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Tropical cyclone 'Biparjoy': a blessing in disguise for the disastrous heat wave event of June 2023 over India

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सार – पूर्वी और उत्तरी भारत में जून 2023 की उष्ण लहर, समकालिक-स्तरीय मौसम संबंधी पैटर्न और उष्णकटिबंधीय चक्रवात गतिविधि के बीच एक जटिल परस्पर क्रिया से प्रेरित थी। 14-18 जून के दौरान इस क्षेत्र के ऊपर लगातार मध्य से ऊपरी क्षोभमंडलीय रिज के कारण मजबूत अवतलन, साफ आसमान और स्थिर वायुमंडलीय स्थितियां उत्पन्न हुईं, जिससे सतह का तापन तीव्र हुआ। इसी समय, अति प्रचंड चक्रवाती तूफान (ESCS) बिपरजॉय उत्तर-पूर्वी अरब सागर में विकसित हुआ और 15 जून को गुजरात के तट पर पहुँचा। बिपरजॉय के तट पर पहुँचने से पहले, निचले स्तरों पर तीव्र उत्तर-पश्चिमी हवाएँ शुष्क क्षेत्रों से गर्म और शुष्क हवा को पूर्वी सिंधु-गंगा के मैदानों में ले आईं, जिससे लू की स्थिति और भी गंभीर हो गई। इस घटना में दिन के समय अत्यधिक तापमान और रात के समय न्यूनतम तापमान में वृद्धि देखी गई, जिससे रात्री में ठंडक कम हुई और गर्मी का तनाव बढ़ गया। भूस्खलन के बाद, बिपरजॉय के अवशिष्ट परिसंचरण ने प्रचलित उत्तर-पश्चिमी हवाओं को बाधित कर दिया और कटक पैटर्न को कमजोर कर दिया, जिसके परिणामस्वरूप उष्ण हवा का संवहन कम हो गया और प्रभावित क्षेत्रों में अधिकतम तापमान में 3-6°C की गिरावट आई।इस विकास के कारण उत्तर-पश्चिम, मध्य और पूर्वी भारत में लू की स्थिति धीरे-धीरे कम हुई। यह मामला उष्णकटिबंधीय चक्रवातों की उत्पत्ति की भूमिका में एक उल्लेखनीय अंतर को उजागर करता है: जहाँ बंगाल की खाड़ी के चक्रवात उष्ण हवाओं को तीव्र कर सकते हैं, वहीं अरब सागर के चक्रवात, जैसे कि बिपरजॉय, भूस्खलन के बाद उन्हें कम कर सकते हैं। ये निष्कर्ष चक्रवात की उत्पत्ति, प्रक्षेप पथ और महाद्वीपीय प्रणालियों के साथ अंतःक्रिया के महत्व पर जोर देते हैं, जो उष्णता की चरम स्थितियों को नियंत्रित करने में सहायक होते हैं तथा उष्णकटिबंधीय चक्रवात के पूर्वानुमान को उष्ण लहर की तैयारी की रणनीतियों में एकीकृत करने की वकालत करते हैं।

ABSTRACT. The June 2023 heat wave over eastern and northern India was driven by a complex interplay between synoptic-scale meteorological patterns and tropical cyclone activity. A persistent mid-to-upper tropospheric ridge over the region during 14–18 June led to strong subsidence, clear skies, and stable atmospheric conditions, fostering intense surface heating. Concurrently, Extremely Severe Cyclonic Storm (ESCS) Biparjoy developed over the northeast Arabian Sea and made landfall over Gujarat on 15 June. Prior to landfall of Biparjoy, strong northwesterly winds at lower levels, advected hot, dry air from arid regions into the eastern Indo-Gangetic Plains, intensifying heat wave conditions. The event was marked by both extreme daytime temperatures and elevated nighttime minima, reducing nocturnal cooling and heightening heat stress. Following landfall, the remnant circulation of Biparjoy disrupted the prevailing northwesterlies and weakened the ridge pattern, resulting in reduced hot air advection and a 3–6°C drop in maximum temperatures across affected regions. This evolution led to the gradual abatement of heat wave conditions over northwest, central, and eastern India. The case highlights a notable contrast in the role of tropical cyclones by origin: while Bay of Bengal systems may tend to intensify heat waves, Arabian Sea cyclones such as Biparjoy may moderate them post-landfall. These findings emphasize the importance of cyclone origin, trajectory, and interaction with continental systems in modulating heat extremes, and advocate for integrating tropical cyclone forecasting into heat wave preparedness strategies.

Keywords – Weather forecasting, Heat waves, Tropical cyclones, Impact-based forecasting, Weather data.

1. Introduction

Heat waves are prolonged periods of excessively hot weather, which may be accompanied by high humidity and have significant implications for health, agriculture, infrastructure, and the economy, as stated in a report by the Intergovernmental Panel on Climate Change (IPCC, 2021). In India, these events are most frequent between April and June, coinciding with the pre-monsoon season (IMD, 2023). The India Meteorological Department (IMD) defines a heat wave based on absolute temperature thresholds and deviations from normal temperatures, varying by region and elevation (IMD, 2023). According to the IMD, a heat wave is declared when the maximum temperature exceeds 40 °C in plains, 37 °C in coastal areas, or 30 °C in hilly areas, and the departure from normal is at least 4.5 °C to 6.4 °C. A severe heat wave is declared when the departure exceeds 6.4 °C (IMD, 2023). Historical climate data reveal an alarming increase in both the number and intensity of heat wave days in India. Between 1961 and 2020, the frequency of heat wave events increased by nearly 24% (Kumar *et al.*, 2021). The rise is attributed to anthropogenic climate change, deforestation, and urbanization, which have collectively intensified regional warming (Kishore *et al.*, 2022).

India's diverse geography makes it highly vulnerable to heat waves, especially in the Indo-Gangetic Plain, Rajasthan, central India, and the Deccan Plateau (Basu *et al.*, 2023). These conditions disproportionately affect vulnerable populations, including outdoor workers, the elderly, children, and the urban poor. In 2015 alone, over 2,000 deaths were reported during a severe heat wave event in Andhra Pradesh and Telangana (Gupta *et al.*, 2015). Urban areas like Delhi, Ahmedabad, and Hyderabad experience additional stress from the Urban Heat Island effect, which raises temperatures, strains power grids, and worsens air pollution (Oke, 1982; Singh *et al.*, 2020). Climate projections warn of more frequent, intense, and prolonged heat waves under high-emission scenarios, threatening food security, water resources, and labor productivity due to crop stress and rising demand for water (IPCC, 2021). The Intergovernmental Panel on Climate Change (IPCC) has warned that under the high-emission scenario (RCP8.5), the number of heat wave days in India could increase threefold by the end of the 21st century.

Tropical cyclones can influence land temperatures through shifts in atmospheric circulation, moisture transport, and rainfall distribution, sometimes temporarily reducing heat wave intensity while at other times prolonging or intensifying heat stress depending on associated weather patterns and delays in monsoon onset. Importantly, this research explores the interconnectedness between tropical cyclonic activity and heat wave formation, an area that remains largely underexplored. While the majority of Indian meteorological research has concentrated on Bay of Bengal cyclones and their associated rainfall and wind impacts (Sharma *et al.*, 2024), this study investigates the indirect effects of Cyclone Biparjoy, which made landfall on the western coast (Gujarat) during the month of June, 2023.

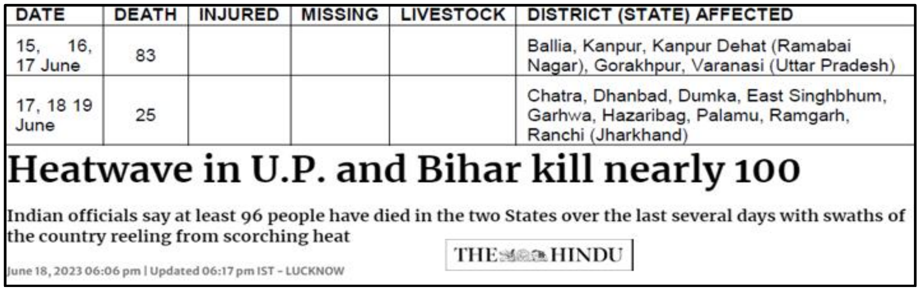
According to multiple media reports, as shown in Fig. 1(a), as well as per the Annual Climate Summary published by IMD, as shown in Fig. 1 (b), June, 2023 witnessed one of the most catastrophic and deadly heat wave episodes in recent history, particularly affecting Uttar Pradesh and Bihar. Over 100 fatalities were reported by media groups like NDTV, The Hindu, and the IMD's Annual Climate summary prepared based on media reports, predominantly concentrated in the eastern districts of Uttar Pradesh and the adjoining regions of Bihar. Many of the deceased were identified as elderly individuals or outdoor labourers, highlighting the heightened vulnerability of these groups during extreme thermal events. Several structural and environmental factors contributed to the high mortality rate during this episode. The affected regions are among the most densely populated in India. This study aims to dissect the meteorological underpinnings of this severe heat wave event, with a specific focus on the synoptic and mesoscale atmospheric parameters that contributed to its intensity and persistence. Factors such as high-pressure anomalies, subsidence inversion, delayed monsoon onset, and reduced surface wind speeds likely played a role in the prolonged buildup of heat stress (Srivastava *et al.*, 2022). Satellite-derived land surface temperatures and surface observations indicated that maximum daily temperatures in some districts exceeded 44 °C for several consecutive days.

