Impact of Climate Change on Monsoonal Variability in Tamil Nadu and Kerala: A Case Study of Floods and Landslides

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Abstract

Climate change has significantly impacted monsoonal variability in the states of Tamil Nadu and Kerala, leading to increased vulnerability to extreme weather events. This study investigates the effects of climate change on monsoon patterns, precipitation, and the occurrence of floods and landslides in these regions. The analysis of historical data and recent case studies, including the Chennai floods of 2015 and 2023 and the Wayanad landslides of 2024, reveals the complex interplay between climate change, anthropogenic factors, and regional vulnerabilities. Tamil Nadu, primarily dependent on the northeast monsoon, has experienced erratic rainfall patterns, with short-duration, high-intensity storms resulting in urban flooding. The 2015 Chennai floods exemplify the consequences of extreme rainfall combined with inadequate urban planning and drainage systems. Similarly, the 2023 floods triggered by Cyclone Michaung demonstrate the increasing intensity of tropical cyclones owing to rising sea surface temperatures. Kerala, relying on the southwest monsoon, has faced an increased frequency of rainfall-induced landslides, as evident in the 2024 Wayanad disaster. Anthropogenic activities, such as deforestation, unregulated urbanisation, and land-use changes, have exacerbated the impacts of extreme weather

Introduction

Monsoons in the Indian subcontinent, a multifaceted and dynamic climatic phenomenon, are vital for South Asia's agricultural, hydrological, and socioeconomic stability. In South India, Tamil Nadu and Kerala depend heavily on seasonal rainfall. Kerala primarily benefits from the southwest monsoon (June-September), whilst Tamil Nadu relies significantly on the northeast monsoon (October-December). Periodic rainfall plays an essential role in supporting agriculture, restoring water resources, enhancing biodiversity, and preserving the hydrological balance of the region. However, climate change has started to change the traditional rainfall patterns, revealing significant vulnerabilities in both states. This research explores the impact of climate change on monsoon variability in Tamil Nadu and Kerala by analysing changes in precipitation trends, the frequency of extreme weather events, and the growing risks of natural disasters. It also examines two significant climate-driven disasters as case studies: the 2015 and 2023 Chennai floods and the 2024 Wayanad landslides. The study assessed disaster mitigation, policy interventions, and sustainable adaptation measures to enhance climate resilience in the two states. Addressing these changing climate challenges demands enhanced regional climate modelling, ecosystem-based adaptation approaches, and anticipatory disaster management practices to ensure long-term environmental and socioeconomic stability in Tamil Nadu and Kerala.

India's mean temperature rose by approximately 0.7°C between 1901 and 2018, primarily due to greenhouse gas (GHG)-induced warming. This warming trend has been partially offset by anthropogenic aerosols and changes in land use and land cover (LULCC). Forecasts suggest that by the end of the century, India's average temperature could increase by about 4.4°C compared to the recent historical baseline. The global warming that has been experienced since the mid-20th century has resulted in pronounced alterations in the global climate and weather. Some of these changes include increased heat waves, droughts, extreme rainfall events, and intense cyclones. Further, changes in precipitation and wind patterns have also been observed, as well as the disruption of the global monsoon systems. The global warming that has been experienced since the mid-20th century has resulted in pronounced alterations in the global climate and weather. Some of these changes include increased heat waves, droughts, extreme rainfall events, and intense cyclones. Further, changes in precipitation and wind patterns have also been observed, as well as the disruption of the global monsoon systems. Ocean warming has also resulted in acidification, melting of ice, sea level rise, and drastic changes in marine and terrestrial ecosystems. These trends highlight the imperative need for improved knowledge of regional and global climate processes to develop targeted adaptation and mitigation measures. This paper examines how climate change and shifting monsoon patterns are affecting the lives and livelihoods of people in Tamil Nadu and Kerala, considering both past experiences and future challenges. These changes in monsoon patterns have significant implications for agriculture, water resource management, and disaster preparedness.

Changes in Rainfall and Regional Climate Dynamics

It is now clear that global warming, triggered primarily by increased GHG emissions and anthropogenic activities in recent decades, is leading to unpredictable changes in monsoon patterns, extreme rainfall, floods, landslides, heatwaves, and droughts. According to the Intergovernmental Panel on Climate Change (IPCC), global warming will continue to increase in the near term (2021-2040) mainly due to increased cumulative CO2 emissions (IPCC-AR6, 2023). The 2024 Global Water Monitor Report from Australian National University (ANU) observed that 'climate extremes in 2024 wreaked havoc on the global water cycle leading to severe floods and crippling droughts (India Today, 7 Jan 2025). 2024 is the hottest year on record, overtaking 2023. Based on the report, an estimated 4 billion individuals from 111 countries have seen their hottest year so far, highlighting the universal effect of climate change. This increased heat has caused intensified sea surface temperature (SST) that strengthened tropical cyclones. In just 2024 alone, disasters caused by water took more than 8700 lives, affected about 40 million people, and caused economic damage worth over $ 500 billion. Highest monthly rainfall amounts were recorded 27 per cent more often than they did in the early 2000s, and daily rainfall rose by 52 per cent. On the other hand, record low rainfall was observed more often.

The Indian subcontinent's climate exhibited great variability over the last century due to natural and anthropogenic causes. Summer monsoon rainfall (June to September), vital for India's agricultural economy, fell by about 6% from 1951 to 2015, particularly in the Indo-Gangetic Plains and Western Ghats. Observations and climate models indicate that anthropogenic aerosol forcing over the Northern Hemisphere has largely counteracted the anticipated increase in precipitation due to GHG-induced warming, leading to the observed decrease. Since the mid-20th century, India's regional climate has experienced rising temperatures, reduced monsoon precipitation, frequent and intense extreme weather events, heightened droughts, rising sea levels, and intensified cyclonic activity. Since the Southwest Monsoon covers most of the country, it has been the focus of the majority of research studies. However, for Tamil Nadu it is the Northeast monsoon that is of more importance, although research on the Northeast monsoon is far less and scant from a climate change perspective. This is now beginning to change given the significant variations observed over the last decade and a half.

