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LETTER

Divergent trends of Tmax-based and Tw-based heat extremes across Asia's climatic divide

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Abstract

This study investigates the contrasting trends in extreme Tmax events and extreme wet-bulb temperature (Tw) events across the monsoon and arid regions of Asia using the ERA5 reanalysis dataset. Our analysis reveals a substantial shift in the monsoon region, where extreme Tw events have risen by 1.95 days, outpacing the increase in extreme Tmax events. In the arid region, extreme Tmax events have increased more significantly, exceeding extreme Tw by an average of 2.05 days in recent years, reflecting the limited moisture availability in this area. Spatiotemporal analyses also reveal the widespread prevalence of humid-heat extremes in monsoon Asia and the intensification of primarily dry heat extremes in arid regions. These divergent trajectories highlight the pivotal role of climatological differences, with the change in monsoonal circulations amplifying humid extremes, while the inherent aridity constrains humidity increases. Our findings emphasize the need for regional adaptation strategies and mitigation efforts to address the escalating impacts on human society and ecosystems across Asia's climatic divide.

Keywords Humid-heat extremes · Heatwaves · Wet-bulb temperature · Moisture transport

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1 Introduction

Heatwaves have become a practical threat across Asia in recent decades, with a notable rise in compound humid-heat extremes that combine extreme temperatures with high humidity (Kyaw et al. 2023). These humid-heat extremes pose severe risks to human health, reducing the human body's ability to regulate temperature and increasing the chance for heat-related illnesses (Buzan and Huber 2020). Moreover, they can result in significant economic losses by decreasing labor productivity and economic output (Parsons et al. 2022).

The complex monsoonal climate of Asia, with distinct monsoon-dominated coastal regions and arid inner lands (Fig. 1a), plays a key role in shaping the diverse heatwave patterns (Wang and Zhang 2020). Under global warming, recent studies have increasingly employed compound heat stress metrics, such as wet-bulb temperature (Tw), apparent temperature, and heat index, to better capture the combined impact of temperature and humidity on human health. Some studies have focused on the climatology and health risks of humid heat extremes across Asia or specific regions (Monteiro and Caballero 2019; Wang et al. 2021; Zhang et al. 2023), while others have examined the seasonal characteristics or long-term evolution of Tw-based heat events in China and the broader Northern Hemisphere (Dong et al. 2024; He and Chen 2023). A parallel line of research has explored compound hot-humid extremes in connection with hydrological hazards or atmospheric circulation patterns (Ganguli and Merz 2024; Luo et al. 2022).

The mechanisms driving humid-heat extremes involve a complex interplay of thermodynamic factors, such as the Clausius-Clapeyron relation, dynamic factors like moisture transport, and anthropogenic factors including irrigation (Ganguli and Merz 2024; Guo et al. 2022; Ha et al. 2022; Zhang et al. 2021). However, most studies have focused on either specific regions or overly generalized global averages, limiting our synoptic-scale understanding of climate change impacts. Moreover, the role of regional climate dynamics, such as monsoon variability and land–atmosphere interactions, in modulating the long-term change of compound humid-heat extremes versus general heat extremes has not been fully explored (Buzan and Huber 2020; Monteiro and Caballero 2019).

Previous studies on heat extremes often focus on single regions or generalize findings globally, potentially overlooking the regional variability across Asia's diverse climate zones. Even with increased use of humidity-compounded metrics, spatial contrasts in heatwave

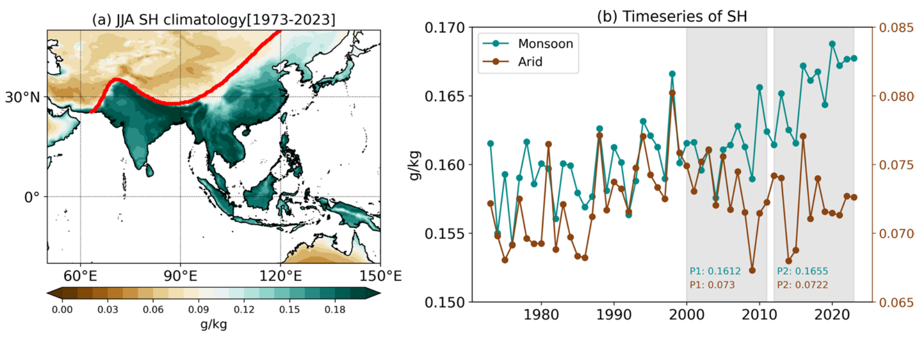

Fig. 1 **a** JJA Specific humidity (SH) climatology from 1973 to 2023. The thick red line denotes the boundary separating the arid(upper) and monsoon(lower) regions. **b** Time-series of annual averages in SH over the monsoon and arid areas. Gray boxes represent the P1(2000–2011) and P2(2012–2023) respectively with corresponding averages labeled in text