Though geographically distant, the presence of Cyclone Biparjoy may have contributed to a blocking pattern in the upper atmosphere, inhibiting the northward progression of the monsoon and fostering stagnant, hot, and dry conditions over eastern India. However, after its landfall and its subsequent northward progression over land disturbed the blocking high formation leading to abatement of heat wave conditions. Such atmospheric interactions underscore the need to consider broader regional circulation patterns when analyzing heat wave dynamics. This multidimensional approach-combining climatology, meteorology, and human vulnerability-provides a more holistic understanding of extreme heat events in the Indian context and emphasizes the urgency of adaptive planning for both urban and rural areas.

2. Data and methodology

2.1. *Physical mechanism of heat waves*

Heat waves are primarily driven by persistent anticyclonic circulations in the middle and upper troposphere, often extending into lower levels. These systems produce subsidence, which induces adiabatic warming, suppresses cloud formation, and maintains clear skies-factors that amplify solar radiation and accelerate surface heating. In regions with low soil moisture and sparse vegetation, these processes contribute to prolonged thermal energy accumulation (Meehl & Tebaldi, 2004;



DATE	DEATH	INJURED	MISSING	LIVESTOCK	DISTRICT (STATE) AFFECTED
15, 16, 17 June	83				Ballia, Kanpur, Kanpur Dehat (Ramabai Nagar), Gorakhpur, Varanasi (Uttar Pradesh)
17, 18 19 June	25				Chatra, Dhanbad, Dumka, East Singhbhum, Garhwa, Hazaribag, Palamu, Ramgarh, Ranchi (Jharkhand)

Heatwave in U.P. and Bihar kill nearly 100

Indian officials say at least 96 people have died in the two States over the last several days with swaths of the country reeling from scorching heat

THE HINDU

June 18, 2023 06:06 pm | Updated 06:17 pm IST - LUCKNOW

Fig. 1(a). Media Reports of Fatalities Due to Heat Waves in June 2023

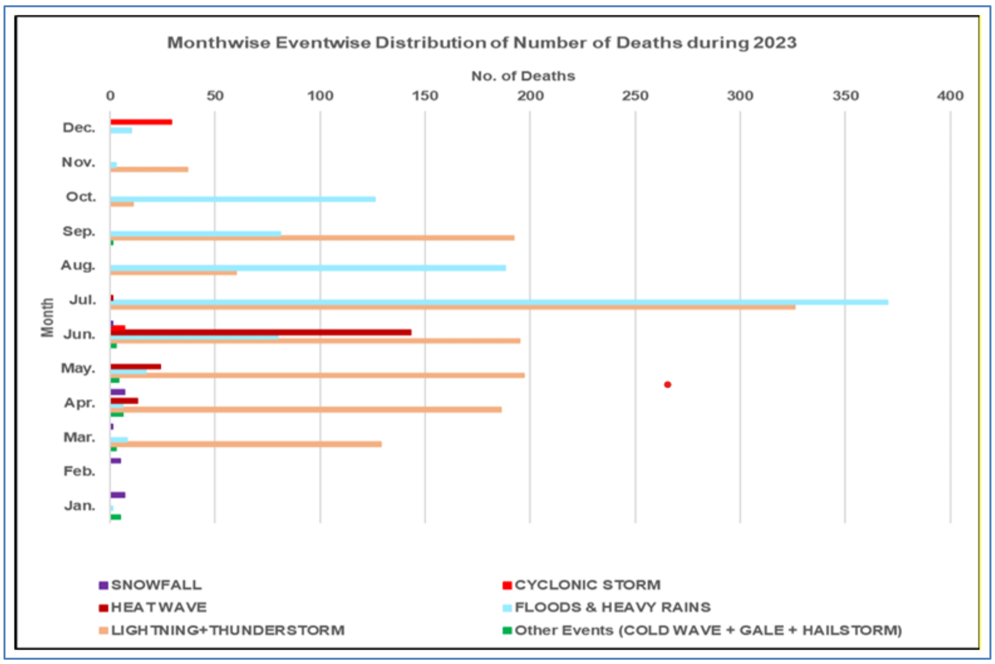
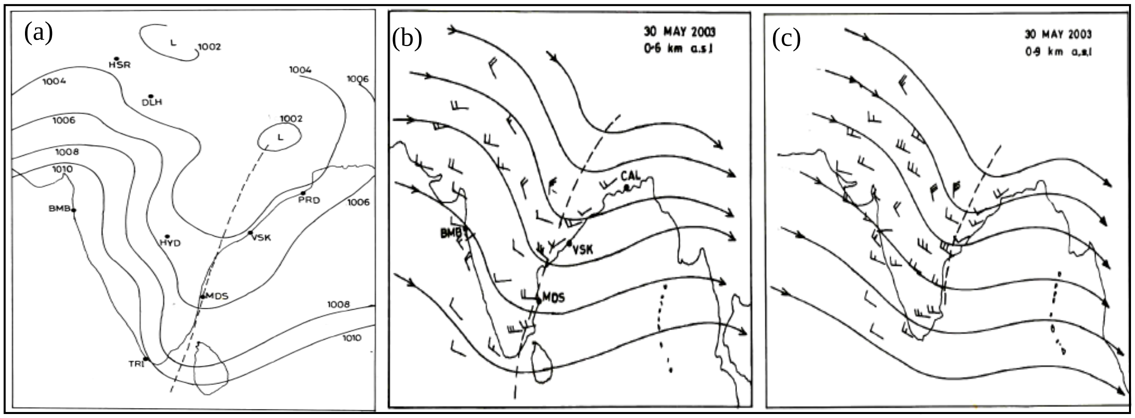


Fig. 1(b). Month-wise Event-wise Distribution of Number of Deaths during 2023 showing maximum heat wave days in the month of June 2023 (Source: Annual Climate Summary 2023 published by IMD Pune)

Perkins, 2015). Across Europe, North America, and Asia, upper-level blocking highs-quasi-stationary anticyclones evident in the 500 hPa geopotential height field-have consistently emerged as precursors to severe, long-lasting heat waves. By inhibiting the eastward movement of weather systems, they trap hot air masses and sustain extreme conditions for several days to weeks (Pfahl & Wernli, 2012).

In India, similar mid-tropospheric ridges are observed during the pre-monsoon season over the Indo-Gangetic Plains, central India, and the Deccan Plateau, acting as effective heat-trapping mechanisms (Pai *et al.*, 2013). Hot air advection serves as a complementary intensifying process. Favorable wind alignments can transport warm, dry air from arid regions such as the Thar Desert, Pakistan, and the Arabian Peninsula into adjoining areas. Strong north-westerly to westerly winds at low levels, combined with suppressed convection, enhance this warming effect. Clear skies and dry air further increase radiative forcing, driving up land surface and wet-bulb temperatures, thereby intensifying human and ecological heat stress (Dash & Mamgain, 2011). Thus, the interaction between anticyclonic blocking systems and thermal advection provides a key dynamical framework for understanding heat wave genesis, persistence, and severity. These dynamics are further shaped by land-atmosphere feedbacks, soil moisture deficits, urbanization, and aerosol loading, which can either amplify or moderate local heat anomalies.

In addition to large-scale features, regional meteorological patterns strongly influence heat wave development over India. Persistent heating over central and southern Pakistan, where surface temperatures often exceed 50 °C in May and June, generates a thermal low that advects hot, dry air into northwestern India-particularly Rajasthan, Haryana, and western Uttar



Figs. 2(a-c). (a) Heat trough along East Coast (surface) (b) Impact of strong and dry hot north-westerly Winds (0.6 km above mean sea level) (c) Highest maximum temperatures extend/shifts to coastal stations taken as representative figures from 30[th] May 2003

Pradesh. This advection often initiates localized heat wave conditions, which subsequently spread eastward and southward as the high-pressure ridge intensifies (IMD, 2023; Pai *et al.*, 2013). In the eastern Gangetic plains-including eastern Uttar Pradesh, Bihar, Jharkhand, and West Bengal-a low-level "heat trough" embedded in the westerlies plays a pivotal role Figs .2(a-c). It channels north-westerly winds from higher terrain onto progressively warmer surfaces, where they undergo adiabatic warming. The absence of moisture during these events suppresses latent heat flux, thereby amplifying sensible heat and eliminating the moderating effect of evaporative cooling (Rohini *et al.*, 2016).

Dry soil conditions, often caused by prolonged rainfall deficits, intensify heat wave severity through a positive feedback loop. Reduced evapotranspiration shifts more net radiation into sensible heat, warming the boundary layer more effectively. This reinforces atmospheric stability, suppresses convective mixing, and traps heat near the surface. Persistent clear skies further accelerate land surface warming (Saha *et al.*, 2014).

In India, pre-monsoon heat waves are strongly shaped by large-scale atmospheric processes. Rossby wave activity in the upper-level jet stream can generate blocking highs over northwest and central India, suppressing convection and prolonging heat (Raju *et al.*, 2017; Holton & Hakim, 2012). A weakened or poleward-shifted Subtropical Westerly Jet reduces upper-level cooling, enhancing surface heating (Dash *et al.*, 2007). Tibetan Plateau heating strengthens upper-tropospheric ridges, driving subsidence and further heat buildup (Xie *et al.*, 2022). Teleconnections such as El Niño, the Indian Ocean Dipole (IOD), and the North Atlantic Oscillation (NAO) modulate these circulation patterns and influence regional heat wave variability (Krishnan *et al.*, 2020; Lau & Nath, 2003).

Along India's coasts, sea breeze circulation plays a dual role. Under normal conditions, it brings cooler, moist maritime air inland, reducing daytime heat stress in cities like Mumbai, Chennai, and Kolkata. However, during strong subsidence or dry continental air intrusions, sea breeze penetration is delayed or weakened, intensifying heat inland from the coast. Thus, the timing and strength of sea breeze circulation critically shape heat wave intensity in coastal and peninsular India (IMD Monograph, 2023).