The monsoon system over South India is predominantly tending to higher intensity and shorter duration precipitation events mainly because of global warming. Research has indicated large-scale changes in the characteristics of the monsoon rainfall. Singh et al. (2014) indicate statistically significant enhancements in the variability of daily precipitation, number of dry spells, and intensity of wet spells between 1951-2011, concurrent with heavy downpours during brief spells. The changes are confirmed by enhanced convective available potential energy, low-level convergence of moisture, and changes in large-scale atmospheric circulation (Singh et al., 2014). While the intensity of wet periods has increased, that of dry periods has decreased (Singh et al., 2014), indicating a more spasmodic and localized trend of precipitation. Greater climate change has caused even more spasmodic and intense monsoons, with more frequent but lesser rainfall. This trend can be seen in the higher rate of extreme weather conditions witnessed over India in 235 out of the 273 days of the first nine months of 2023. The count has gone up to 255 days of extreme weather against 274 days in the first nine months of 2024 in India. This has caused 2716 fatalities and significant damage/loss to assets and properties. Additional climate records have been broken. January 2024 was the driest January since 1901. February 2024 recorded the second-highest minimum temperature in 123 years. July, August, and September recorded the highest minimum temperatures. East and northeast India experienced the 12th driest July in 123 years. Warm nights were 4.5 degrees to 6.4 degrees Celsius higher than usual, affecting human health considerably. Rao et al. (2020) predict increased intensity and frequency of precipitation extremes in the majority of South peninsular India during the northeast monsoon period under future climatic conditions.

The southern Indian states of Tamil Nadu and Kerala have faced a decade and a half of extreme weather fluctuations, marked by intense rainfall and flooding alternating with severe droughts. The years 2015 and 2023 stand out as particularly significant, highlighting the escalating impacts of climate change and monsoon variability in the region. In 2015, Tamil Nadu experienced devastating floods, especially in Chennai, resulting in a significant loss of life and property (World Weather Attribution, December 2015). Similarly, Kerala faced its worst floods in nearly a century in 2018, underscoring the vulnerability of these states to extreme weather events (World Weather Attribution 2018).

The northeast monsoon, which is crucial for Tamil Nadu, has been particularly unpredictable, contributing to both floods and droughts (Laasya Shekar, 2024). In Kerala, climate change has been linked to more intense monsoon downpours, such as those seen in recent years (Tandon, Ayesha and Chandrashekar, Aruna., 2024). The shift towards more intense rainfall events in shorter periods increases the risk of floods and landslides while potentially reducing the overall effectiveness of rainfall for agriculture due to increased runoff (Singh et al., 2014). Understanding and adapting to these changing monsoon characteristics is crucial for mitigating the impacts of climate change in South India.

Although climate change is prevalent on a global scale, its impacts are not uniform across the planet. For example, temperatures in the Arctic are increasing at much higher rates compared to the global average, while sea level rise displays high spatial variability. Likewise, climate change at the regional scale, for example, over South Asia, is controlled by specific physical and meteorological processes. Despite these regional differences, it is a challenge to comprehend them due to sparse observational data and knowledge deficits regarding region-specific climate processes. However, understanding current and future regional climate changes is essential for risk mitigation, disaster planning, and developing effective, locally applicable adaptation plans. Policymakers and stakeholders need reliable and accurate regional climate models and data to manage the socioeconomic and environmental issues caused by climate variability and protect vulnerable people and ecosystems (Burkett et al., 2014).

Tamil Nadu

Tamil Nadu, the southernmost part of the Indian subcontinent, has a varied landscape that is conventionally divided into five broad physical divisions: the Kurinji (hilly region), Mullai (forest region), Marudham (agricultural plains), Neidhal (coastal region), and Palai (desert region). Each division is marked by distinctive geographical features and distinct climatic conditions, which are responsible for the state's high biodiversity. This natural richness is protected by a system of five National Parks, seventeen Wildlife Sanctuaries, and three Biosphere Reserves.

The state receives an average annual rainfall of approximately 997 mm, which is notably lower than the national average of 1,138.8 mm and accounts for only 2.5% of India’s total water resources (IMD Rainfall Report, MoES., 2022). Tamil Nadu has shown impressive economic growth and considerable human development improvements in recent times. The state is the most urbanised state in India, with 48.45% of its population living in urban areas. Yet, rapid urbanisation comes with considerable environmental problems. Climate change will enhance the frequency and intensity of natural hazards and hence increase the risk of climate-related disasters in all Indian states. Though there has been progress in community awareness, Tamil Nadu remains highly sensitive and vulnerable to climate change impacts due to the lack of integrated regional climate models and vulnerability studies.

Tamil Nadu depends heavily on monsoon rainfall to replenish its water supplies; when the monsoon fails, severe water shortages and droughts frequently occur. The northeast monsoon supplied 48% and the southwest monsoon contributed 35% of the state's average annual rainfall of about 898 mm between 1989 and 2018. However, in recent decades, there have been instances of exceptionally heavy rainfall resulting in excess precipitation. Temperatures in Tamil Nadu typically range from 18°C during winter to 45°C in summer (Tamil Nadu Climate Change Mission Document, n.d.).

