



Westward shift of Indian summer monsoon precipitation and heat wave frequency patterns over South Asia

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Abstract

The phenomenon of climate change has significantly impacted weather patterns across the globe, particularly in South Asia. This study indicates a notable westward shift in precipitation and heat wave frequency over India, Pakistan and their adjacent regions. This shift is characterized by altered monsoon patterns, increased frequency of extreme weather events, and changing temperature regimes, which collectively pose challenges to water resources, cryosphere, agriculture, and public health. To comprehensively understand the dynamic nature of heat wave frequency, here we choose average vertical pressure velocity (ω), geopotential height, meridional wind vector and average temperature anomalies and heat wave frequency number of days meeting the criteria of at least three consecutive days above the 90th percentile. Our findings reveal a pronounced westward shift in heat wave frequency, particularly between June 1990 to August 2000, and from March 2000 to 2010. Additionally, the northwestern regions of India and Pakistan and eastern region (Myanmar) have experienced notable positive precipitation anomalies from 2000 to 2024, closely linked to Middle East warming. In contrast, negative precipitation anomalies over Tibet and the Himalayas threaten glacier and permafrost health. This finding suggests the upper atmospheric anticyclone or atmospheric blocking are a major drivers of Heat waves. In light of these extreme weather changes, advancing climate-resilient infrastructure is essential to mitigate risks and to ensure long-term environmental and socioeconomic stability.

Keywords: Climate change, Heat waves, Permafrost, Precipitation anomalies, Atmospheric anticyclone, Middle east warming

Received: April 08, 2025

Revised: May 05, 2025

Accepted: May 12, 2025

Citation

Kumar O., and Pani B., and Saikia A., and Sharma S., and Kumar N. (2025). Westward shift of Indian summer monsoon precipitation and heat wave frequency patterns over South Asia. *Int. J. Disaster Studies Climate Resil.* 1(1):47–54.



1 Introduction

Monsoons play a crucial role in the tropical and sub-tropical climates of various regions worldwide (Huffman et al., 2001; Geen et al., 2020; Wang et al., 2014; Kumar et al., 2021; Tierney et al., 2011). The Indian summer monsoon and westerly precipitation are key drivers influencing glacier dynamics, agricultural productivity, river flow maintenance, and the wellbeing of diverse ecosystems across different timescales (Kumar et al., 2021; Mandal et al., 2020; Mishra et al., 2020; Kotlia et al., 2018; Kumar et al., 2020; Fig. 1). The changing climate is reshaping weather patterns across the globe, leading to significant alterations in precipi-

tation and the frequency and intensity of heat waves (Rohini et al., 2016; Pai et al., 2013; Prein et al., 2023). In Western India and Pakistan, fluctuations in precipitation pose a considerable threat to communities, as these changes significantly influence various socioeconomic factors and the overall well-being of the population. Over the past few decades, Pakistan and northwestern India frequently experienced heavy precipitation and floods (Lyngwa and Nayak, 2021; Sreenath et al., 2022; Yadav, 2016).

In the last decades, the mortality rate linked to heat-waves has risen in South Asia (Im et al., 2017; Jenamani, 2012; Mazdiyasn et al., 2017; Knowlton et al., 2014). The India Meteorological Department (IMD) states that a

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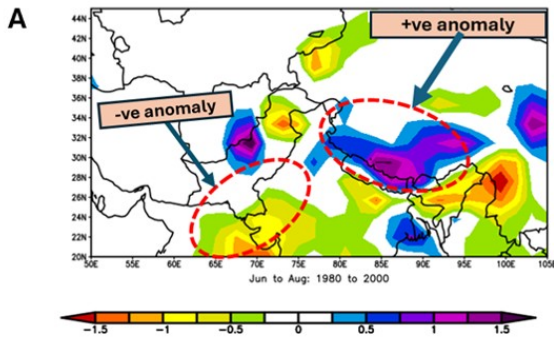
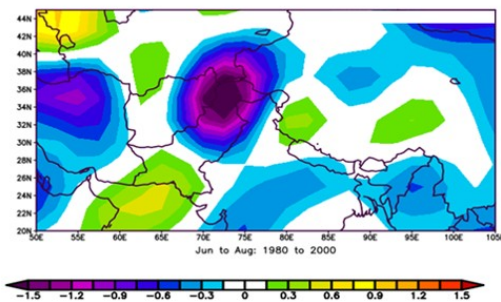
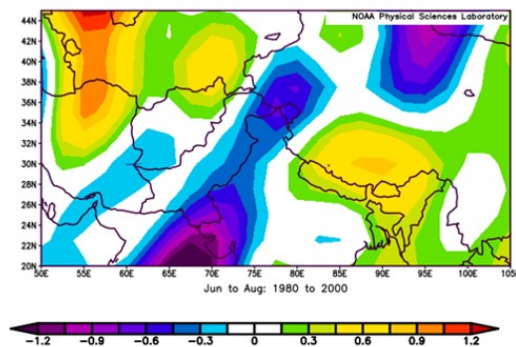
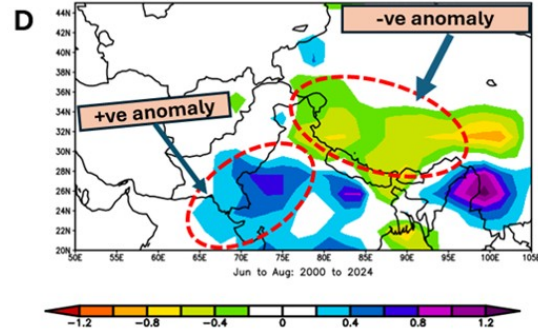
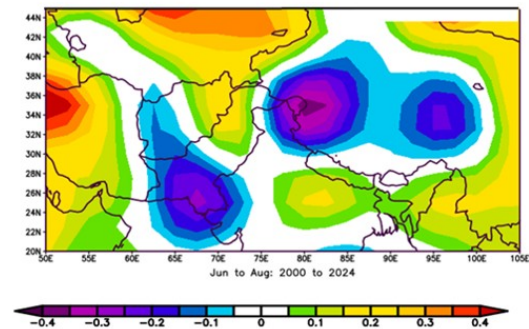
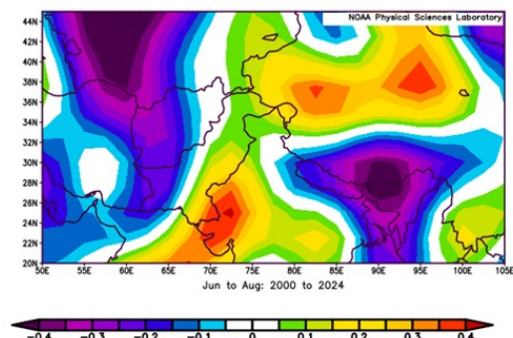
Surface precipitation rate (mm/day) anomaly**B Air temperature anomaly****C Meridional wind (700 mb) anomaly****Surface precipitation rate (mm/day) anomaly****E Air temperature anomaly****F Meridional wind (700 mb) anomaly**