trends, especially between monsoon and arid regions, have received limited attention. In contrast, our study not only offers insights into these dynamics but also uniquely examines both general heat (Tmax) and humid-heat (Tw) extremes across Asia's monsoon and arid regions. By capturing both types of heat extremes, a more nuanced understanding of heat stress across the region's climatic divide is provided, pointing out the need for targeted adaptation strategies.

Given the significant impacts of compound humid-heat extremes and the contrasting trends observed across different regions, a key research question emerges: How have the frequencies and intensities of compound humid-heat heat extremes and general heat extremes changed across the monsoon and arid regions of Asia over recent decades, and what are the underlying mechanisms driving these divergent trends? Using historical datasets, this study examines recent changes in compound humid-heat extremes across Asia's monsoon and arid regions.

2 Data and methods

To characterize heatwave trends across Asia, particularly focusing on the monsoon and arid regions, the fifth generation European Centre for Medium-Range Weather Forecasts (ECMWF) atmospheric reanalysis (ERA5) is employed, which provides high-resolution estimates of temperature, humidity and other atmospheric variables from 1940 to present (Hersbach et al. 2018). ERA5 was selected for its reliability in capturing climate variability across diverse regions, including Asia (Kim and Lee 2022; Lal et al. 2013; Yan et al. 2024). Given its accuracy in temperature and humidity representation, it is suitable for analyzing large-scale climate patterns. To further validate our use of ERA5, the summer season time-series against the Climatic Research Unit Time-series version 4.08(CRU TS4.08) dataset for monsoon and inner Asia regions (University of East Anglia Climatic Research Unit et al. 2024) was cross-checked, finding a strong agreement (correlation coefficients of 0.89 for monsoon Asia and 0.86 for inner Asia).

From ERA5, hourly 2-m temperature (T2m) and 2-m dewpoint temperature (D2m) with a spatial resolution of $0.25° \times 0.25°$ are extracted, along with total column water vapor (TCWV) and vertical integral of water vapor divergence (VIWVD, $\nabla \bullet Q$) from monthly single-level data to figure out the basic climatic states related to the heat extremes. VIWVD is multiplied by −1 to represent moisture convergence (positive) and divergence (negative).

The daily maximum temperature (Tmax) referred to the highest value of T2m within a given day and relative humidity (RH) were calculated using the Bolton (1980) method, based on T2m and D2m values (Eq. 1 to 3). Subsequently, wet-bulb temperature (Tw) was computed using Tmax and RH using Stull (2011) (Eq. 4), a widely adopted metric for humid-heat extremes (Coffel et al. 2017; Liao et al. 2021; Luo et al. 2022; Monteiro and Caballero 2019; Raymond et al. 2020). Tmax was used for Tw calculation, as it captures peak heat stress, critical for assessing the danger level of extreme humid-heat events (Coffel et al. 2017; Li et al. 2020; Luo et al. 2022).

$$RH\ [\%] = \frac{e}{e_s} \times 100 \tag{1}$$

$$e = 6.112 \times \exp\left(\frac{17.67T_d}{T_d + 243.5}\right) \tag{2}$$

$$e_s = 6.112 \times \exp\left(\frac{17.67T}{T + 243.5}\right) \tag{3}$$

$$\begin{aligned} T_w[^{\circ}\mathrm{C}] = T \times \operatorname{atan}\left[0.151997(RH + 8.313659)^{\frac{1}{2}}\right] + \operatorname{atan}(T + RH) \\ -\operatorname{atan}(RH - 1.676331) + 0.00391838 \times RH^{\frac{3}{2}} \times \operatorname{atan}(0.023101RH) - 4.686035 \end{aligned} \tag{4}$$

Extreme heatwaves were identified using a percentile-based approach to ensure comparability across diverse climatic zones. At each grid point, the 90th percentile threshold of daily maximum temperature (Tmax) and wet-bulb temperature (Tw) were computed based on the full analysis period from 1973 to 2023. A day was classified as extreme if the daily value exceeded its respective grid-specific threshold. This approach offers alternative to fixed absolute thresholds (e.g., 33 °C or 35 °C), which may not be universally applicable across Asia's varied climate regions (Coffel et al. 2017; Sherwood and Huber 2010). Two categories of extremes were defined: (1) extreme Tmax events, representing general heatwaves, and (2) extreme Tw events, indicating humid heatwaves. The annual frequency of these events was calculated as the number of extreme days per year at each grid point.