Despite economic growth and urbanisation, Tamil Nadu faces significant environmental challenges. Tamil Nadu, compared to all the states in India, is most susceptible to extreme weather conditions such as cyclones and frequent droughts. Predictions for future climate show increased possibility of extreme temperature events with temperatures projected to increase by 3.30°C during the day and 3.55°C at night by the turn of the century. These projections also suggest a 3.24% decrease in annual rainfall, although extreme rainfall events are expected to intensify. The probability of short-duration, high-intensity rainfall events, such as 1-day rainfall, is projected to surpass longer-duration events, such as 5-day rainfall. This indicates that shorter but more severe storms will increase the risk of flash floods and storm-related disasters by the 2080s (Tamil Nadu Climate Change Mission Document, n.d.). Climate change is expected to heighten the occurrence of natural hazards and raise the risk of climate-related disasters. Over the last few decades, heavy rainfall has caused catastrophic flooding and over precipitation. For example, in the 2015 Chennai floods, a day experienced 500 mm of rainfall, which caused extensive damage and economic loss of over $3 billion (van Oldenborgh et al., 2017). These trends call for the imperative need for successful climate adaptation and mitigation measures to safeguard the state's population and infrastructure.

Case Study 1: Chennai Floods (2015 & 2023)

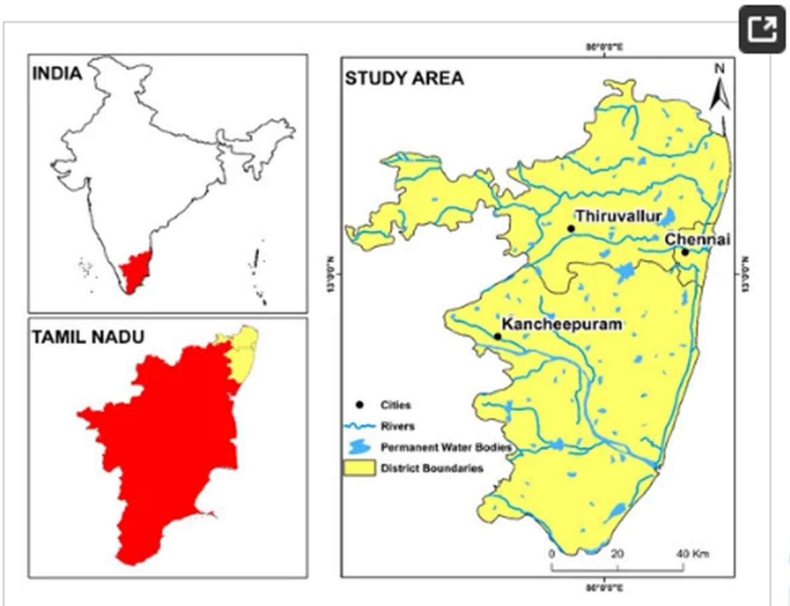

Figure 1: Map of Chennai, Kanchipuram, and Tiruvallur Districts of Tamil Nadu, India

Chennai, the capital city of Tamil Nadu, is the fourth largest metropolis in India and one of the fastest-growing urban centres. Situated on the east coast at 13°N, 80°E, the city faces the Bay of Bengal, which makes it naturally vulnerable to tropical cyclones. The city's topography is mostly flat, with only a few isolated hillocks to the southwest near St. Thomas Mount, Pallavaram, and Tambaram. The average elevation of the city is approximately 6.7 meters (20 feet). The city experiences minimal seasonal temperature variation. The weather stays humid and hot for most of the year. Known locally as Kathiri Veyyil, the hottest months are late May and early June, when temperatures can reach 38–42°C (100–107°F). December through February is the coolest time of year, with minimum temperatures typically averaging between 19 and 20°C (66 and 68°F) (Sundarmoorthy et al., n.d.). Chennai receives monsoon rains between October and January when the cooler dry NE monsoon winds from the Himalayas and Indo-Gangetic Plain draw water vapour from the Bay of Bengal and then pour it over India (mainly in Tamil Nadu and northeast India) and parts of Sri Lanka (Alam et al., 2003).

The city, prone to inundation, has been the subject of numerous studies examining its flood vulnerability. Research conducted in 2007, which evaluated flood risk exposure and created flood risk maps, revealed that flooding is a common occurrence in the metropolis. The investigation documented 26 flood events between 1943 and 2006, noting a significant increase in their frequency from the 1970s onwards. Nevertheless, before linking this increase directly to climate change, the study highlighted that meteorological data spanning back to 1813 showed no apparent rise in the city's yearly rainfall. Notably, the floods of 1996 and 2005 were primarily triggered by extreme precipitation events, with anthropogenic factors further intensifying the impact of flooding.

Chennai Floods 2015: Impact of Extreme Rainfall and Reservoir Dynamics

Over the past few years, the city of Chennai and its adjacent districts, Kancheepuram and Tiruvallur, have been subjected to substantial inundations. These events have shed light on the intricate relationships among climate patterns, water-related processes, and urban adaptability. Notably, the flooding incidents in 2015 and 2023 have underscored the area's susceptibility to severe weather events. The 2015 floods were associated with the 2014–16 El Niño event, which contributed to unusually heavy rainfall during the northeast monsoon in November and December (Akilan et al., 2017). Chennai received record rainfall, with over 494 mm on December 1, 2015, causing widespread flooding and significant damages. The floods resulted in more than 500 deaths, displaced over 1.8 million people, and caused extensive economic losses estimated between ₹200 billion and ₹1 trillion (van Oldenborg, G.J et al. 2016). The area's water management capabilities are further influenced by its intricate system of water bodies, including Chembarambakkam and Poondi reservoirs, which play a crucial role in handling excess rainfall and water inflow. Urban development has substantially transformed the physical landscapes of Chennai, Kancheepuram, and neighbouring cities, thereby intensifying the difficulties faced by these urban centres.