Fig. 1. A & D. Surface precipitation rate anomalies (mm/day) for the periods 1980–2000 and 2000–2024. B & E. Air temperature anomalies for the same periods 1980–2000 and 2000–2024. C & F. Meridional wind anomalies for the periods 1980–2000 and 2000–2024 respectively.

‘Heat Wave’ is identified when the maximum temperature at a location hit at least 40°C in plains or a minimum of 30°C in hilly regions. This is generally determined by the count of consecutive days in which the maximum temperature exceeds the 90th percentile threshold. Typically, this time frame is either three or five days, based on regional climate norms and impact evaluations (Perkins and Alexander, 2013). The effects of heat waves arise from the combination of elevated dry-bulb temperatures and high wet-bulb temperatures, along with the vulnerability of the population (WHO, 2023). The intensification of prolonged and highly frequent heatwaves is expected in India, potentially leading to increased heat stress and a higher mortality rate (Ravindra et al., 2024). In several Indian states, particularly those in the western and eastern regions such as Bihar, Jharkhand, Odisha, Punjab, Haryana, Chandigarh, Delhi, Rajasthan, Maharashtra, western Madhya Pradesh, and

Gujarat heat waves have emerged as a growing issue of concern. The frequency and intensity of these extreme heat events, however, are not evenly spread throughout the entire country. The shifting patterns of extreme weather events such as heat wave and precipitation could accelerate thawing of permafrost and the melting of glaciers in the northwestern Himalayas, Tibet, Kazakhstan, and surrounding regions (Fig. 2, 3). The processes behind these climatic changes are still poorly comprehended, but their effects on regional hydrology, ecosystem resilience and long-term environmental sustainability are significant. Among the multiple hazards, heat waves is one of the extreme events severely impacting globe including India and its surrounding region (Campbell et al., 2018; Fig. 2, 3). Heat waves are often linked to anticyclonic flows in the middle and upper troposphere, which create blocking patterns that extend downward, driving subsidence and warm air