The analysis period (1973–2023) focuses on the northern summer season (June-July–August, JJA) to capture long-term trends in heat extremes across Asia. Although ERA5 data are available from 1940, our analysis is limited to 1973 onward due to well-documented uncertainties in humidity variables before the 1970's (Simmons et al. 2010; Soci et al. 2024), ensuring more reliable assessment of humid-heat extremes. To examine the recent humidity divergence, this period is further divided into 2000–2011 (P1) and 2012–2023 (P2). This division is based on specific humidity (SH) trends, which show a pronounced divergence after 2000: SH in arid Asia peak around that time and gradually declined, whereas SH in monsoon Asia accelerated rapidly, particularly after the early 2000 s (Figure S1). This pattern highlights a growing humidity contrast between the two regions.

3 Results and discussion

3.1 Divergent trends in extreme heat events across the monsoon-arid gradient

Our analysis reveals striking differences in how the frequencies of compound humid-heat heat extremes and general heat extremes have changed across the monsoon and arid regions of Asia over recent decades. Figure 1 showcases the SH climatology (1973–2023) across the monsoon and arid regions, delineated based on the distinct climate regimes (Red line in Fig. 1a). This separation captures climatological differences in SH, encompassing typical arid zones and monsoon areas within the Asian-Pacific monsoon region (Wang et al. 2017; Yihui and Chan 2005). For simplicity, Asia is divided into two subregions, with the arid region covering the transitional area. The time-series of SH shows an increasing trend in both regions until 2000, after which trend diverges significantly (Fig. 1b). SH stagnated in the monsoon area during 2000–2011 (P1) but increased sharply in 2012–2023 (P2). In stark contrast, the arid area saw a slight decrease in SH since 2000. This divergent trend suggests increasing aridity in the arid area while the monsoon area experiences moistening, corresponding to the consistent increase in temperature (Figure S2) across both regions.

Figure 2 compares extreme Tmax event and extreme Tw event frequencies. Positive values (brown) indicate more frequent dry heat extremes, while negative values (red) highlight increasing humid-heat extremes. These contrasts are particularly pronounced during the P2 period. This discrepancy between monsoon and arid Asia remains consistent when extreme Tmax events and extreme Tw events are calculated based on daily mean temperature (see Figure S3), emphasizing the robustness of the result regardless of whether daily maximum or mean temperature is used.

In the monsoon region, Fig. 2a and b show that humid heat extremes have become interestingly dominant in recent decades. Figure S4 supports this by highlighting that in areas such as the Indo-Gangetic Plain and southern China, extreme Tmax event exhibits statistically insignificant changes, whereas extreme Tw event shows a significant increase, suggesting that rising humidity has intensified humid-heat extremes. In Southeast Asia, both extreme Tmax and Tw events have increased, but the increase in extreme Tw is more pronounced, indicating that humidity plays a stronger role in recent heat stress.