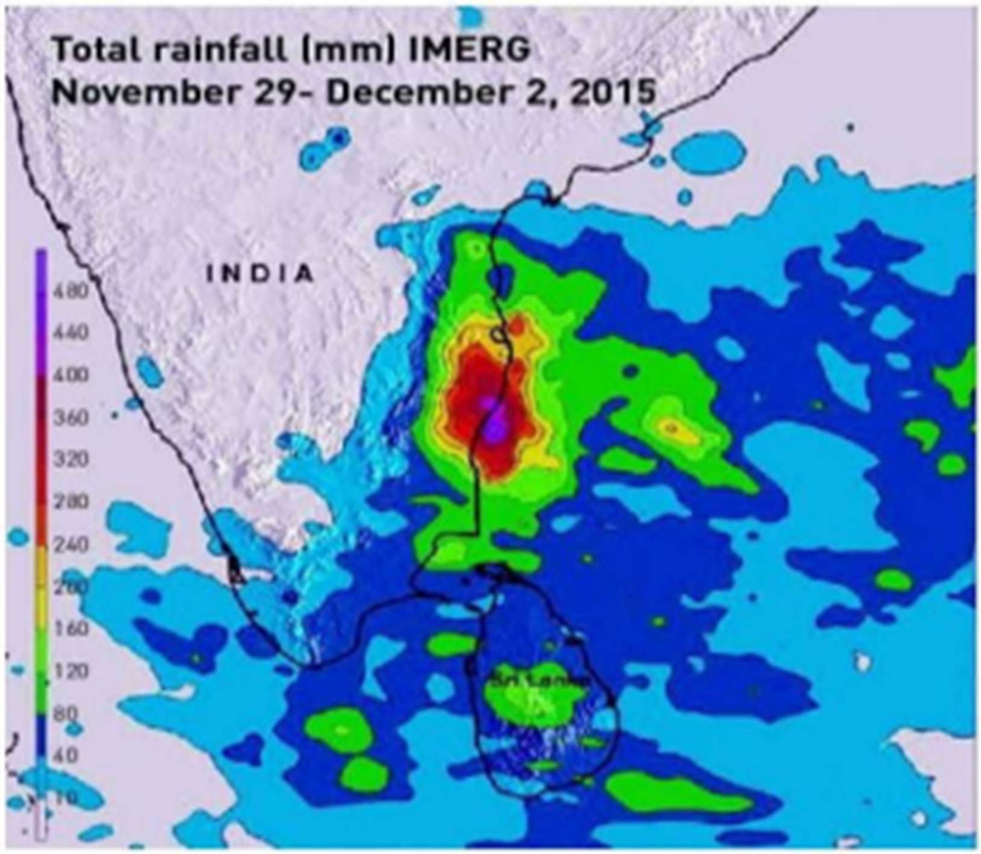

Figure 2: Total rainfall between November 29 and December 2, 2015, over Chennai and its neighbourhood, measured by NASA's GPM satellites

Source: Interdisciplinary Centre for Water Research (ICWaR), IISC, Bangalore

The 2015 monsoon period coincided with an exceptionally robust El Niño, unprecedented global surface warmth, and heightened Indian Ocean temperatures. This El Niño episode, ranked among the most potent on record, began to develop in 2014. El Niño phenomena are known to influence the Northeast Monsoon, often leading to a modest amplification of its strength (Zubair & Ropelewski, 2006). A plausible hypothesis posits that the strong El Niño phenomenon contributed to a robust easterly flow during November-December 2015, which likely facilitated increased moisture transport to Chennai's eastern coast, resulting in intensified rainfall.

Another potential contributing factor could be the warming of the Bay of Bengal (BoB), which facilitated the transport of substantial moisture from the BoB and resulted in heavy precipitation over the southeast coast of India (Narasimhan et al., 2016). The Bay of Bengal exhibited sea surface temperatures (SSTs) that, whilst exceeding the observed trend, were lower than other Indian Ocean areas during the 2015 rainy season. In the past 35 years, the northern and western Bay of Bengal have demonstrated minimal SST increases compared to global warming trends. This phenomenon is thought to be caused by increased air pollution in the region, particularly the 'brown cloud' that hinders solar radiation. This counteracts the widespread warming induced by greenhouse gases, especially in pre-monsoon maximum temperature, a process termed the 'aerosol effect'. Although the Bay of Bengal generally had cooler temperatures than other Indian Ocean regions, a localised warm water area was identified just off Chennai's coast on 1 December (Bulletin of the American Meteorological Society Vol. 97, No. 12 December 2016). The 2015 floods in Chennai and the surrounding Tamil Nadu areas underscored the importance of developing a scientific understanding of urban flooding to improve engineering, administrative, and societal resilience (Narasimhan et al., 2016).

Chennai and Southern Tamilnadu Floods 2023: Cyclone Michaung and Urban Vulnerabilities

In December 2023, Chennai witnessed a disastrous urban flooding disaster triggered by the intense Cyclonic Storm Michaung. This cyclonic system was a moderate tropical cyclone that formed in the Bay of Bengal during the 2023 North Indian Ocean cyclone season. The storm's genesis can be traced to a low-pressure system in the Gulf of Thailand, which subsequently intensified into a deep depression upon entering the Bay of Bengal on 2 December. As the system continued to gain strength, it was designated Michaung, becoming the ninth depression and sixth storm of the season.The cyclone moved in a north-westward path, peaking at its landfall close to Bapatla, Andhra Pradesh, on 5 December with sustained winds of 110 km/h (70 mph). This powerful meteorological event caused extensive precipitation in northeastern Tamil Nadu, with Chennai being the worst-hit by the cyclone's rain (Dev L. K & Saravanan, 2024).

Between December 3rd and 4th, the city experienced unprecedented rainfall, with the Indian Meteorological Department (IMD) recording nearly 500 mm of precipitation in Nungambakkam and Meenambakkam within 24 hours. Chennai's normal annual rainfall was surpassed by the actual rainfall in some northern regions, which topped 600mm. Widespread flooding resulted from inadequate drainage systems and an already saturated area from earlier rainfall. Chennai's metropolitan infrastructure, such as its stormwater management and drainage systems, was overloaded, underscoring the necessity for stronger flood prevention measures.