In sum, heat waves in India arise from a complex interplay of synoptic-scale forcing, soil–atmosphere feedbacks, regional air mass dynamics, and land-use modifications. A nuanced understanding of these interactions is essential for improving early warning systems and designing adaptive responses in vulnerable regions (IMD Monograph, 2023; Pai *et al.*, 2013).

2.2. *Tropical cyclones Biparjoy in the Arabian sea in June 2023*

The Arabian Sea sees a lesser number of tropical cyclones as compared to the Bay of Bengal (Mohapatra *et al.* 2021). As per the e-atlas of tropical cyclones, there were a total of 8 systems during the period from 1891 to 2024 formed in the Arabian Sea during the month of June and making landfall in Gujarat and neighborhood over the Indian region. Out of these, tropical cyclone Biparjoy also formed in June 2023 and made landfall in Gujarat. The spatial progression of the Extremely Severe Cyclonic Storm (ESCS) "Biparjoy" (pronounced as Biporjoy), which was centred over the northeast Arabian Sea on 14 June 2023 is shown in Fig 3. The cyclone tracked northeastward and subsequently made landfall along the coastal regions of Gujarat on 15[th] June 2023, significantly influencing regional atmospheric dynamics.

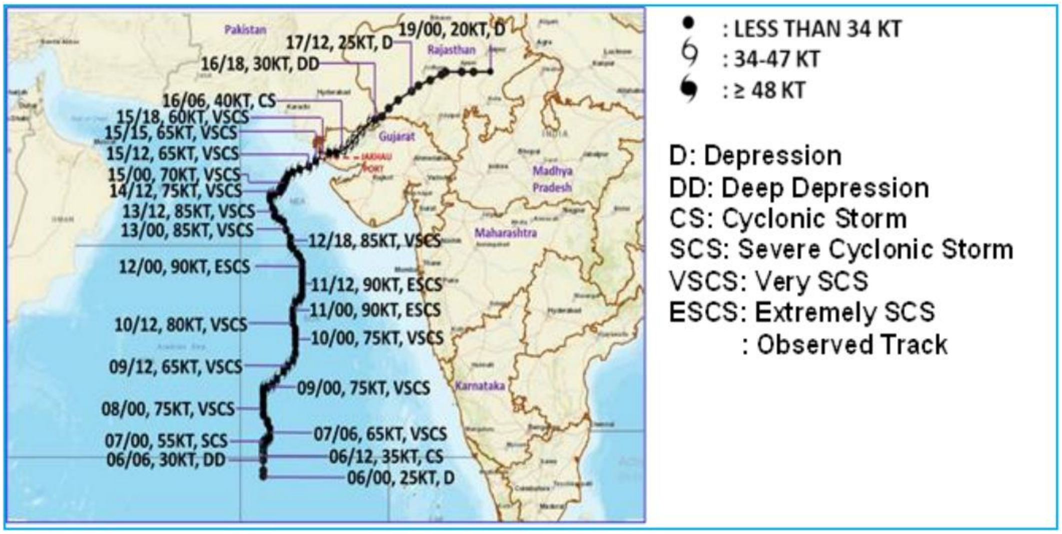


Fig. 3. Observed track of extremely severe cyclonic storm ‘BIPARJOY” over the Arabian Sea during 6th -19th June, 2023. (*Source RSMC Annual Report 2023*)

Sub-Division	Heat Wave Days in June 2023																				
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
SHWB & Sikkim	H1	H1	H2	H1	H1	H2	H1										H1				
Gangetic WB	H1	H1	H1	H1	H1	H2	H2	H2	H2		H1	HH1	H1	H2	HH1	HH3	HH3	H1			
Orissa								H1	H1	HH1	HH1	HH2	H2	HH2	HH1	HH3	HH3	HH3	HH1	HH2	H1
Jharkhand						H1			H1	H1	H1	H1	H2	H2	HH1	HH3	HH3	HH3	HH1	H1	H1
Bihar	H1	H1	HH2	HH1	HH2	HH2	HH2	HH2	HH2		HH1	HH1	H1	HH2	HH2	HH3	HH3	HH2	HH2	H1	
East UP									H1			H1	H1		H1	H2	HH3	H1	H2	H1	H1
Chhattisgarh										H1		HH2	HH3	HH1	HH1	HH3	HH3	HH3	HH2	HH3	HH1
Coastal AP						H1	H1	H1	H1	HH1	HH1	H2		HH2	HH3	HH3	HH3	H3	H2		
Telangana						H1	H1			H1	H1	H1	HH2	HH1	H1	HH3	HH3	H3	HH2	H2	

Fig. 4 (a). Observed Heat Wave days in different meteorological subdivisions during June 2023

2.3. *Heat waves observed across eastern parts of India during June 2023*

The observed heat wave days over different meteorological subdivisions in eastern and adjoining south peninsular India for the heat wave spell in June 2023 is shown in Figs. 4(a & b).

The numeric letters 1,2,3,4 indicate the distribution of the heat waves. 1 indicates isolated (< 25% of stations in meteorological subdivision), 2 indicates scattered (< 50% of stations in meteorological subdivision), 3 indicates fairly widespread (< 75% of stations in meteorological subdivision), and 4 indicates widespread (>75% of stations in meteorological subdivision) heat wave conditions. Single H signifies the heat wave conditions and HH signifies severe.

The rainfall, maximum and minimum temperature anomalies for June 2023 are shown in Figs. 5(a-c). The rainfall anomaly figure shows a large deficiency of rainfall over eastern parts of the country, particularly over

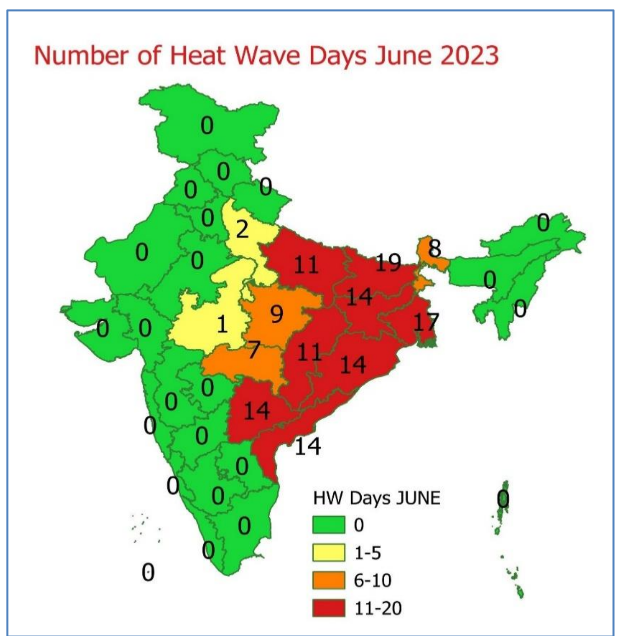
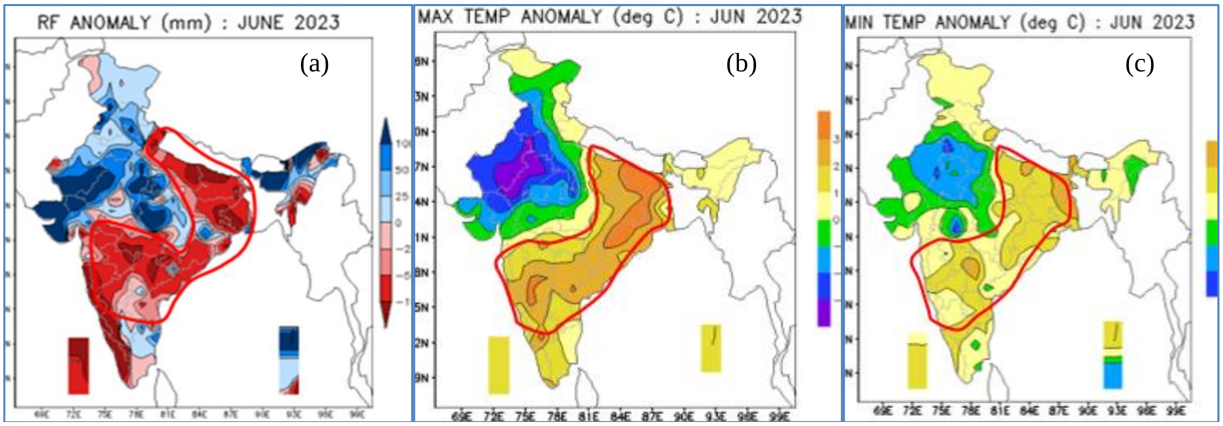
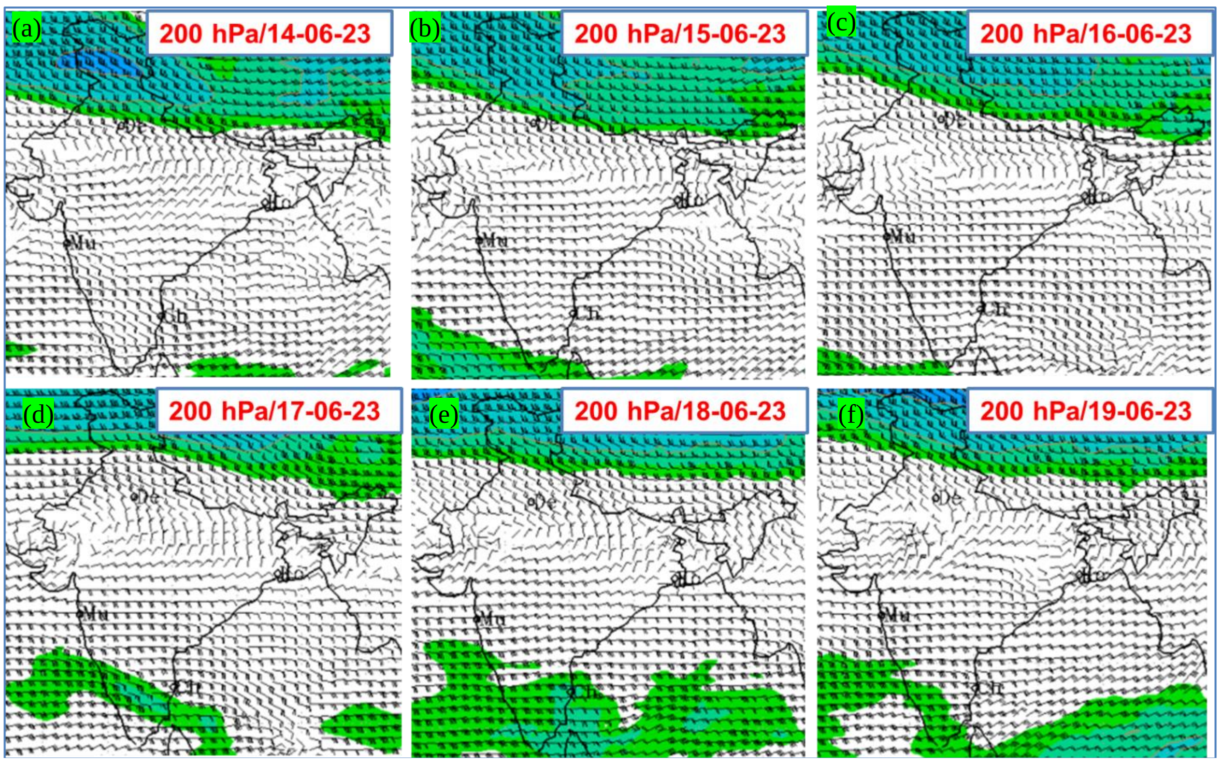