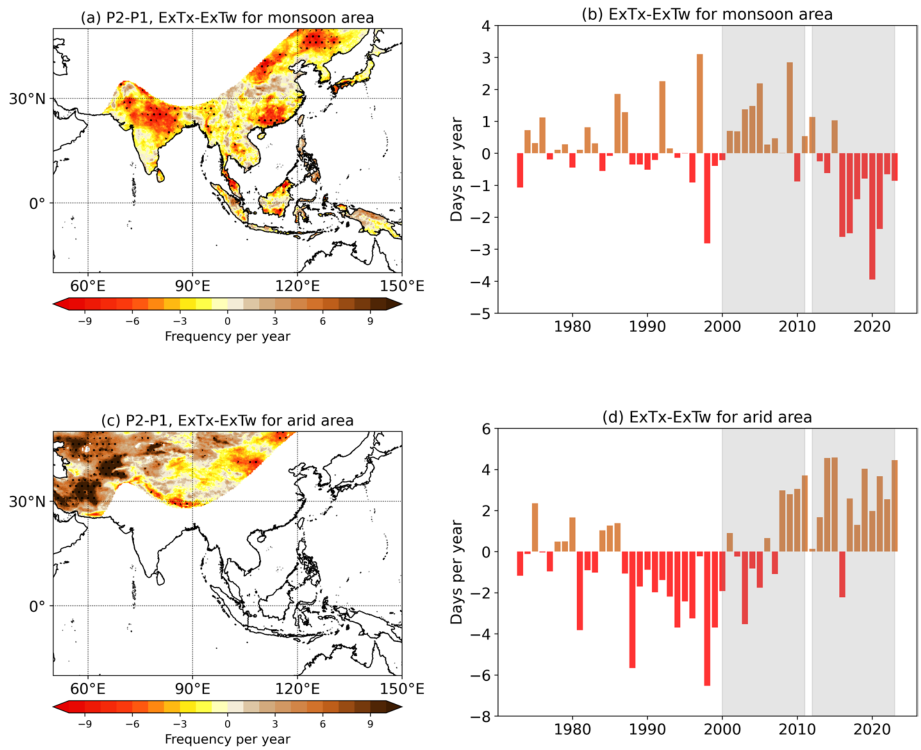

Fig. 2 The difference between extreme Tmax and extreme Tw events. **a**, **c** Spatial differences between periods P2 and P1. **b**, **d** Corresponding time-series of annual differences, with shaded areas indicating the respective regions. The upper panels exclusively depict the monsoon area, while the lower panels specifically describe the arid area. Visually, negative value (red) denotes where extreme Tw event is more frequent than extreme Tmax event, while positive (brown) indicates where extreme Tmax event is more frequent than extreme Tw event

In contrast, most arid regions show a decrease in both types of extremes, with some exceptions in transition zones (Fig. 2c and d). Western Asia exhibits a statistically significant increase in extreme Tmax events and a concurrent decrease in extreme Tw events, confirming the intensification of dry heat extremes under global warming and limited moisture availability (Figure S4). Mid-Asia, acting as a transition zone, displays a more heterogeneous pattern (Wang et al. 2017). While some areas resemble the arid regime with dominant extreme Tmax increases, others show signals closer to monsoonal regime or event decreasing trends in both metrics. Notably, northern Mongolia shows a local cooling trend, with both extreme Tmax and Tw events decreasing. This may reflect the region's unique cryospheric and topographic conditions, including persistent permafrost, low soil moisture, and cold ground temperatures that inhibit warming (Ishikawa et al. 2005; Klinge et al. 2018; Sharkhuu 2003).

As shown in Figure S5, humid-heat extremes increased markedly in the monsoon region during P2, whereas general-heat extremes dominated in the arid region. This divergence is further emphasized in the post-2000 trends (Figure S6) and quantified in Fig. 2b and d. In the monsoon region, extreme Tw events rose sharply from P1 to P2, shifting the extreme Tmax – extreme Tw difference from 0.79 to −1.16 (−1.95 days), reinforcing humid-heat extremes (Li et al. 2020). In contrast, the arid regions showed an increases from 0.39 to 2.44 (+2.05days), reflecting an increase in extreme Tmax frequency but without a corresponding rise in extreme Tw (Fig. 2), consistent with its limited moisture availability.

3.2 Underlying mechanisms driving the divergent trends

The basic climatic conditions driving these divergent trends are elucidated in Fig. 3. Tmax shows an increasing trend, particularly in the monsoon region (Fig. 3a), suggesting more frequent humid-heat and general heat extremes (Figure S3). However, SH and TCWV exhibit contrasting regional patterns (Fig. 3b and c). In the monsoon region, both quantities increase substantially, with TCWV also rising over adjacent ocean areas, reinforcing the observed rise in extreme Tw events ($p < 0.05$). This increase is linked to enhanced moisture transport from the ocean converging to the monsoon land (Fig. 3d and e), consistent with previous studies (Ganguli and Merz 2024; Ha et al. 2022).

Building on this large-scale thermodynamic background, the spatial variability in humid-heat intensification can be further attributed to region-specific factors such as SST-driven moisture availability, monsoonal wind transport, and anthropogenic influences including urbanization and irrigation. Sea surface temperature (SST) over the ocean adjacent to monsoon Asia has markedly increased during the recent period (Figure S7), enhancing evaporation and providing a stronger source of atmospheric moisture (Ha et al. 2022). This SST warming has likely intensified moisture transport from the ocean to nearby coastal regions. In India, despite relatively modest surface temperature increases, a pronounced increase in specific humidity has led to a substantial rise in humid-heat extremes. This pattern is likely associated with rapid urbanization, which enhances the urban heat island (UHI) effect, and adds anthropogenic moisture to the lower atmosphere, contributing to persistently high humidity levels (Guo et al. 2022; Zhang et al. 2023). In southern China, moisture is transported from the Bay of Bengal across the Indochina Peninsula to the South China coast by strengthened southwesterly low-level winds (Figure S7). This oceanic moisture advection, combined with the westward expansion of the Western Pacific Subtropical High (WPSH)