On December 17 and 18, 2023, southern Tamil Nadu, especially the districts of Tirunelveli and Thoothukudi, faced extreme weather events marked by unprecedented rainfall and severe flooding (Sphere India, 19 Dec 2023). The downpour was extraordinary, with Kayalpattinam in Thoothukudi district receiving 94.6 cm (or 950 mm, according to some reports) within just 24 hours—nearly matching the district's average annual rainfall. Similarly, Tiruchendur recorded 679 mm, while Tirunelveli saw 363.6 mm of rainfall in a single day, which was an astonishing 5094 per cent higher than the usual rainfall for that day (New Indian Express, 29 December 2023).

Major rivers like the Thamirabarani overflowed as a result of the heavy rains, and low-lying areas were submerged. Many cities and villages were impacted by flooding, which seriously disrupted infrastructure and daily life. A slow-moving, low-altitude upper air circulation system over Sri Lanka was the main contributor to the heavy rainfall. Intense rainfall resulted from this system's enhanced moisture convergence over southern Tamil Nadu. This is not typically associated with such intense rainfall. This unpredictability highlights the changing nature of weather patterns owing to climate change. It is also linked to an active northeast monsoon fuelled by El Niño conditions (Laasya Shekar, 10 January 2024).

The Role of Climatic Events in Chennai's Flood Risk

Extremely heavy precipitation was the primary cause of flooding in 2015 and 2023. Stations that received higher amounts of rainfall were located near water bodies, such as lakes and rivers, suddenly causing tanks to fill with surplus floodwater (Radhakrishnan et al., 2024).

During the 2015 flood event, intense rainfall associated with the northeast monsoon (NEM) occurred in three distinct spells (Narasimhan et al. 2016). The heaviest rainfall on 9 November 2015 led to significant inflows into reservoirs, including Poondi Lake, by 12 November. However, the release of floodwaters from Poondi and Chembarambakkam lakes was delayed until 17 November 2015. Rainfall from 9 to 10 November exceeded 500 mm, filling the reservoirs and causing flooding in both urban and agricultural areas (National Disaster Management Authority, n.d.). As the reservoirs reached their limits, surplus water was discharged. Additional rainfall and reservoir releases on 1–2 December worsened flooding, particularly due to the third spell of intense rainfall, which triggered sudden floodwater releases.

In contrast, the 2023 flood event in Chennai was caused by Cyclone Michaung, which brought heavy rainfall that rapidly filled reservoirs, leading to large floodwater discharges. The Poondi Reservoir, influenced by the cyclone's precipitation, contributed significantly to the flooding on 4 December 2023. The sustained rainfall and excess water from the reservoirs overwhelmed the drainage systems, causing prolonged water stagnation in urban areas. The cyclone’s impact emphasized the connection between meteorological events and hydrological outcomes, exacerbating the flooding and resulting in severe inundation (Radhakrishnan et al., 2024).

The analysis of Chennai's 2015 and 2023 floods underscores the critical role of cyclones, climate change, and extreme precipitation in shaping flood risk maps. These factors, in conjunction with urban encroachments and inadequate drainage infrastructure, significantly exacerbate flood risk in urban areas, revealing the complex interplay that influences flood scenarios. In 2015, the flood event characterised by prolonged monsoonal rains resulted in exceptional precipitation that exceeded 2000 mm at most stations. During this period, the Poondi and Chembarambakkam reservoirs were instrumental in managing and discharging floodwaters, surpassing 35,000 cu. Secs. Conversely, the 2023 flood event precipitated by Cyclone Michaung followed a distinct trajectory. The discharge of floodwaters during intense rainfall exceeded 15,000 cusecs owing to the cyclone, which caused reservoirs to reach their maximum capacity. This altered dynamic transformed the flooding scenario into a more severe condition characterised by extensive inundation and prolonged water stagnation.

The comparison between the events of 2015 and 2023 elucidates the interplay of several climatic factors, with El Niño contributing to the 2015 flood and Cyclone Michaung playing a decisive role in 2023. The storm surge associated with Cyclone Michaung introduced additional complexity to the flood scenario, emphasising the importance of integrating meteorological data into flood management strategies. This meteorological phenomenon exemplifies the intricacies of tropical cyclone development, underscoring the dynamic nature of atmospheric systems and their potential impacts on coastal regions. Timely monitoring and analysis conducted by meteorological agencies play a crucial role in informing and preparing communities for the evolving conditions associated with such weather events.

Kerala

Kerala, located on India's southwestern coast, is nestled between the Arabian Sea to the west and the Western Ghats Mountain range to the east. It covers approximately 1.18% of India's total land area (Nair et al., 2014). Kerala experiences approximately 2,000 mm of seasonal rainfall with unique rainfall patterns due to the geographical features of the western ghats (Premlet, 2019). The state is geographically divided into three distinct climatic regions: the eastern highlands, characterised by rugged and cool mountainous terrain; the central midlands, featuring gently rolling hills; and the western lowlands, which consist of coastal plains. This diverse topography makes Kerala particularly susceptible to the impacts of climate change. Rainfall patterns across these regions vary significantly both spatially and temporally, with fluctuations observed on monthly and seasonal scales.

The southwestern state of Kerala plays a pivotal role in India's climatic patterns, earning it the moniker "Gateway of Summer Monsoon". Situated along the country's southwestern coastline, Kerala serves as the initial point of contact for moisture-laden southwest monsoon winds that traverse the Indian Ocean. The state's unique geographical configuration creates optimal conditions for monsoon inception. Upon encountering the Western Ghats, these winds undergo ascension, cooling, and condensation, culminating in copious rainfall over Kerala. This meteorological event signified the formal commencement of the monsoon season in India. Consequently, the Indian Meteorological Department (IMD) vigilantly observes Kerala's atmospheric conditions to officially announce the arrival of the monsoon.