Fig. 4 (b). Spatial map of observed Heat Wave days in different meteorological subdivisions during June 2023



Figs. 5(a-c). (a) Rainfall anomaly (b) Maximum Temperature anomaly (c) Minimum Temperature anomaly during June 2023

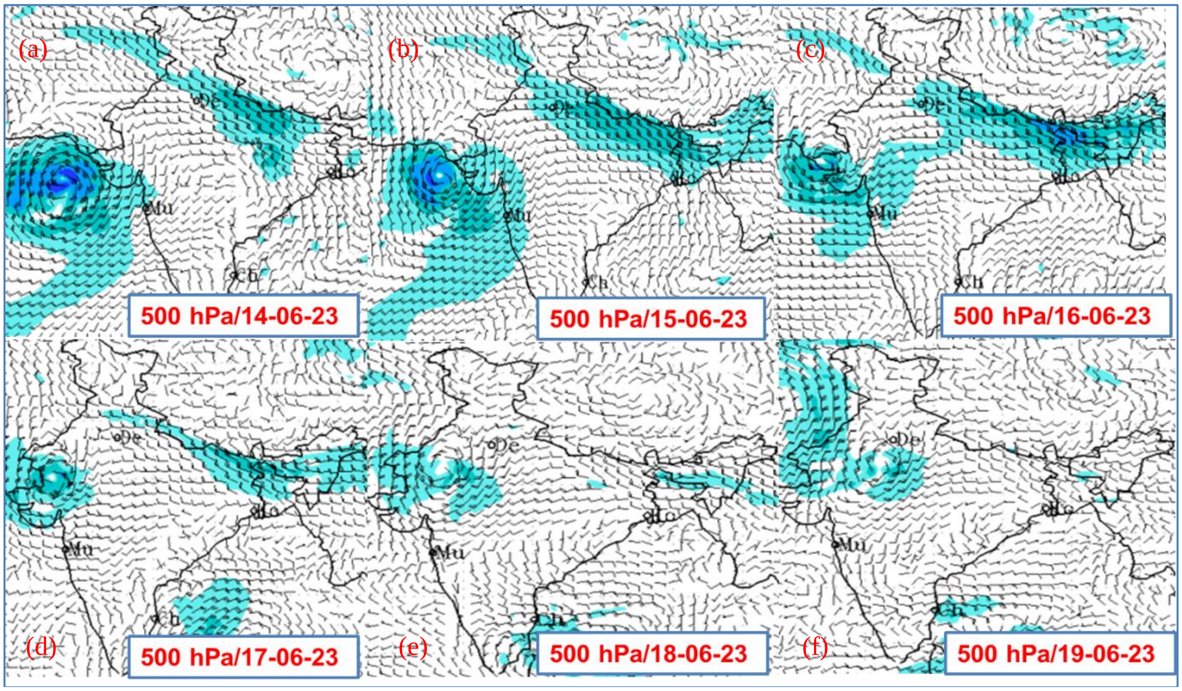


Figs. 6 (a-f). 200 hPa wind Analysis from IMD-GFS model for 14th to 19th June 2023 based on 00 UTC

Bihar, Gangetic West Bengal, Odisha and eastern Uttar Pradesh and over northern parts of south peninsular India. The maximum temperature anomaly for June also indicates that the maximum positive anomaly is seen over the eastern parts of the country, including Bihar, East Uttar Pradesh, Jharkhand, Gangetic West Bengal and interior Odisha. The positive minimum temperature anomaly is also seen over the eastern parts of the country, which include Bihar, Gangetic West Bengal, eastern Uttar Pradesh, Jharkhand, and Odisha. This shows that eastern India, particularly, was very vulnerable with respect to aggravated heat wave conditions due to deficient rainfall activity and above normal maximum as well as minimum temperatures over the region during June 2023.

2.4. *large-scale features related to heat waves of June 2023*

Figs. 6 (a-f) illustrates the evolution of upper-air synoptic features, specifically the development and eastward extension of an anticyclone/ridge pattern spanning from northwestern to eastern India during the period 14-18 June 2023. This persistent mid-to-upper tropospheric ridge, identifiable through anticyclonic wind



Figs. 7(a-f). 500 hPa wind Analysis from IMD-GFS for 14th to 19th June 2023 based on 00 UTC

patterns in the 200 hPa fields, shows induced large-scale subsidence over the entire northwest and adjoining central and eastern India.

The descending air masses associated with this anticyclonic circulation led to adiabatic warming, clear-sky conditions, and suppression of convective activity-all of which collectively contributed to a significant rise in surface temperatures and the establishment of heat wave conditions, particularly over the Indo-Gangetic Plains and adjoining central and eastern regions.

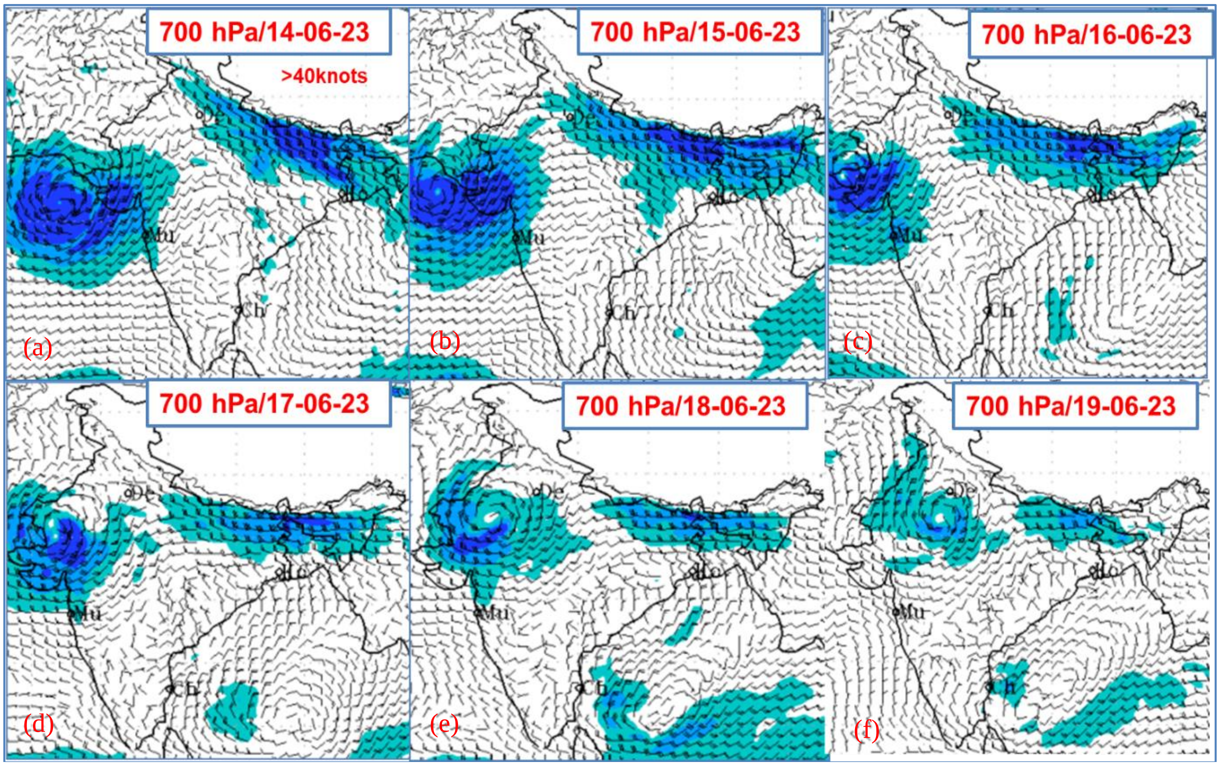
The stability introduced by the ridge pattern played a critical role in inhibiting vertical mixing and trapping heat near the surface, thereby enhancing heat stress conditions over multiple consecutive days. The spatial extent and temporal persistence of this synoptic feature, as shown in Figs. 6(a-f) & 7(a-f), underscores the central role of upper-level atmospheric dynamics in the genesis and maintenance of extreme heat wave episodes over the Indian subcontinent.