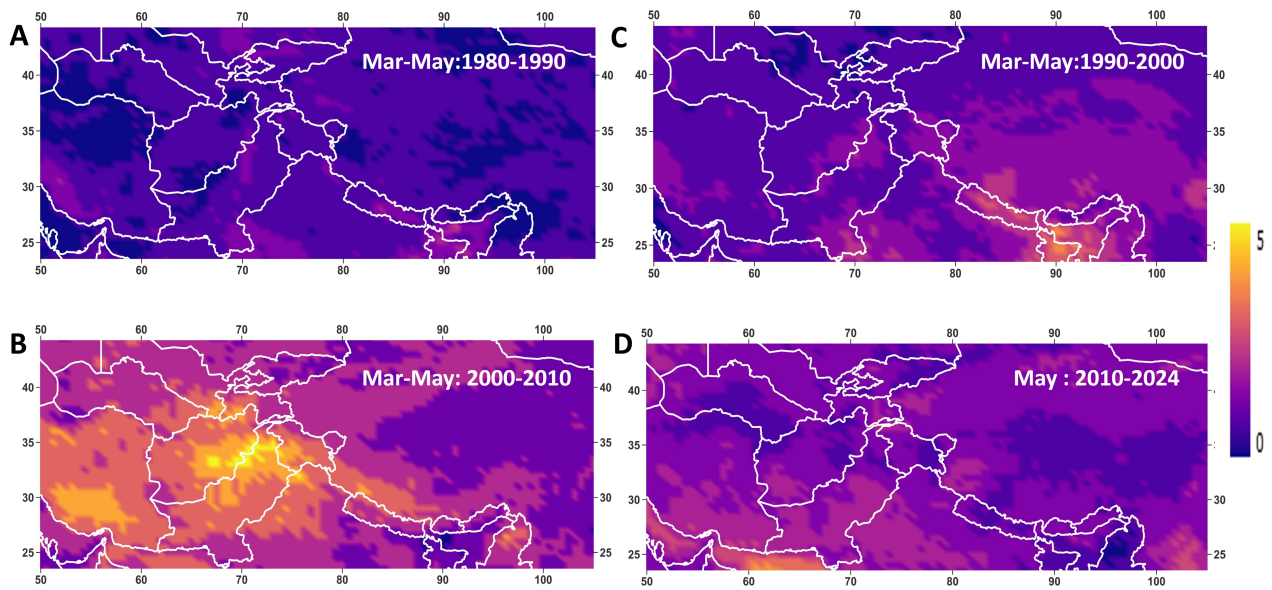


Fig. 2. Heat wave frequency represented as the number of days meeting the criteria of at least three consecutive days above the 90th percentile. A. Illustrates heat wave occurrences from March 1980 to May 1990, (B). March 2000 to May 2010, (C) March 1990 to May 2000 and (D) Frequency data from March 2010 to May 2024.

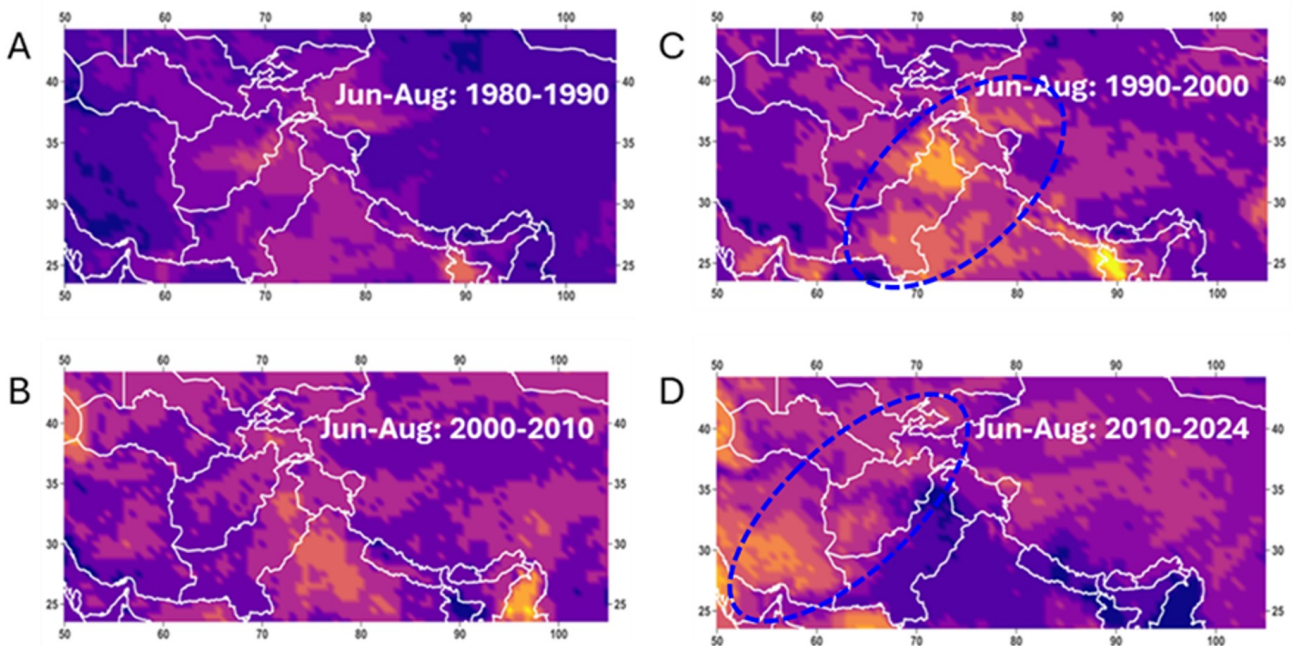


Fig. 3. Heat wave frequency represented as the number of days meeting the criteria of at least three consecutive days above the 90th percentile in monsoon season. A. Heat wave frequency from Jun 1980 to Aug 1990, B. June 2000 to August 2010. C. June 1990 to August 2000 and D. Frequency data from June 2010 to August 2024.

advection. These conditions lead to prolonged surface heat waves. In mid-latitudes, heat waves are tied to atmospheric blocking (Carril et al., 2008; Tomczyk and Bednorz, 2019), while in central and southern Europe (Sousa et al., 2018), and Australian region associated with subtropical ridges (Perkins, 2015), both associated with upper-atmospheric anticyclones. This study examines the drivers of heat waves and precipitation shifts from 1980 to 2024, offering insights into evolving climatic trends and their impact on environmental sustainability.

2 Methods

We have utilised the surface precipitation rate (mm/day), air temperature anomaly, meridional wind anomaly, heat wave frequency data (1980–2024) to understand extreme weather events within the study region (20°N–45°N, 50°E–105°E, Fig. 1A–F). We utilize the MEERA-2 reanalysis dataset from NASA Earth Data (Wilson, 2025) to calculate the number of days that meet the heat wave criteria, defined as at least three consecutive days

exceeding the 90th percentile. This analysis is conducted monthly for the period from March 1980 to May 2000 and from June 2000 to August 2024, using a spatial resolution of $0.5^\circ \times 0.625$. The NCEP/NCAR reanalysis data is utilized for geopotential height, precipitation, air temperature, and wind vector anomalies, with anomalies calculated based on the 1991–2000 period. All the heatwave frequency data were analysed using QGIS 3.34.9 at Delhi School of Climate Change and Sustainability, Institution of Eminence (IoE), University of Delhi.