Kerala's function as the monsoon gateway is not merely symbolic but profoundly practical. The state's diverse topography, comprising the eastern highlands, central midlands, and western lowlands, engenders a microclimate that amplifies the effects of monsoons, rendering it a natural indicator of monsoon activity. Historically, Kerala has been a focal point for monsoon studies because of its consistent and predictable patterns, and its traditional agricultural practices, such as paddy cultivation, are intricately linked to the monsoon cycle. In recent years, Kerala's significance as the monsoon gateway has become increasingly pronounced owing to the impacts of climate change. Irregularities in monsoon onset and intensity, such as delayed arrivals or excessive precipitation, are frequently first observed in Kerala, establishing it as a barometer for studying climate variability. Events such as the devastating floods of 2018 and 2019 have highlighted the state's vulnerability to extreme monsoon events. Man-made alterations to geographical and topographical features can significantly impact atmospheric circulation at different altitudes. This could be a contributing factor to the recent uncertainties in monsoon variability and rainfall distribution over Kerala.

Landslides Vulnerability due to Climate Change Impact

Climate change has largely contributed to landslides frequency and intensity throughout monsoons in Kerala, including Wayanad. Evidence comes through some of the factors: heavy rainfalls have grown in frequency and cause many landslides. For example, between 1-19 August 2018, Kerala received 758.6 mm rainfall, 164% above average, causing 5191 landslides and 483 deaths (Tapas R Martha et al., 2019). Heavy rainfall also led to 13 of Kerala's 14 districts being affected by flooding. Likewise, during August 2019, unusual heavy monsoon rain precipitated landslips in Kavalappara and Puthumala with 400% of the normal average rainfall (Wadhawan et al., 2020). Seasonal rainfall patterns have been noticed to change, thus enhancing the chances of landslides.

A study of Kerala's rainfall extremes from 1954 to 2003 showed increasing trends in winter and autumn extreme rainfall, indicating a higher probability of flooding during these seasons. Conversely, extreme spring rainfall showed decreasing trends, suggesting an increased likelihood of water scarcity in the pre-monsoon period and a delayed monsoon onset (Pal & Al-Tabbaa, 2009).It's interesting to note that although climate change has increased the likelihood of landslides, recent disasters may not be primarily caused by short-term changes in land use (a study of Kerala's 2018 landslides revealed that 90% of landslide locations showed no noticeable change in major land use and land cover in the period 2010-2018 (Hao et al., 2022). Climate change has had a significant impact on the occurrence of landslides in Kerala, particularly through altered rainfall patterns, but other factors, such as geological settings, anthropogenic activities, and long-term land use changes, also play significant roles in landslide susceptibility (Ramasamy et al., 2020; Wadhawan et al., 2020).

Case Study 2 - Wayanad Landslides (2024)

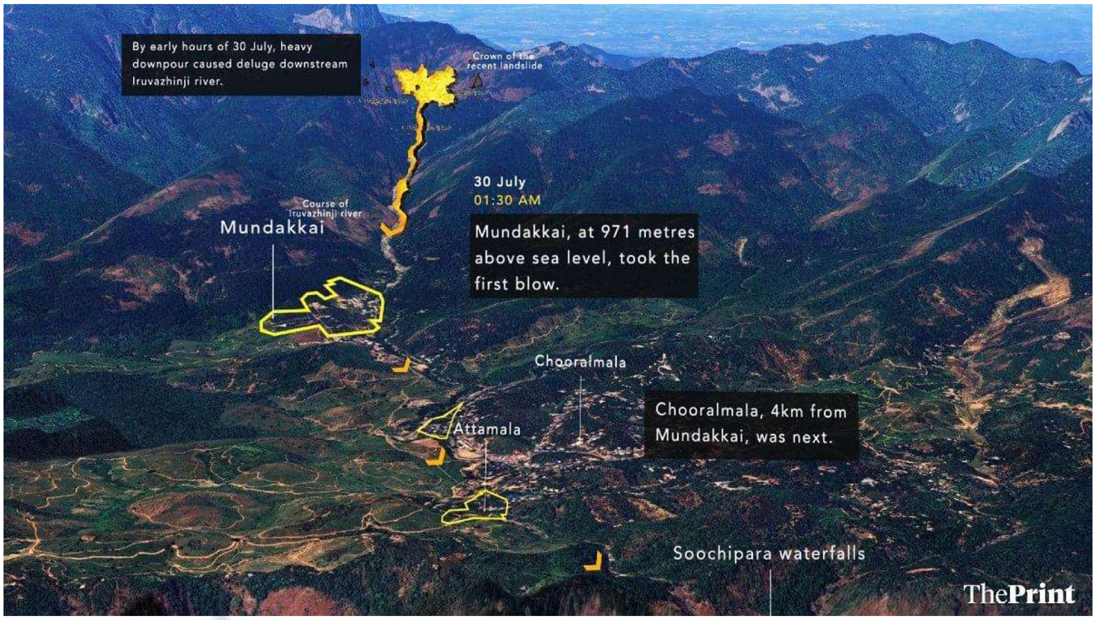

Figure 3: Visual representation of the devastating landslides in Wayanad, Kerala on July 30. The image highlights the impact of heavy rainfall along the Iruvazhinji River, affecting Mundakkai, Chooralmala, and surrounding regions
Source: The Print.

In the early hours of 30 July 2024, a series of catastrophic landslides occurred in the villages of Mundakkai and Chooralmala in Kerala's Wayanad district, precipitated by prolonged and intense precipitation. Located on the eastern flanks of the Vellarimala Hills and near a significant tributary of the Chaliyar River, these villages are situated in a geographically vulnerable area, which has played a crucial role in the disaster. The first landslide occurred in Mundakkai in the early hours, with three more following within three hours, impacting nearby areas, such as Chooralmala and Attamala. The consecutive nature of these incidents not only caused widespread devastation but also led to the destruction of the main bridge linking the affected area to the nearest town, hampering rescue and relief efforts. The World Weather Attribution (WWA) service's analysis revealed that the rainfall affecting Wayanad on 30 July was the third most intense in the region's history, even exceeding the heavy precipitation that caused the Kerala floods in 2018 (World Weather Attribution, 1 Aug 2024). In the two weeks preceding the event, the Kasargod, Kannur, Wayanad, Calicut, and Malappuram districts experienced persistent heavy precipitation due to the influence of an active monsoon offshore trough over the Konkan region. This prolonged rainfall resulted in extensive soil saturation across these areas. The following Monday, the development of a deep mesoscale cloud system over the Arabian Sea led to intense precipitation across North Kerala, particularly affecting the districts of Wayanad, Calicut, Malappuram, and Kannur. This extreme rainfall is believed to have been a significant factor triggering landslides in the region (India Today, 2024). Notably, similar large-scale synoptic weather patterns were observed during extreme rainfall events that caused the devastating Kerala floods in 2018 (Kumar et al., 2020).