Furthermore, the percentile analysis of minimum temperatures (Figs. 10 (a-c)) during the period from 14 to 18 June 2023 reveals that not only were maximum temperatures anomalously high, but minimum temperatures were also elevated, often remaining in the 90th percentile or higher. This lack of nocturnal cooling, a hallmark of extreme heat wave events, significantly contributed to increased heat stress and mortality risk, especially among vulnerable populations without access to adequate cooling infrastructure.

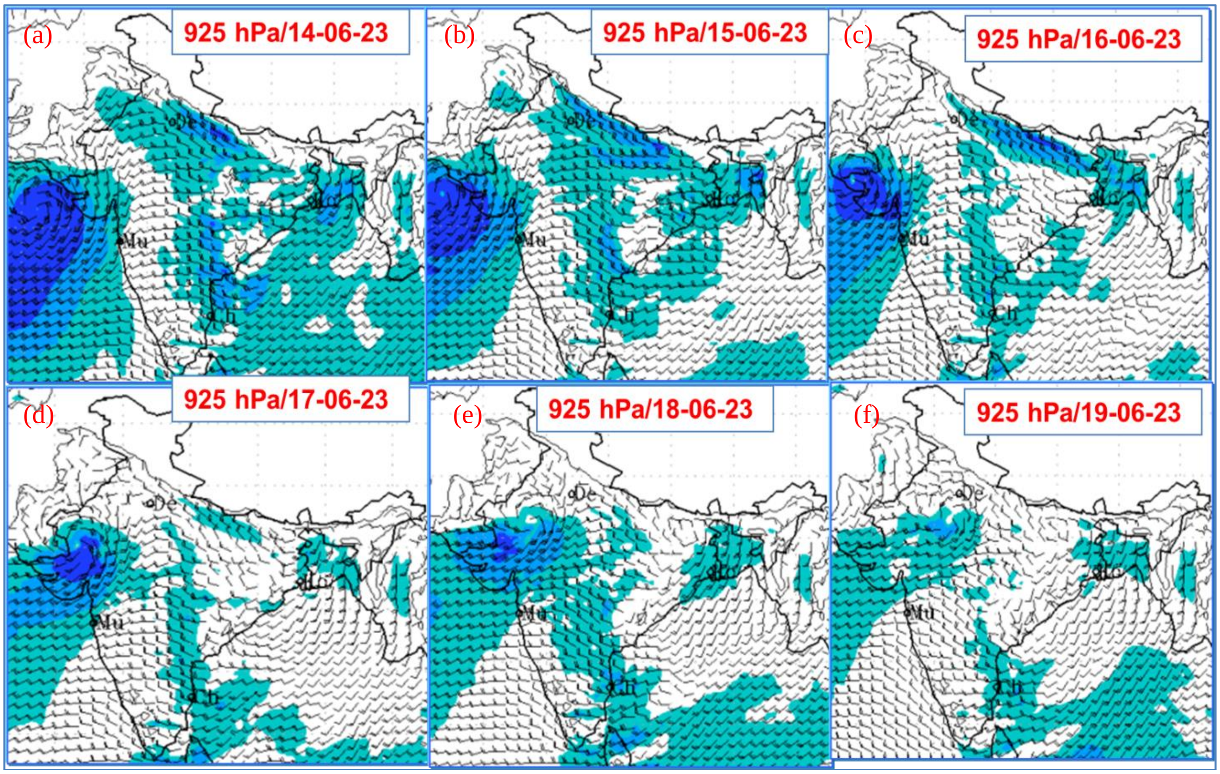
2.5. *Climatologically anomalous heat wave pattern over east India and west & northwest India in June 2023.*

Climatologically, May is the peak month for heat waves over India. In the month of June, Heat waves are mainly seen over western parts of the country (West Rajasthan & adjoining Pakistan), central parts of the country (north Madhya Pradesh, south Uttar Pradesh & adjoining regions of Bihar, Jharkhand and Chhattisgarh) and also in some parts of southeast India (Coastal Andhra Pradesh, Telangana and Vidarbha) (Pai *et al*. 2013). The year 2023 was peculiar in a way that the west and northwest India, like Rajasthan and Gujarat state, didn't observe any heat wave days, whereas there were above normal heat wave days over East India, like West Bengal (Figs. 4b & 11).

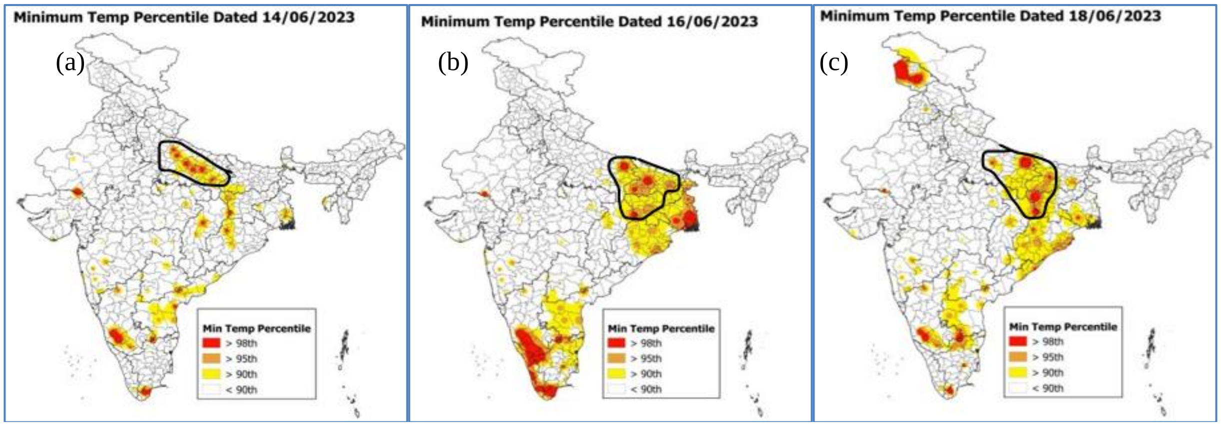
There was a strong anticyclonic anomaly during 9th June to 19th June 2023 in the upper troposphere at 200 hPa, which indicated subsidence motion favourable for rising temperatures over northwest, west and east India as seen in Figs. 11(a & b). This positive anomaly was not seen at 500 hPa over west and northwest India, but was seen over east India, indicating favourable conditions for a rise in surface temperatures over east India and favoring reduced temperatures over west and northwest India, leading to probable reasons for no heat wave conditions.



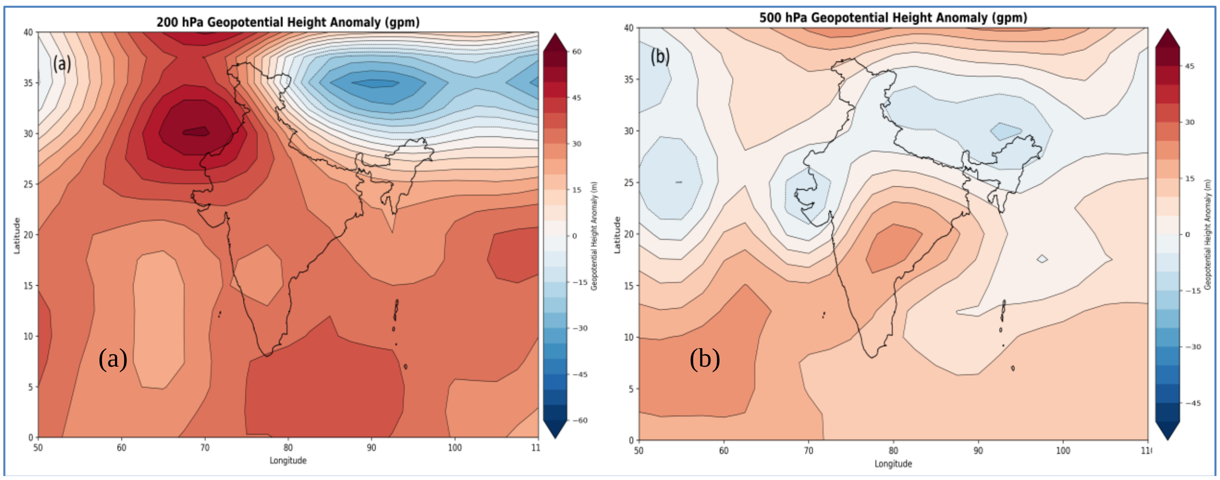
Figs. 8(a-f). 700 hPa wind Analysis from IMD-GFS for 14th to 19th June 2023 based on 00 UTC