3 Results and Discussion

3.1 Spatiotemporal frequency of heat wave in pre-monsoon season (1980–2024)

We examine the summer-season variations in surface precipitation anomalies, air temperature anomalies, and meridional wind patterns across the study region (Fig. 1A–D). The surface precipitation anomaly maps (Fig. 1A, D) reveal distinct spatio-temporal patterns over the study region. From 1980 to 2000, a positive precipitation anomaly was observed over the Tibetan Plateau and the Himalayan region, while a negative anomaly was evident over the western parts of India and Pakistan (Fig. 1A). However, this pattern underwent a significant shift during the 2000 to 2024 period, with a negative precipitation anomaly now observed over the Tibetan Plateau and Himalayas, and a positive anomaly emerging over the western regions (Fig. 1D). The surface precipitation anomalies (Fig. 1A & D) reflect shifting moisture availability across South Asia, which directly influences land surface heating and monsoon dynamics. The negative precipitation anomalies over Tibet and the Himalayas (2000–2024) could be indicating a decline in cloud cover and evaporative cooling, potentially intensifying surface heating and increasing heatwave frequency in adjacent regions. Conversely, the positive precipitation anomalies over northwestern India and Pakistan contribute to intermittent periods of increased humidity, which, combined with anticyclonic subsidence, may exacerbate extreme heat conditions. Fig. 1(B, E) illustrate the variations in air temperature anomalies across two distinct periods from 1980–2000 and 2000–2024. Furthermore, air temperature anomalies (Fig. 1B & E) highlight significant warming trends, particularly in western India, reinforcing the growing intensity and frequency of heat waves. These variations in temperature patterns underscore the broader climatic shift driving heat stress and altering seasonal monsoon behaviours. Similarly, Fig. 1(C & F) depict the meridional wind anomalies during the summer season, highlighting temporal shifts in atmospheric circulation patterns. Additionally, these modified atmospheric circulation patterns could contribute to the westward shift in heatwave occurrences.

Strengthened westerly winds transport warm, dry air further inland, sustaining extreme heat conditions over northwestern India and its neighbouring regions. Fig. 2(A–D) shows the decadal heat wave frequency patterns in pre-monsoon season over the study region (20°N – 45°N , 50°E – 105°E). Fig. 2A shows that during the pre-monsoon season (March–May, 2000–2010) the highest heat wave frequency was concentrated in the central and eastern region

(Bangladesh and Bhutan). This suggests that the central and eastern areas experienced the most intense and prolonged heat wave events, with at least three consecutive days above the 90th percentile. In the previous decades (1990–2000; Fig. 2C), regions experiencing the most frequent heat waves shifted slightly, with certain southern and eastern areas reflecting a rise in heat wave occurrences. In Fig. 2D, data spanning 2010–2024, indicating that the frequency pattern of heat waves continued to change, with new regions in the east and west facing more severe heat wave occurrences. The westward heat wave shift from 2000–2010 (Fig. 2B) to 2010–2024 (Fig. 2D) aligns with intensified westerly winds (Fig. 1F), suggesting a broader atmospheric circulation change driving extreme events. This indicates that although the spatial distribution has altered over the years, certain regions have consistently been more susceptible to heat wave occurrences.

3.2 Spatiotemporal frequency of heat wave in monsoon season (1980–2024)

The dynamic patterns of heat wave frequency in monsoon season (June–August) from 1980 through 2024 is demonstrated in Fig. 3. The observed region underwent most severe and extended heat wave occurrences, featuring at least three consecutive days exceeding the 90th percentile. The Fig. 3A shows that the frequency of heat waves is mostly concentrated over the western and northwestern regions from 1980 to 1990. Additionally, during the summer season (1990–2000; Fig. 3C), it is evident that the areas experiencing the most frequent heat waves shifted slightly, with certain southern and western (parts of India, Pakistan and Afghanistan) eastern regions (Bangladesh) now exhibiting more occurrences. This pattern indicates a spatial redistribution of heat wave hotspots compared to the previous decade. From 2000–2010 (Fig. 3B) illustrates that the heat wave frequency pattern continued to develop, with additional regions in the northeast and southwest experiencing more intense heat wave occurrences. This demonstrates the dynamic nature of heat wave occurrences and how they can shift across different regions as time progresses.

The period from 2010 to 2024 (Fig. 2D) illustrates a persistent shift in the heat wave frequency patterns, with the north-western and eastern regions (Bangladesh) once more experiencing the high occurrences. This increased monsoon heat wave frequency in northwest India reflects enhanced land-surface heating, amplifying convection (positive ω , Fig. 4B) and flood risk in arid regions. This indicates that the spatial distribution has evolved over the decades, with certain areas continuing to be more vulnerable to heat wave occurrences. In general, the series of heat wave frequency highlights the changing and evolving nature of heat wave patterns throughout the analysed area. The shifting nature of extreme weather occurrences, such as the frequency of heat waves, presents significant threats to glaciers, permafrost, and public health.