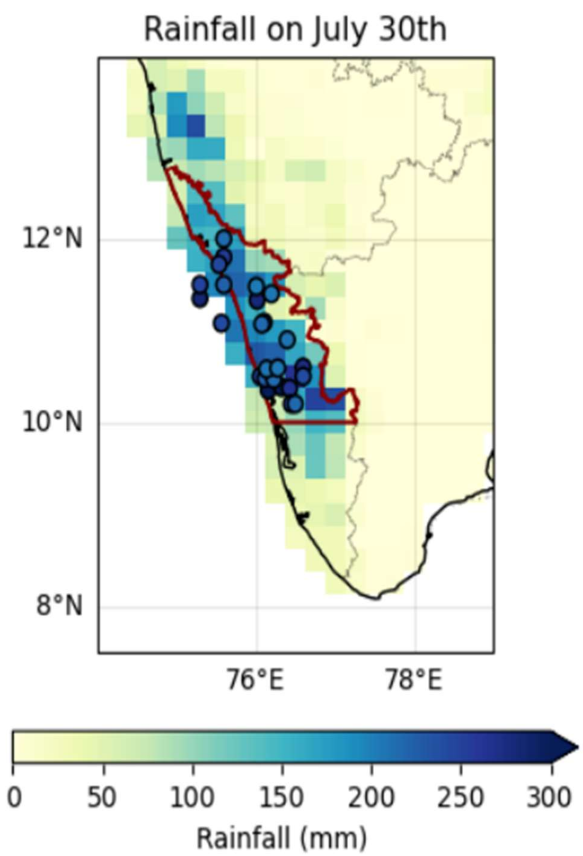

Figure 4: Rainfall on the 30th of August 2024 in IMD.
Source: National Weather Forecasting Centre, IMD, Ministry of Earth Sciences

Between 2015 and 2022, Kerala accounted for nearly 59% of the landslides recorded across India (Ramasamy et al., 2020). Among the state's districts, Wayanad is identified as one of the most vulnerable to this natural hazard (Sharma et al., 2024). The district's mountainous topography, characterised by steep slopes and high elevations in conjunction with prolonged heavy precipitation and extensive land-use modifications, renders it highly susceptible to landslides (Arumugam et al., 2023). Kerala experienced recurrent landslide disasters, particularly in 2018, 2019, and 2020, resulting in widespread destruction, loss of life, and severe economic repercussions (Wadhawan et al., 2020). The increasing frequency and intensity of landslides underscore the urgent necessity for enhanced disaster preparedness, early warning systems, and sustainable land-use policies. The region's fragile ecology, further compromised by deforestation, unregulated construction, and infrastructure expansion, exacerbates the risks associated with extreme weather events.

Landslides are influenced by a variety of geophysical and anthropogenic factors. Slope angles, soil and rock composition, vegetation cover, drainage patterns, and land-use changes all contribute to the susceptibility of a region to landslides (Jones et al., 2021). Among these, heavy rainfall remains the most prevalent trigger, rapidly increasing soil saturation and reducing slope stability (Ajmal & Saud, 2021).

Steep gradients and weak geological formations render certain regions vulnerable to landslides, as unstable rock and soil strata succumb to water infiltration. Vegetation is instrumental in slope stabilisation, reinforcing soil structure, and mitigating excess moisture. However, deforestation and land-use modifications driven by urban expansion, agriculture, and infrastructure development heighten landslide risks. Anthropogenic activities, including road construction, quarrying, and large-scale projects, disrupt the natural slope equilibrium, elevating the likelihood of slope failure. In areas such as Wayanad, which is characterised by heavy monsoon precipitation, unplanned development compounds this risk.

Land Use and Land Cover (LULC) changes influence landslide susceptibility by altering slope stability and soil structure. LULC is a crucial conditioning factor in landslide susceptibility models. It encompasses land utilisation (urbanisation, agriculture, forestry, etc.) and physical characteristics of the Earth's surface (vegetation, water bodies, barren land, etc.). LULC modifications can mitigate or exacerbate landslide risks depending on their impact on the natural equilibrium of a terrain.

LULC Influence on Landslide Events in Wayanad

Empirical data indicate that 58% of landslides in Wayanad occurred in densely vegetated regions, suggesting that natural terrain and hydrological factors contribute significantly to slope instability. The remaining 42% were associated with modified landscapes—25% in forest plantations and built-up areas—highlighting the role of anthropogenic land-use changes in exacerbating landslide risk. The 2018 Wayanad landslides were attributed to infrastructural expansion and stone quarrying, resulting in slope destabilisation. In 2019, unsustainable rubber plantation practices, particularly on steep slopes of up to 30°, were identified as a major factor. The extensive use of heavy earth moving equipment to dig rain pits in these plantations created artificial depressions that, when inundated by monsoon rainfall, triggered slope failure. Inadequate water drainage infrastructure and unregulated residential expansion also aggravated the situation (Wadhawan et al., 2020).