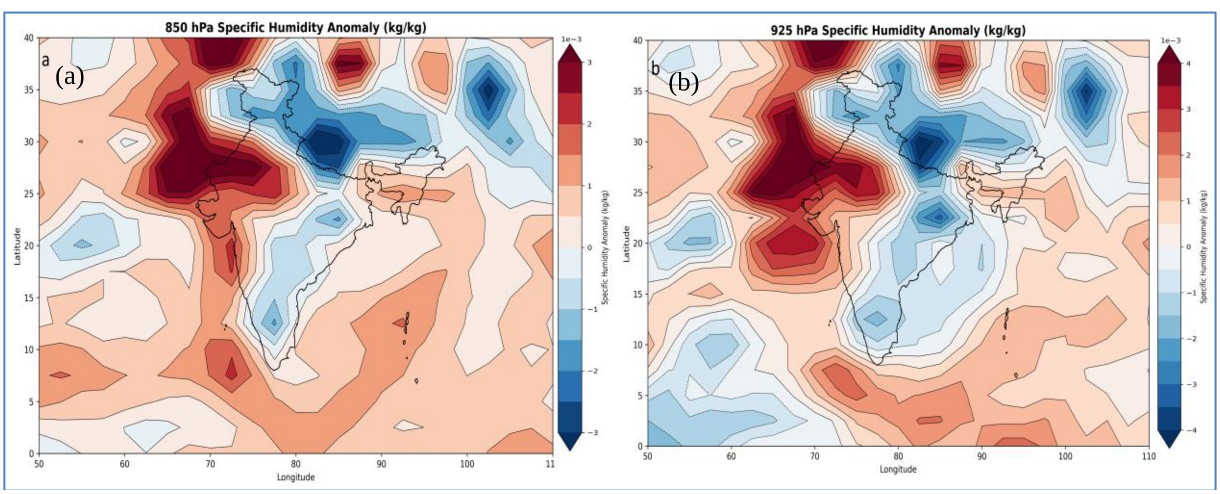
Figs. 9(a-f). 925 hPa wind Analysis from IMD-GFS for 14th to 19th June 2023 based on 00 UTC



Figs. 10(a-c). Minimum temperature percentile plots of 14th, 16th & 18th June 2023

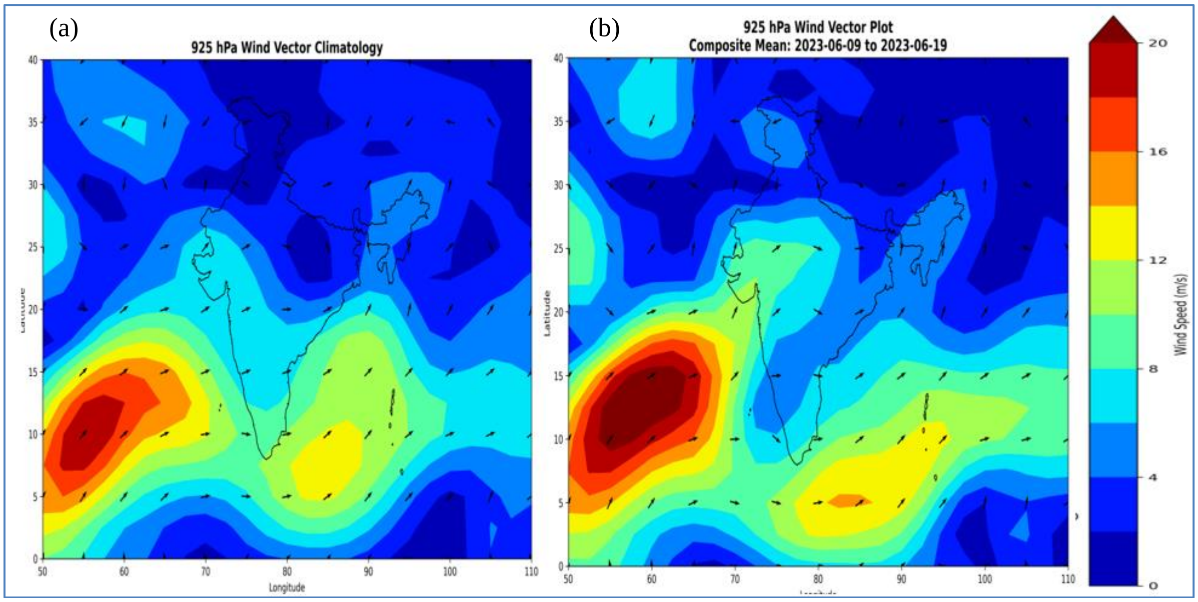


Figs. 11(a&b). 200 hPa and 500 hPa geopotential height anomaly from NCEP Reanalysis for the period 09th June to 19th June 2023



Figs. 12(a&b). 850 hPa and 925 hPa specific humidity anomaly from NCEP Reanalysis for the period 09th June to 19th June 2023

The specific humidity anomaly over the region for the duration 9th June to 19th June 2023 from NCEP Reanalysis data set at lower levels (925 & 850 hPa) is shown in Figs. 12 (a & b). It indicates high and positive specific humidity availability in the lower tropospheric levels over west and northwest India, whereas there is a negative anomaly with respect to specific humidity over the eastern parts of the country. Thereby making west and northwest India moist and east India drier in comparison to climatology. Moist air is less dense than dry air and



Figs. 13(a&b). 925 hPa climatology from NCEP Reanalysis for the period 09th June to 19th June 2023

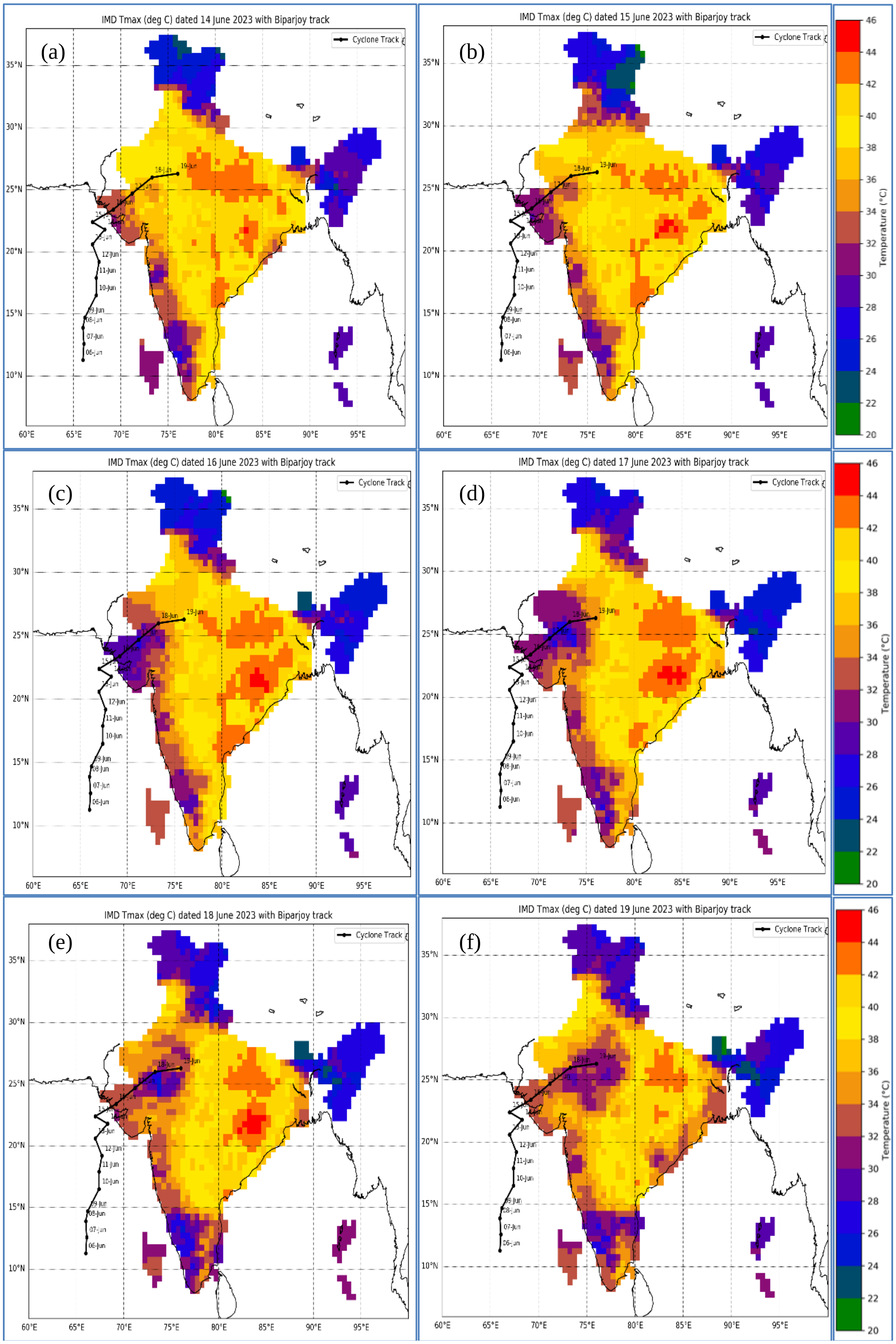
therefore rises rather than sinks. This occurs because water Vapour molecules are lighter than the nitrogen and oxygen molecules they replace, reducing the overall density of the air mass. This principle drives convection, where warm, moist air ascends, transporting heat upward and ultimately leading to cloud development and precipitation. One of the most important reasons for this higher specific humidity was the movement of tropical cyclone Biparjoy, which pulled a lot of moisture toward its track. This ultimately led to lower surface air temperatures over west and northwest India, whereas higher surface air temperatures over east India caused abnormal heat wave conditions over east India and no heat wave conditions over west and northwest India.