3.3 Drivers of the extreme events

Extreme events like heat waves are shaped by multiple physical drivers and processes, including atmospheric

Average vertical pressure velocity (ω) : 1980–2000 Average vertical pressure velocity (ω) : 2000–2024

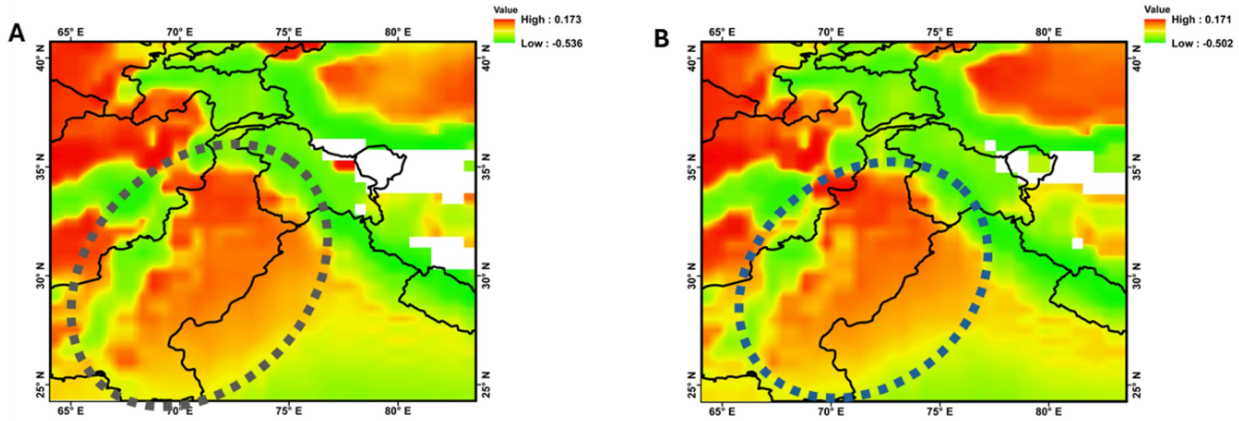


Fig. 4. Shows variations in monsoon season vertical pressure velocity during two periods (1980–2000 and 2000–2024). (A) Average vertical pressure velocity (ω) from 1980–2000 in monsoon season (Jun–Aug) and (B). Average vertical pressure velocity (ω) from 2000–2024 in monsoon season (Jun–Aug).

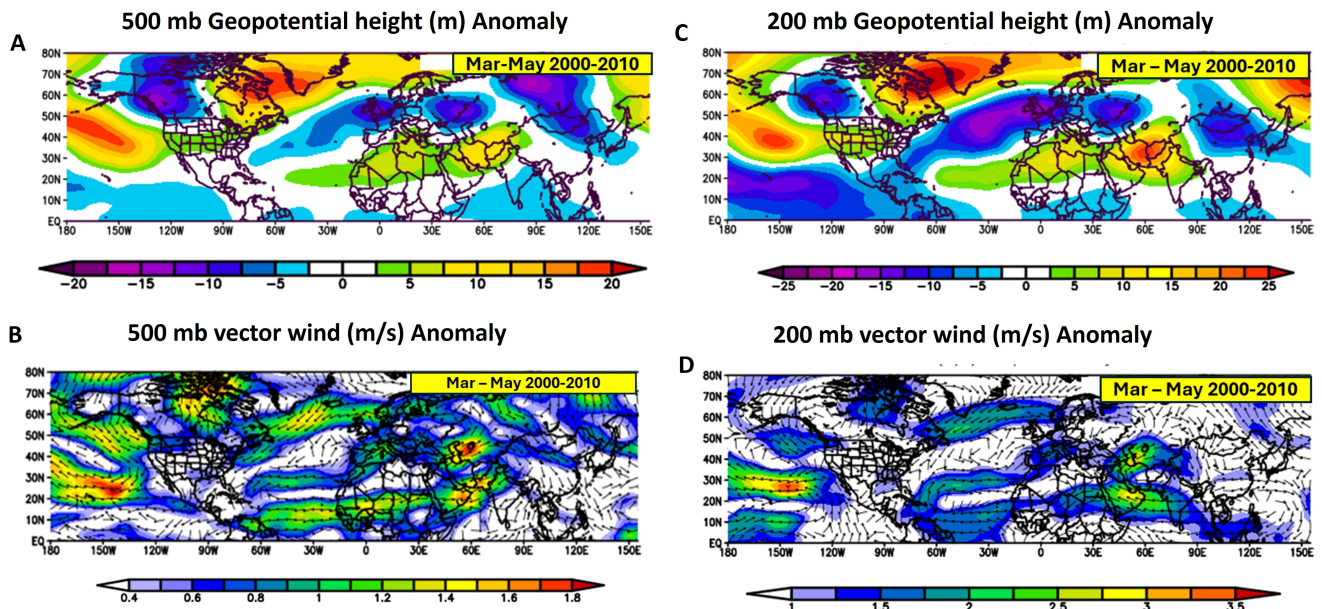


Fig. 5. Geopotential height (m) and wind vector (m/s) anomaly (A, C) Geopotential height anomaly at 500 mb and 200 mb respectively. (B) Wind vector anomaly at 500 mb and (D) Wind vector anomaly at 200 mb.