Deforestation has significantly altered the ecological stability of Wayanad. Between 1950 and 2018, the district saw a 62% reduction in natural forest cover. Concurrently, commercial tea plantations expanded by 1800%, replacing resilient forested landscapes with monocultures that lack deep root systems to anchor soil and prevent erosion. The transition from native forests to plantations diminishes the ability of slopes to withstand heavy rainfall and alters the region's hydrological balance. By 2012, Wayanad had undergone substantial LULC modifications, with plantations expanding from 913 km² to 1215 km² and forest cover shrinking from 888 km² to 672 km². The dominance of commercial plantations and urban settlements over natural vegetation exacerbates soil instability, alters drainage patterns, and amplifies the risks from extreme rainfall. The absence of adequate slope management in these modified landscapes further compounds landslide susceptibility.

Implications for Disaster Risk Management

The interplay between LULC changes and landslide susceptibility in Wayanad underscores the need for sustainable land-use planning and conservation strategies. Unregulated urban expansion, deforestation, and unsustainable agricultural practices must be addressed through policies focused on afforestation, slope stabilisation, and stricter land-use regulations. Incorporating geospatial technologies can enhance risk assessment and inform proactive mitigation strategies. Although natural factors remain critical drivers of landslides, human-induced LULC transformations in Wayanad have heightened the vulnerability of the region. An integrated approach that balances economic development with ecological resilience is essential for mitigating future landslide risks and safeguarding both human settlements and natural ecosystems.

Key Takeaways and Recommendations

One of the top priorities for Tamil Nadu and Kerala is to enhance climate-resilient infrastructure to withstand extreme weather events. For Tamil Nadu, sustainable urban development investment is crucial, including the development of stormwater drainage infrastructure and wetland restoration to effectively handle heavy rainfall. Kerala must strengthen slope stabilisation, implement stricter land-use regulations, and promote afforestation in high-risk areas.

Strengthening disaster preparedness is critical for both states. The unpredictability of monsoonal rainfall necessitates improved early warning systems using AI and real-time meteorological data for precise forecasts. Tamil Nadu and Kerala should expand community-based disaster preparedness programs, particularly in vulnerable areas. Evacuation drills, emergency response teams, and disaster awareness campaigns can enhance public readiness and reduce casualties. Tamil Nadu should focus on restoring urban wetlands and expanding green spaces to reduce flood risks. In Kerala, reforestation in landslide-prone regions is essential for stabilising slopes and preventing soil erosion. Controlling the expansion of commercial plantations is necessary because monoculture farming weakens soil integrity and increases landslide vulnerability.

A shift toward sustainable development policies is imperative to mitigate climate-related disasters. In Tamil Nadu, zoning laws should restrict construction in flood-prone areas and ensure urban expansion does not encroach upon natural drainage systems. Kerala must regulate construction in ecologically fragile zones, where unregulated land use exacerbates landslides. Sustainable urban planning frameworks that integrate climate risk assessments can help both states minimise long-term damage from extreme weather events.

Expanding regional climate research will play a crucial role in the development of effective mitigation strategies. Both Tamil Nadu and Kerala require localised climate models that analyse historical and projected rainfall patterns, allowing policymakers to design tailored adaptation plans. Collaboration with global climate research institutions can enhance forecasting accuracy and provide insights into the evolving monsoon patterns affecting South India. By prioritising climate resilience, disaster preparedness, and environmental conservation, Tamil Nadu and Kerala can better safeguard their populations and infrastructure against climate change.

The Intersection of Climate Change, Monsoonal Variability, and Regional Vulnerability

The analysis of monsoonal variability in Tamil Nadu and Kerala highlights the mounting vulnerability of these states to extreme climatic events caused by global climate change. Changing rainfall patterns have intensified cyclonic activity, and rising temperatures have disrupted historical climate norms, posing significant risks to populations. The case studies of the 2015 and 2023 floods in Chennai and southern Tamil Nadu, along with the 2024 landslides in Wayanad, provide compelling evidence of these changes and highlight the pressing need for sustainable adaptation measures. The effects of climate change on monsoon patterns in Tamil Nadu and Kerala are multifaceted. Tamil Nadu, which is largely reliant on the northeast monsoon, has experienced unpredictable rainfall, with high-intensity, short-duration storms resulting in urban flooding. The 2015 Chennai floods are a classic example of the impacts of heavy rainfall compounded by lack of proper urban planning and inadequate drainage. Similarly, in 2023, Michaung demonstrated that tropical cyclones, influenced by rising sea surface temperatures, exacerbate flooding risks in coastal cities. The extreme rainfall event in southern Tamil Nadu, resulting in unprecedented flooding, was caused by static upper air circulation, excess moisture incursion, and the El Niño Southern Oscillation effect, reflecting the unpredictability of climate change impacts on monsoon patterns. Kerala's dependence on the southwest monsoon makes it susceptible to extreme rainfall-induced landslides, as evidenced by the Wayanad disaster in 2024. The frequency of such events raises concerns about land use changes, deforestation, and unregulated urbanisation, which aggravate natural disaster risks.

Anthropogenic activities amplify climate risk. In Tamil Nadu, rapid urbanisation, land encroachment, and poorly maintained reservoirs have contributed to flood severity. In Kerala, commercial plantation expansion, deforestation, and unsustainable land use practices have increased landslide risk. The shift from native forests to monoculture plantations has disrupted soil stability, making steep slopes more vulnerable to extreme rainfall events.

Policy interventions, technological advancements, and community-driven initiatives are essential for mitigating the effects of climate change on monsoons. Urban flood management in Tamil Nadu must prioritise sustainable infrastructure, improved stormwater drainage, and flood-resilient urban planning. In Kerala, stricter land-use regulations, afforestation programs, and early warning systems for landslides are crucial for reducing disaster risks. Regional climate modeling and real-time data monitoring must be intensified to improve preparedness and response measures. The inclusion of climate resilience in policy platforms, supporting sustainable development, and the improvement of scientific research on monsoonal changes will be the solution to preventing these regions from future climate-related threats. The management of the climate-monsoon relationship is not just an environmental requirement but also a socio-economic concern to save millions of livelihoods and lives in South India.

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