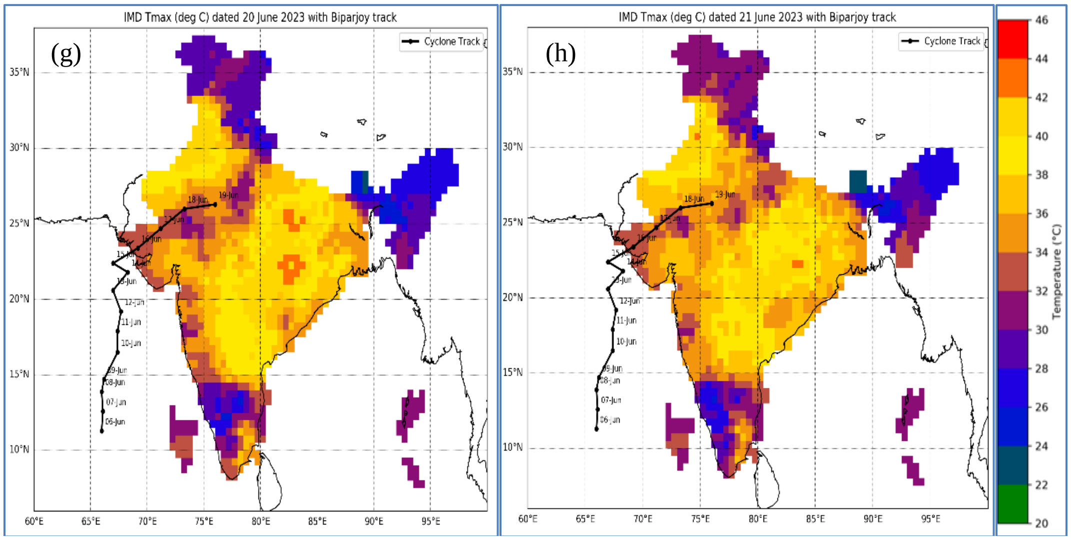
The wind climatology and composite mean at 925 hPa during 9th June to 19th June 2023 from NCEP Reanalysis in Figs. 13 (a & b) shows that there was more moisture incursion over west and northwest India as compared to the climatology. Also, over East India, particularly West Bengal, the winds climatologically during this time are from the sea (southerly/southeasterly); however, from June 9th to 19th 2023, the winds were westerly and continental in nature. There by reducing moisture incursion and increasing the temperatures and heat wave conditions.

2.6. *Impact of tropical cyclone Biparjoy in the Arabian sea making landfall in Gujarat on the heat waves of June 2023.*

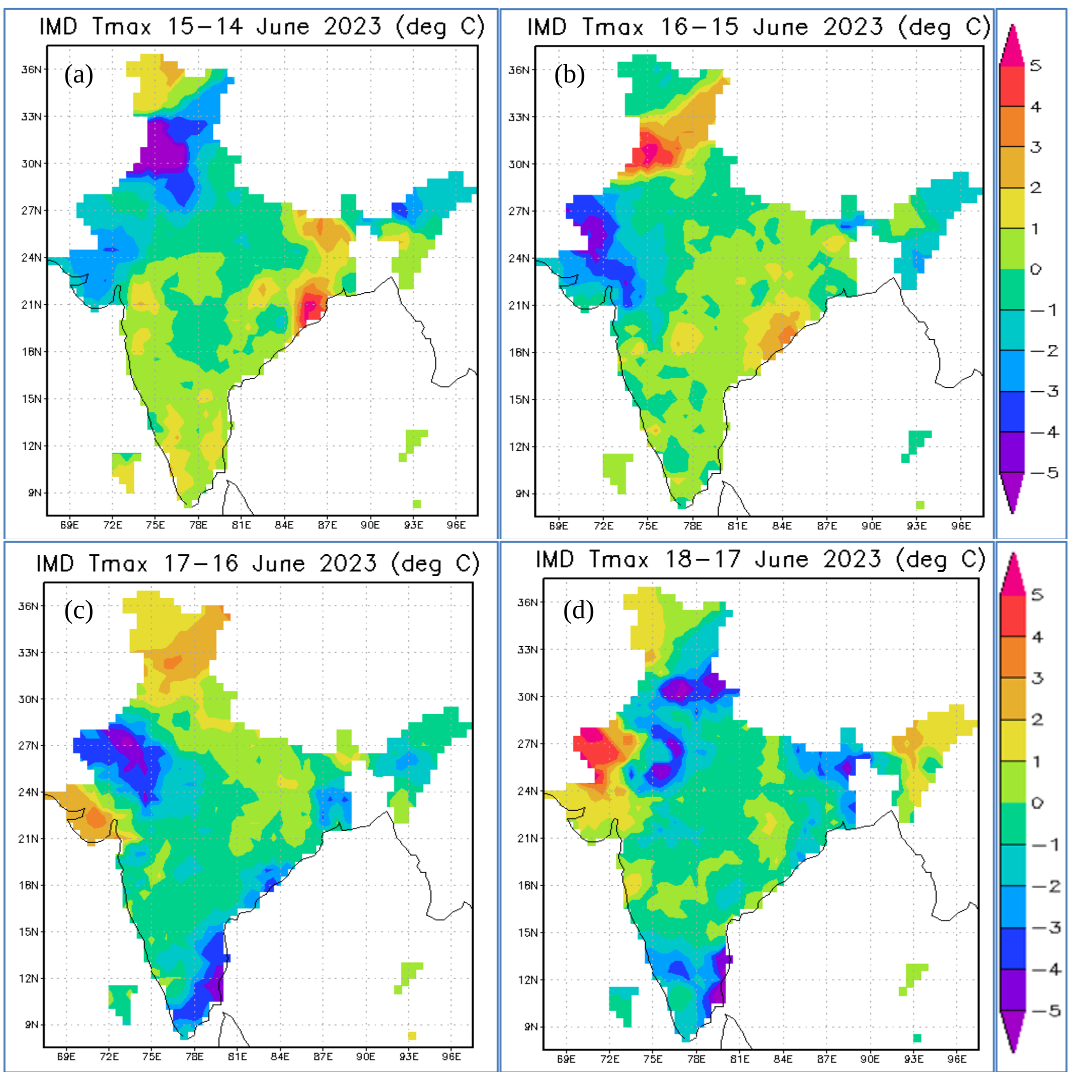
Fig. 3 depict the spatial progression of the Extremely Severe Cyclonic Storm (ESCS) “Biparjoy” (pronounced as Biporjoy), which was centred over the northeast Arabian Sea on 14 June 2023. The cyclone tracked northeastward and subsequently made landfall along the coastal regions of Gujarat, significantly influencing regional atmospheric dynamics. Prior to landfall, subsidence on the eastern flank of the system contributed to the stabilization of the atmosphere over adjacent inland areas, while moisture incursion and cyclonic circulation patterns around the storm altered typical pre-monsoon flow regimes.

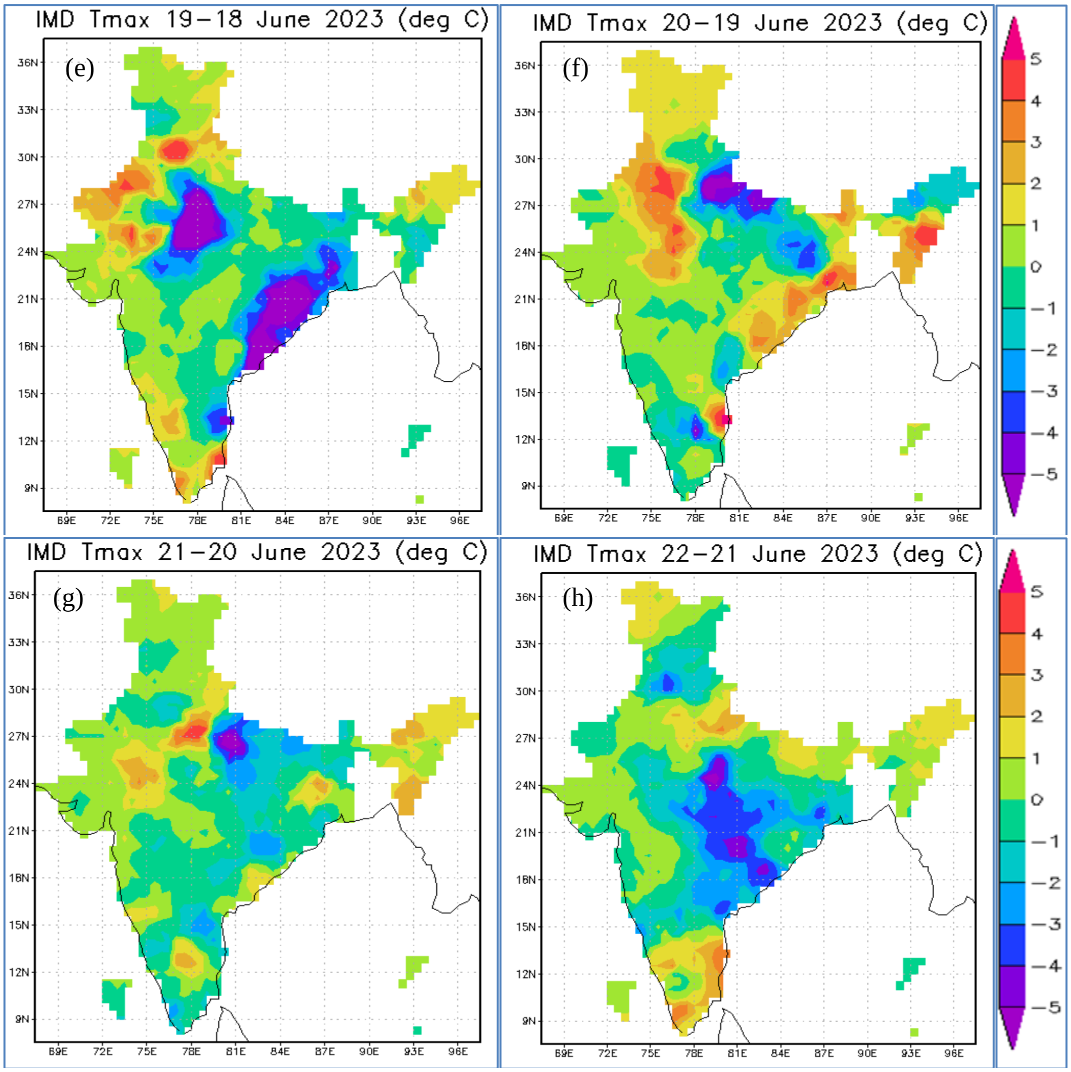
The strong cyclonic circulation associated with TC Biparjoy, altered the mid-tropospheric pressure field. The subsidence-driven ridge over northwest India weakened because the cyclone’s rising motion and large-scale circulation disturbed the otherwise stable high-pressure zone. This reduced the “heat dome” effect that usually sustains heat waves. Normally, westerly/northwesterly winds bring hot, dry air from Pakistan into India. But TC Biparjoy's circulation reorganized regional wind patterns as it pulled in moist maritime air from the Arabian Sea and weakened or deflected the inflow of hot continental winds. It could be seen from the upper air analysis, Fig. 6 to Fig. 9, that cyclone enhanced moisture transport into parts of western and central India, resulting in enhanced cloud cover. This reduced solar insolation at the surface, limiting daytime heating and providing relief from extreme temperatures. Therefore, TC Biparjoy played an important role in the abatement of the 2023 heat wave mainly by disturbing the mid-tropospheric ridge and cutting off hot-air advection from Pakistan/Thar Desert, while also injecting moisture and cloudiness into northwest India. However, for the eastern coastal parts,