circulation patterns, sea surface temperatures, soil moisture levels and cloud cover. To better understand their dynamics, we focus on geopotential height anomalies, upper-atmosphere meridional anomalies, and vertical pressure velocity (ω). The average vertical pressure velocity (ω) can indicate the overall stability or instability of the atmosphere. Areas with high positive ($\omega > 0$) are typically connected to subsiding motion, whereas areas with negative ω showing air is rising in the atmosphere. This sinking motion (positive ω) lead to clear skies, reduced humidity and warm temperature at the surface whereas a negative omega means rising motion. This upward motion can create cloud cover and reflects the solar radiation. Fig. 4 indicates that positive ω is present in the northwestern regions of India and across Pakistan during the periods 1980–2000 and

2000–2024, while there is negative ω indicating ascending motion in the central Himalayas. The highest upward ω values in northwestern parts of India and over regions of Pakistan create a condition for heat waves (Fig. 2B, Fig. 3) whereas negative ω value over central and parts of western Himalayas. The ω values, both negative and positive, are affected by factors such as Himalayan topography, thermal contrasts between land and sea, and patterns of atmospheric circulation. These variations in vertical pressure velocity results in a change in the frequency of extreme weather events. Some other processes such as the upper-tropospheric anticyclones act as dynamic precursor for the formation of surface heat waves over India, Pakistan and surrounding region during March 2000–May 2010 (Fig. 5). Heat waves in mid-latitudes are often linked to atmospheric blocking

(Carril et al., 2008; Tomczyk and Bednorz, 2019), while in central and southern Europe (Sousa et al., 2018) and the Australian region, they are associated with subtropical ridges (Perkins, 2015). Both phenomena are connected to upper-atmospheric anticyclones. In this study region (Fig. 2, 3), the geopotential height (m) in upper atmosphere at 500 hPa and 200 hPa reveals high geopotential heights (gpm) anomalies over northwest India, the North Atlantic, and western North America (Fig. 5A, C). Wind vector analysis and gpm at the same pressure levels indicates the formation of anticyclonic conditions over northwestern India and adjacent regions (Fig. 5). Overall, geopotential height is abnormally high at pressure levels such as 500 hPa and 200 hPa, it often indicates the presence of strong, persistent anticyclonic systems. These systems suppress vertical air movement, reducing cloud cover and allowing intense solar radiation to heat the surface. In regions like northwest India, the North Atlantic, and western North America, such anomalies contribute to the development and intensification of heat waves by reinforcing stable and dry atmospheric conditions. This positive vertical pressure velocity and development of anticyclone can transport heat and influences the cryosphere of northwestern Himalaya and adjacent areas. The teleconnected heat wave patterns significantly influence the environmental variability in these regions. The delayed onset of the monsoon, frequently linked to El Niño (Murari et al., 2016; Im et al., 2017) and various teleconnected mechanisms, soil moisture, further intensifies these conditions. The northwestern regions of India and eastern India have experienced notable positive precipitation anomalies from 2000 to 2024, closely linked to Middle East warming (Fig. 1E). Numerous studies emphasize the physical drivers that modulate the Indian summer monsoon and influence shifting precipitation patterns across India and its neighbouring regions (Yadav, 2016, 2017, Yadav et al., 2018, Yadav, 2021, 2024; Li et al., 2023).

3.4 Extreme weather events and climate resilient infrastructure

Rising temperatures (Coumou et al., 2013) results in intense heatwaves that endanger lives, agriculture, and energy systems, whereas changing rainfall patterns cause severe flooding in Pakistan and adjacent areas (Li et al., 2023) and extended droughts in mainly western and eastern part of India (Gautam and Bana, 2014; Mishra et al., 2019). The extreme heat is a kind of natural hazards whose occurrence has risen in 21st century with the most significant increase observed between March 2000 and May 2010 (Fig. 3). The development of climate resilient infrastructure is important in this warming world to address the challenges posed by the rising frequency of heat waves and the shift in precipitation patterns towards the west in developing nations like India, Pakistan, and nearby regions (Fig. 1–3). To tackle these issues, resilient infrastructure should integrate sustainable urban development, strong cooling solutions, effective water management systems, and disaster-resistant construction designs. Early alert systems, flood-resistant infrastructure, and green solutions, including urban woodlands and permeable surfaces, can reduce the dangers associated with

climate change. By incorporating these adaptations into development plans, countries can protect communities and economies from the uncertain impacts of climate-related disasters while promoting sustainable growth.

4 Conclusions

This research highlights the dynamic nature of extreme weather phenomena like heat waves and shifts in precipitation across the study area. The analysis utilizing data from 1980 to 2024 indicates that northwestern, western, and eastern India, along with nearby regions, have experienced a frequent occurrence of heat waves. In addition, the western region of India starts receiving heavy precipitation during the monsoon season. Our findings shows that the average vertical velocity omega is positive over the western parts of India and Pakistan. The heat wave frequency and heavy precipitation is observed in western region. The shifting hotspots highlight the necessity for continuous observation and adaptation strategies to tackle the effects of these severe weather events. Additionally, the northwestern regions of India and adjacent areas have experienced notable positive precipitation anomalies from 2000 to 2024, closely linked to Middle East warming. In contrast, negative precipitation anomalies over Tibet and the Himalayas threaten glacier and permafrost health. This finding suggests the upper atmospheric anti-cyclone or atmospheric blocking are a major drivers of Heat waves. A strong policy must be established that takes into account climate-resilient infrastructure in both western and eastern regions of India. These trends demand region-specific policies, flood-resistant infrastructure in the west and heat mitigation in the east to safeguard 1.5 billion reliant on monsoon stability.