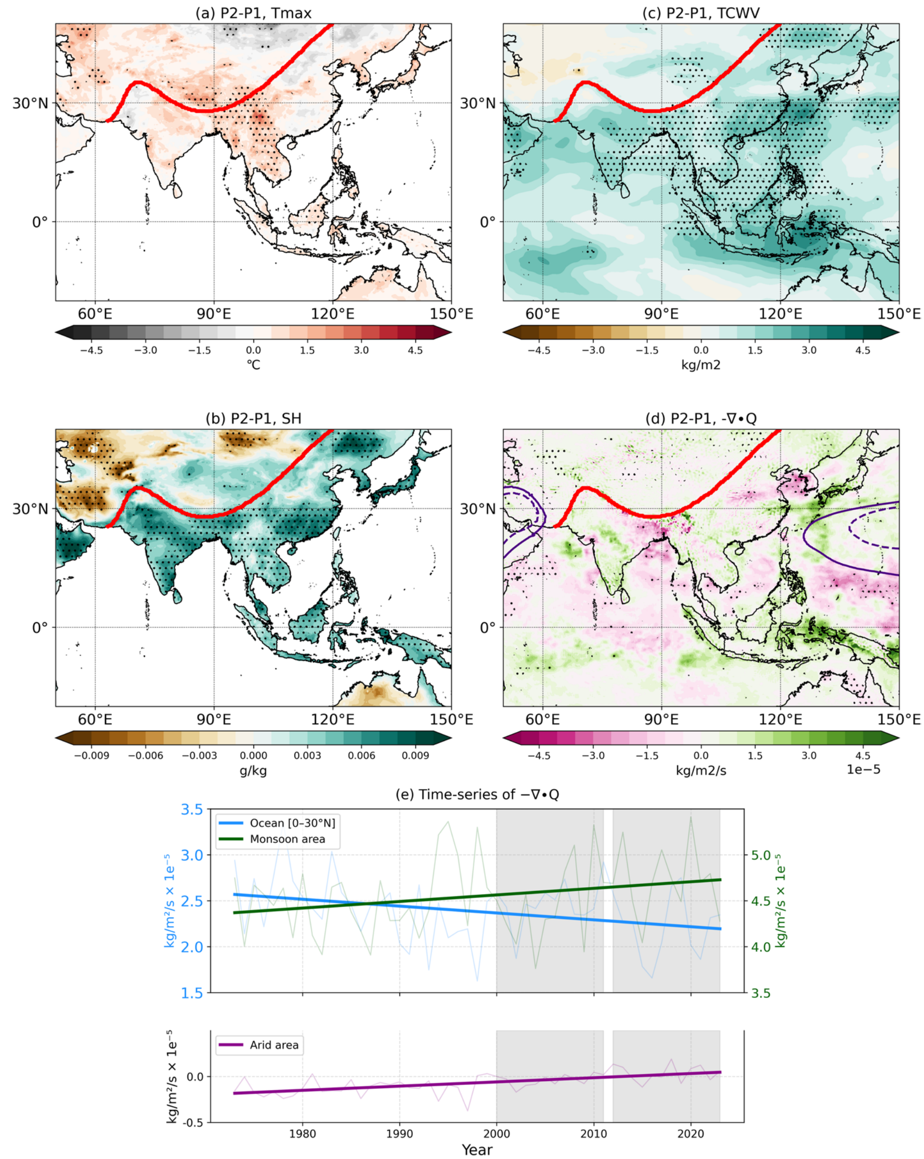

Fig. 3 Differences in JJA climatology between P1 and P2 for **a** Tmax, **b** SH, **c** TCWV, and **d** VIWVD. The red line marks the boundary between monsoon and arid regions, while purple lines in **d** indicate the 5880gpm contour at 500hPa, representing the western Pacific subtropical high (WPSH). Solid and dashed lines show P1 and P2 climatologies, respectively. Panel **e** displays yearly average trends of VIWVD over the monsoon and arid regions, with linear regressions. Gray boxes indicate averages for P1 and P2. Ocean and arid regions show statistically significant trends at the 95% confidence level, while the land region is significant at the 90% level

during the monsoon season (purple line in Fig. 3d), enhancing moisture transport to the southern China and much of East Asia (Guo et al. 2023; Luo et al. 2022).