IMD Tmax (deg C) dated 14 June 2023 with Biparjoy track
(a)
IMD Tmax (deg C) dated 15 June 2023 with Biparjoy track
(b)
IMD Tmax (deg C) dated 16 June 2023 with Biparjoy track
(c)
IMD Tmax (deg C) dated 17 June 2023 with Biparjoy track
(d)
IMD Tmax (deg C) dated 18 June 2023 with Biparjoy track
(e)
IMD Tmax (deg C) dated 19 June 2023 with Biparjoy track
(f)
Cyclone Track
Temperature (°C)



Figs. 14(a-h). IMD daily gridded Maximum temperature 0.5-degree resolution during 14th to 21st June 2023 with TC Biparjoy track plotted at 00 UTC from 06th to 19th June 2023 based on best track information from RSMC New Delhi





Figs. 15(a-h). IMD gridded maximum temperature difference from the previous day between 15th June to 22nd June 2023 based on best track information from RSMC New Delhi

like in West Bengal, the tropical cyclone Biparjoy circulation pattern didn’t allow a southeasterly wind setup, which is climatologically observed. This led to an increase in temperature & heat wave conditions over West Bengal and the neighbourhood.

The maximum temperature based on the 0.5-degree gridded IMD temperature data along with TC Biparjoy track is shown in Fig. 14 indicated the maximum temperature on different days of progress of ESCS Biparjoy. It shows the fall in maximum temperature as the cyclone moves northeastwards after landfall over northwest and adjoining central and eastern parts of the country.

It is seen from the Fig. 15 that the reduction in maximum temperature followed the track of remnant of tropical cyclone Biparjoy after its landfall and the system brought the cooling effect on the maximum temperature along with its progress by disturbing the stable high-pressure zone established over northwest & adjoining central India which was fueling the heat wave conditions over Uttar Pradesh & Bihar.

3. Results & discussion

The June 2023 heat wave over eastern and northern India was a result of complex interactions between synoptic-scale meteorological patterns and tropical cyclone activity. Upper-air analyses revealed a persistent mid-to-upper tropospheric anticyclone or ridge pattern extending from northwest to eastern India during 14–18 June as seen from Figs. 6 (a-f) & 7(a-f). This system induced strong subsidence, clear skies, and stable atmospheric conditions, all of which contributed to sustained surface heating.

Simultaneously, the Extremely Severe Cyclonic Storm (ESCS) Biparjoy evolved over the northeast Arabian Sea and made landfall over Gujarat on 15th June night. Prior to its landfall, strong northwesterly winds at lower tropospheric level (mainly at 925 hPa level) transported hot, dry air from arid northwest regions toward the eastern Indo-Gangetic Plains, exacerbating heat wave conditions as show in Figs. 8(a-f) & 9 (a-f).

Importantly, the event was characterized not only by extreme maximum temperatures but also by unusually high minimum temperatures, as revealed by percentile analyses. The elevated nighttime temperatures reduced the scope for nocturnal cooling, amplifying heat stress and health risks, especially in densely populated regions.

However, following the landfall of Cyclone Biparjoy on 15 June night as shown in Fig. 3, the system's remnant circulation began to disrupt the established northwesterly flow pattern. As shown in the highlighted black box in Figs. 9 (a-f), wind speeds gradually decreased from 18 June onwards, weakening the advection of hot air and allowing for the moderation of surface temperatures. The surface temperature was seen along the movement of tropical cyclone Biparjoy. This can be seen in the daily IMD observed maximum temperatures based on the 0.5-degree grid along with the observed track of tropical cyclone Biparjoy as shown in Figs. 14(a-h). This also weakened the strong anticyclonic circulation in the northwest to central & adjoining eastern parts of India, gradually reducing the heating source. This synoptic evolution corresponded with the abatement of severe heat wave conditions over much of eastern parts of northwest India, adjoining east and central India as indicated in day-to-day basis difference in maximum temperatures shown in Figs. 15 (a-h). The maximum temperature fall in the vicinity of the centre of the system is of the order of 3-5 degrees C.

Numerous studies have highlighted that tropical cyclones originating in the Bay of Bengal often exacerbate heat wave conditions over the eastern and northeastern parts of India, primarily due to their influence on regional wind patterns, moisture transport, and atmospheric stability (Rohini *et al.,* 2016). These systems, particularly in their pre-landfall phases, are known to induce subsidence and hot, dry air advection over inland regions, thereby intensifying surface heating and prolonging heat wave episodes. In contrast, landfalling tropical cyclones from the Arabian Sea, such as Cyclone Biparjoy in June 2023, exhibit a modulating effect on surface temperatures, especially across the northwest, central, and eastern plains of India. As observed during this event, the post-landfall movement of Biparjoy's remnant circulation introduced increased moisture and disrupted the prevailing northwesterly lower-tropospheric flow, leading to the gradual weakening of the heat wave conditions. This demonstrates that while Bay of Bengal cyclones may enhance thermal stress, Arabian Sea cyclones have the potential to mitigate ongoing heat waves, depending on their trajectory, intensity, and interaction with continental weather systems.

This contrasting behavior underscores the need for differentiated analysis of cyclone-heat wave interactions based on cyclone origin, track, and timing, and calls for greater integration of tropical cyclone forecasting into national heat wave preparedness frameworks.

4. Conclusions

The June 2023 heat wave over northern and eastern India was characterized by prolonged extreme temperatures, shaped by both synoptic and mesoscale factors. A dominant mid-to-upper tropospheric ridge over northwest India induced subsidence, clear skies, and suppressed convection, driving strong surface heating. Simultaneously, northwesterly winds in the lower troposphere advected hot, dry air from Pakistan and Rajasthan into eastern India, further intensifying the event. Elevated minimum temperatures and limited nocturnal cooling compounded thermal stress.

Western disturbances generally terminate prolonged heat wave events in India. However, in this case, a landfalling tropical cyclone played a key role. Tropical Cyclone Biparjoy, originating in the Arabian Sea and making landfall in Gujarat, disrupted lower-tropospheric circulation and transported moisture-laden winds inland. This process weakened the hot, dry north-westerlies and lowered surface temperatures across northwest, central, and adjoining eastern India, thereby contributing to the heat wave's abatement (Hunt *et al.*, 2018; Srivastava *et al.*, 2024). However, for some of the coastal regions of East India, like West Bengal, the climatologically expected maritime winds in southerly/southeasterly direction are not set up, leading to an increase in the surface air temperatures and enhanced heat wave conditions.

This study highlights the dualistic influence of tropical cyclones on regional heat dynamics. While Bay of Bengal cyclones have been studied for their role in intensifying heat waves over eastern India, this novel analysis shows that Arabian Sea cyclones-depending on their trajectory and post-landfall evolution-can act as a natural mitigating force against heat extremes over inland regions of the country. This novel understanding brought out in the present study is based on one Tropical Cyclone. Therefore, further research on tropical cyclone formation across the Indian Ocean basins and their influence on heat waves in India is essential for integrating these impacts into disaster mitigation frameworks. These findings highlight the need for an integrated forecasting and disaster management approach that accounts for both the intensifying and mitigating influences of tropical cyclones on heat waves in India.

Data availability

The Observation data used in the study are freely available on the websites of the India Meteorological Department. The IMD-GFS model analysis data is made available from the NWP division of IMD on a request basis. The tropical cyclone data is available on the Regional Specialised Meteorological Centre (RSMC, New Delhi) website. The NCEP Reanalysis data is freely available on the website.

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Authors' contributions

Akhil Srivastava: Conceptualisation, Analysis, Visualisation, Validation, Writing, and Editing.
Naresh Kumar: Concept and Analysis.
M. Mohapatra: Review and Supervision.
Kunal Sulekh : Visualisation.

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