Acknowledgements

We sincerely acknowledge NOAA/NASA for granting access to the remote sensing data utilized in this study.

Availability of data

The datasets used in this study can be accessed through publicly available resources (<https://search.earthdata.nasa.gov/search>) or requested directly from the corresponding author.

Conflict of Interest

The authors declare that there are no conflicts of interest

CRediT statement

O.K.: Formulation of research concept, structured study design, drafted the manuscript. O.K., B.P, A.S., S.S., N.K.: Insights, discussions, formulation of results and discussions.

Sources of Support

Om Kumar has been awarded a postdoctoral fellowship by the Delhi School of Climate Change and Sustainability, an Institution of Eminence at the University of Delhi. This financial support played a crucial role in facilitating this research.

References

- Campbell, S., Remenyi, T.A., White, C.J., Johnston, F.H., 2018. Heatwave and health impact research: A global review. *Health & Place* 53, 210–218. doi:10.1016/j.healthplace.2018.08.017.
- Carril, A.F., Gualdi, S., Cherchi, A., Navarra, A., 2008. Heatwaves in Europe: areas of homogeneous variability and links with the regional to large-scale atmospheric and SSTs anomalies. *Clim. Dynam.* 30, 77–98. doi:10.1007/s00382-007-0274-5.
- Coumou, D., Robinson, A., Rahmstorf, S., 2013. Global increase in record-breaking monthly-mean temperatures. *Climatic Change* 118, 771–782. doi:10.1007/s10584-012-0668-1.
- Gautam, R.C., Bana, R.S., 2014. Drought in India: Its impact and mitigation strategies a review. *Indian Journal of Agronomy* 59, 179–190. doi:10.59797/ija.v59i2.4544.
- Geen, R., Bordoni, S., Battisti, D.S., Hui, K., 2020. Monsoons, ITCZs, and the concept of the global monsoon. *Reviews of Geophysics* 58. doi:10.1029/2020RG000700. e2020RG000700.
- Huffman, G.J., Adler, R.F., Morrissey, M.M., Bolvin, D.T., Curtis, S., Joyce, R., McGavock, B., Susskind, J., 2001. Global precipitation at one-degree daily resolution from multisatellite observations. *Journal of Hydrometeorology* 2, 36–50. doi:10.1175/1525-7541(2001)002.
- Im, E.S., Pal, J.S., Eltahir, E.A., 2017. Deadly heat waves projected in the densely populated agricultural regions of south Asia. *Science Advances* 3, 1603322. doi:10.1126/sciadv.1603322.
- Jenamani, R., 2012. Analysis of ocean-atmospheric features associated with extreme temperature variation over east coast of India: A special emphasis to Orissa heat waves of 1998 and 2005. *Mausam* 63, 401–422. doi:10.54302/mausam.v63i3.1231.
- Knowlton, K., Kulkarni, S.P., Azhar, G.S., Mavalankar, D., Jaiswal, A., Connolly, M., Ahmedabad Heat and Climate Study Group, 2014. Development and implementation of south Asia's first heat-health action plan in Ahmedabad (Gujarat, India). *International Journal of Environmental Research and Public Health* 11, 3473–3492. doi:10.3390/ijerph110403473.
- Kotlia, B.S., Singh, A.K., Joshi, L.M., Bisht, K., 2018. Precipitation variability over northwest Himalaya from 4.0 to 1.9 ka bp with likely impact on civilization in the foreland areas. *Journal of Asian Earth Sciences* 162, 148–159. doi:10.1016/j.jseaes.2017.11.025.
- Kumar, O., Ramanathan, A.L., Bakke, J., Kotlia, B.S., Shrivastava, J.P., 2020. Disentangling source of moisture driving glacier dynamics and identification of 8.2 ka event: evidence from pore water isotopes, western Himalaya. *Scientific Reports* 10, 15324. doi:10.1038/s41598-020-71686-4.
- Kumar, O., Ramanathan, A.L., Bakke, J., Kotlia, B.S., Shrivastava, J.P., Kumar, P., Sharma, R., Kumar, P., 2021. Role of Indian summer monsoon and westerlies on glacier variability in the Himalaya and East Africa during late Quaternary: Review and new data. *Earth-Science Reviews* 212, 103431. doi:10.1016/j.earscirev.2020.103431.
- Li, B., Zhou, L., Qin, J., Zhou, T., Chen, D., Hou, S., Murtugudde, R., 2023. Middle east warming in spring enhances summer rainfall over Pakistan. *Nature Communications* 14, 7635. doi:10.1038/s41467-023-43463-0.
- Lyngwa, R.V., Nayak, M.A., 2021. Atmospheric river linked to extreme rainfall events over Kerala in August 2018. *Atmos. Res.* 253, 105488. doi:10.1016/j.atmosres.2021.105488.
- Mandal, A., Ramanathan, A., Azam, M.F., Angchuk, T., Soheb, M., Kumar, N., Pottakkal, J.G., Vatsal, S., Mishra, S., Singh, V.B., 2020. Understanding the interrelationships among mass balance, meteorology, discharge and surface velocity on Chhota shigri glacier over 2002–2019 using in situ measurements. *Journal of Glaciology* 66, 727–741. doi:10.1017/jog.2020.42.
- Mazdiyasni, O., AghaKouchak, A., Davis, S.J., Madadgar, S., Mehran, A., Ragno, E., Sadegh, M., Sengupta, A., Ghosh, S., Dhanya, C.T., Niknejad, M., 2017. Increasing probability of mortality during Indian heat waves. *Science Advances* 3, 1700066. doi:10.1126/sciadv.1700066.
- Mishra, V., Thirumalai, K., Singh, D., Aadhar, S., 2020. Future exacerbation of hot and dry summer monsoon extremes in India. *npj Climate and Atmospheric Science* 3, 10. doi:10.1038/s41612-020-0113-5.
- Mishra, V., Tiwari, A.D., Aadhar, S., Shah, R., Xiao, M., Pai, D.S., Lettenmaier, D., 2019. Drought and famine in India, 1870–2016. *Geophysical Research Letters* 46, 2075–2083. doi:10.1029/2018GL081477.
- Murari, K.K., Sahana, A.S., Daly, E., Ghosh, S., 2016. The influence of the El Niño Southern Oscillation on heat waves in India. *Meteorological Applications* 23, 705–713. doi:10.1002/met.1594.
- Pai, D.S., Nair, S., Ramanathan, A.N., 2013. Long term climatology and trends of heat waves over India during the recent 50 years (1961–2010). *Mausam* 64, 585–604.
- Perkins, S.E., 2015. A review on the scientific understanding of heatwaves—their measurement, driving mechanisms, and changes at the global scale. *Atmospheric Research* 164, 242–267. doi:10.1016/j.atmosres.2015.05.014.
- Perkins, S.E., Alexander, L.V., 2013. On the measurement of heat waves. *Journal of Climate* 26, 4500–4517. doi:10.1175/JCLI-D-12-00383.1.
- Prein, A.F., Mooney, P.A., Done, J.M., 2023. The multi-scale interactions of atmospheric phenomenon in mean and extreme precipitation. *Earth's Future* 11, 2023 003534. doi:10.1029/2023EF003534.
- Ravindra, K., Bhardwaj, S., Ram, C., Goyal, A., Singh, V., Venkataraman, C., Bhan, S.C., Sokhi, R.S., Mor, S., 2024. Temperature projections and heatwave attribution scenarios over India: A systematic review. *Heliyon* 10. doi:10.1016/j.heliyon.2024.e26431.
- Rohini, P., Rajeevan, M., Srivastava, A.K., 2016. On the variability and increasing trends of heat waves over India. *Scientific Reports* 6, 1–9. doi:10.1038/srep26153.
- Sousa, P.M., Trigo, R.M., Barriopedro, D., Soares, P.M.M., Santos, J.A., 2018. European temperature responses to blocking and ridge regional patterns. *Clim. Dynam.* 50, 457–477. doi:10.1007/s00382-017-3620-2.
- Sreenath, A.V., Abhilash, S., Vijaykumar, P., Mapes, B.E., 2022. West coast India's rainfall is becoming more convective. *npj Clim. Atmos. Sci.* 5. doi:10.1038/s41612-022-00258-2.
- Tierney, J.E., Russell, J.M., Damsté, J.S.S., Huang, Y., Verschuren, D., 2011. Late Quaternary behavior of the East African monsoon and the importance of the Congo air boundary. *Quaternary Science Reviews* 30, 798–807. doi:10.1016/j.quascirev.2011.01.017.
- Tomczyk, A.M., Bednorz, E., 2019. Heat waves in Central Europe and tropospheric anomalies of temperature and geopotential heights. *Int. J. Climatol.* 39, 4189–4205. doi:10.1002/joc.6067.
- Wang, P.X., Wang, B., Cheng, H., Fasullo, J., Guo, Z.T., Kiefer, T., Liu, Z.Y., 2014. The global monsoon across timescales: coherent variability of regional monsoons. *Climate of the Past* 10, 2007–2052. doi:10.5194/cp-10-2007-2014.

