4 Regional Hotspots in India**

According to CMIP6 projections, which designates the heatwave vulnerable areas across India — especially the Indo-Gangetic Plain, central India, and eastern coastal regions, which are home to millions of people (Mishra et al., 2020).

The study raises serious concern for the eastern coastal states of Odisha and Andhra Pradesh — regions where rising sea-surface temperatures and an increasingly erratic monsoon are set to sharply intensify the burden of combined temperature–humidity heat stress on local communities (Kumar et al., 2023). The cities are going to affect by the urban heat island effects are turning heatwaves into a far deadlier threat — one that disproportionately endangers those least able to cope (Intergovernmental Panel on Climate Change, 2021).

#### **8.5 Implications for Climate Risk and Adaptation**

The projected intensification of heatwaves under CMIP6 scenarios has important implications for public health, agriculture, water resources, and energy demand (Intergovernmental Panel on Climate Change, 2021).

The Increase of heatwave frequency may lead to higher mortality rates, crop yield reductions, and increased electricity demand for cooling, particularly in rapidly urbanizing regions (Mishra et al., 2020).

Consequently, we need for early warning systems, heat-action plans, climate-resilient urban planning, and adaptation strategies to mitigate future heatwave risks (Intergovernmental Panel on Climate Change, 2021). Table. 2 shows the future climate scenarios and the respective heatwave projections. Similarly, Table 3. Presents the projected heatwave features.

**Table 2: Future Climate Scenarios and Heatwave Projections (CMIP6 SSP Pathways)**

<b>Scenario</b>	<b>Socioeconomic Pathway Description</b>	<b>Approx. Radiative Forcing by 2100</b>	<b>Global Mean Temperature Increase by 2100</b>	<b>Projected Heatwave Changes (India &amp; South Asia)</b>
<b>SSP1-2.6</b>	Sustainability pathway with strong mitigation and low emissions	~2.6 W m <sup>-2</sup>	~1.5–2.0 °C above pre-industrial	Moderate increase in heatwave frequency; heatwave duration increases slightly; extreme events remain episodic but more frequent than historical climate
<b>SSP2-4.5</b>	Intermediate pathway with moderate mitigation and continued development	~4.5 W m <sup>-2</sup>	~2.5–3.0 °C	Significant increase in heatwave frequency and duration; many regions in India experience 2–3 times more heatwave days compared with the late 20th century
<b>SSP3-7.0</b>	Regional rivalry scenario with high emissions and weak climate policy	~7.0 W m <sup>-2</sup>	~3.5–4.0 °C	Strong amplification of heat extremes; persistent multi-week heatwaves become more common across central and northwestern India
<b>SSP5-8.5</b>	Fossil-fuel intensive development with very high emissions	~8.5 W m <sup>-2</sup>	~4.0–5.0 °C	Severe increase in heatwave frequency, intensity, and duration; heatwave days may increase by 4–10 times

<b>Socioeconomic Scenario Pathway Description</b>	<b>Approx. Radiative Forcing by 2100</b>	<b>Global Mean Temperature Increase by 2100</b>	<b>Projected Heatwave Changes (India &amp; South Asia)</b>
			across parts of India; extreme humid heat stress becomes widespread

**Table 3: Projected Changes in Heatwave Characteristics over India (CMIP6)**

<b>Metric</b>	<b>Historical (1981–2010)</b>	<b>SSP1-2.6 (2100)</b>	<b>SSP2-4.5 (2100)</b>	<b>SSP5-8.5 (2100)</b>
Average heatwave days per year	3–5 days	6–10 days	10–20 days	20–40+ days
Maximum heatwave duration	4–6 days	7–10 days	10–15 days	15–25 days
Extreme temperature anomaly	~+2 °C	+2–3 °C	+3–4 °C	+5–7 °C
Very strong heat stress days (UTCI > 38°C)	Rare	Increasing	Common	Very frequent

**Early warning of Heatwave:**

The India Meteorological Department (IMD), India's nodal authority for weather forecasting, issues daily heatwave bulletins during the season (March–June). These predictions require integrating key data across temporal and spatial scales, including seasonal and subseasonal levels.

## **Artificial Intelligence and Machine Learning with NWP in the Heatwave Prediction**

Indian Institute of Tropical Meteorology has developed Extended-range prediction frameworks developed by combining dynamical model outputs with data-driven techniques to improve heatwave forecasting. The Extended Range Prediction System version 2 (ERPSv2) uses a multi-model ensemble approach to improve subseasonal prediction skill of heatwaves across India (Mandal et al., 2025).

In addition to dynamic model, nowadays artificial Intelligence (AI) and Machine Learning (ML) methods are increasingly applied to improve prediction of heatwaves by identifying nonlinear relationships between atmospheric variables, land–surface processes, and large-scale climate drivers. These approaches understand and complement the dynamical climate models by extracting patterns from large meteorological datasets, including satellite observations, reanalysis products, and climate model outputs.

Artificial Neural Networks (ANN) are widely used for climate prediction because of their ability to model nonlinear interactions among meteorological variables such as temperature, humidity, atmospheric pressure, and radiation. ANN-based frameworks were successfully examined to categorize heatwaves and improve short-term forecasting skill (Hassan et al., 2024). Convolutional Neural Networks (CNN) are useful for analyzing spatial climate datasets. These models extract spatial features from gridded meteorological fields as well understanding the synoptic heatwaves by analysing persistent high-pressure systems and regional temperature anomalies (Choudary et al., 2025). Similarly, Recurrent Neural Networks (RNNs) and Long Short-Term Memory (LSTM) models have been widely adopted for time-series prediction, owing to their ability to capture temporal dependencies in climate data, and have demonstrated strong predictive performance in short-term heatwave forecasting using historical atmospheric datasets (Byagar et al., 2023; Hassan et al., 2024). Ensemble machine learning approaches, including Random Forest, XGBoost, and LightGBM, improve prediction robustness by combining multiple decision trees and capturing nonlinear interactions among climate predictors. Comparative studies exhibit that boosting algorithms such as XGBoost often outperform traditional statistical models in heatwave prediction tasks (Choudary et al., 2025).

Finally, the CNN–LSTM models framework works for the bridge the gap of the spatial feature extraction and temporal sequence learning within a single architecture. By simultaneously capturing spatial circulation patterns and the temporal evolution of atmospheric variables, these models have shown notably improved skill in predicting extreme temperature events (Divyashree et al., 2025).

## Conclusion

Heatwave has been emerging a fatal extreme weather phenomena in this century, With combine effect of global warming, regional climate variability, and land–atmosphere interactions. Among the most influential planetary-scale climate drivers, the El Niño–Southern Oscillation (ENSO), the Indian Ocean Dipole (IOD), and the Madden–Julian Oscillation (MJO) collectively govern the frequency, intensity, and spatial distribution of heatwave events through their modulation of large-scale atmospheric and oceanic circulation. The urban heat island because of the rapid urbanization also amplifies heat stress. Climate projections studies in CMIP6 and AI-based prediction systems have already proven the understanding and forecasting of extreme heat events. Improving early warning capability and strengthening climate resilience to future heatwave risks are required continued development of high-resolution climate models, subseasonal forecasting systems, and urban heat mitigation strategies will be essential.

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