- Wilson, B.E., 2025. Data use and citation guidance, in: NASA Earth Science Data and Information System Standards Coordination Office. doi:[10.5067/DOC/ESCO/ESDS-RFC-055](https://doi.org/10.5067/DOC/ESCO/ESDS-RFC-055).
- World Health Organization, 2023. URL: <https://www.who.int/>.
- Yadav, R.K., 2016. On the relationship between Iran surface temperature and northwest India summer monsoon rainfall. *International Journal of Climatology* 36, 4425–4438. doi:[10.1002/joc.4648](https://doi.org/10.1002/joc.4648).
- Yadav, R.K., 2017. Midlatitude Rossby wave modulation of the Indian summer monsoon. *Quarterly Journal of the Royal Meteorological Society* 143, 2260–2271. doi:[10.1002/qj.3083](https://doi.org/10.1002/qj.3083).
- Yadav, R.K., 2021. Relationship between Azores high and Indian summer monsoon. *npj Climate and Atmospheric Science* 4, 26. doi:[10.1038/s41612-021-00180-z](https://doi.org/10.1038/s41612-021-00180-z).
- Yadav, R.K., 2024. The recent trends in the Indian summer monsoon rainfall. *Environment, Development and Sustainability*, 1–15doi:[10.1007/s10668-024-04488-7](https://doi.org/10.1007/s10668-024-04488-7).
- Yadav, R.K., Srinivas, G., Chowdary, J.S., 2018. Atlantic Niño modulation of the Indian summer monsoon through Asian jet. *npj Climate and Atmospheric Science* 1, 23. doi:[10.1038/s41612-018-0029-5](https://doi.org/10.1038/s41612-018-0029-5).