In contrast, for the arid region, while SH increases moderately in mid-Asia, some areas like Siberia and western Asia even experience declines (Fig. 3b). TCWV changes are minimal, and VIWVD remains weak (~ 1% of monsoon levels), limiting moisture transport and favoring extreme Tmax events over extreme Tw events (Fig. 2).

While these general patterns provide a broad overview of the climatic trends, it is important to note the spatial variability within the regions, particularly the monsoon area. In Northeast China, extreme Tmax events increased faster than extreme Tw events in P2 (Fig. 2a), corresponding to smaller Tmax and SH increases (Fig. 3a and b) and moisture divergence (Fig. 3d). The WPSH enhances atmospheric convergence over Japan and the East China Sea, but leads to divergence in northern Yangtze regions (Matsumura and Iizuka 2023). Such exceptions illustrate the influence of specific regional climate dynamics and underscore the importance of considering spatial variability when interpreting spatial variability of these trends, even within broadly defined climatic zones.

These spatial variation in climatic variables contribute to the complex dynamics of atmospheric moisture balance, shaped by surface freshwater fluxes (P-E), VIWVD, and the tendency of the vertical integral of atmospheric water vapor (dw/dt) (Mayer et al. 2021). While reanalysis data biases inherently exist, these errors have remained constant over time. Nevertheless, discernible fluctuations in the biases among these components are apparent over time (Figure S8). The bias between two terms has diminished over time in land areas, whereas the bias in the ocean decreased around the year 2000, only to increase again thereafter. Despite the similarities in the overall trends across the components, a keen awareness of these errors and spatial variations is paramount for a comprehensive interpretation of the water vapor budget and its implications for extreme heat events across different regions.

4 Conclusion

Our results reveal striking differences in the trends of humid-heat extremes and general heat extremes across the monsoon-arid gradient of Asia. In the monsoon region, extreme Tw events have surged in frequency, driven by widespread warming, enhanced ocean-to-land moisture transport, and consistent increases in atmospheric humidity. This intensification reflects the synergy of multiple drivers, including SST warming in adjacent oceans that enhances evaporation, strengthened low-level monsoonal winds that facilitate ocean-to-land moisture advection, and anthropogenic influences such as rapid urbanization and extensive irrigation that elevate local humidity levels. The westward expansion of the WPSH further supports northward moisture transport, particularly into East Asia (Ganguli and Merz 2024; Guo et al. 2023; Ha et al. 2022).

In contrast, the arid region exhibits a dominant rise in extreme Tmax events, without a comparable increase in extreme Tw events. This reflects a thermodynamic constraint imposed by limited atmospheric moisture and weak moisture convergence, as confirmed by the minimal changes in TCWV and VIWVD over these regions. Despite similar warming trends, the divergent humidity dynamics yield contrasting heat stress profiles. Humid-heat extremes dominate in the monsoon region, while general heatwaves intensify in the arid interior.

These findings illustrate how the contrasting patterns of temperature and humidity changes across the monsoon-arid gradient underlie the divergent trajectories of humid-heat versus general heat extremes. While the arid regions may experience a lower relative increase in humid-heat extremes, escalating general heatwaves also pose significant risks to water resources, agriculture, and biodiversity (Sobolewski et al. 2020). Addressing these impacts requires refining climate models to better represent regional climate dynamics like monsoon variability and land–atmosphere interactions (Mishra et al. 2020).

A key limitation of this study lies in the reliance on current reanalysis data and climate models, which often struggle to simulate humid-heat extremes accurately. Advances in model physics and resolution can improve heatwave predictions and adaptation strategies. Moreover, RH plays a critical role in defining heat stress in monsoon regions. Developing heat indices that better integrate temperature and humidity would improve assessments of heatwave impacts.

By addressing these modeling limitations and advancing our understanding of compound heat extremes, future studies can improve the accuracy of heatwave projections, offering actionable insights for climate adaptation planning.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10584-025-04035-x.

Author contributions This study is conceptualized by Jina Park, Shih-Yu (Simon) Wang, and Jin-Ho Yoon. Jina Park did data analysis, visualization, and writing the original draft. Supervision was done by Shih-Yu (Simon) Wang, and Jin-Ho Yoon. All authors were involved in the reviewing and editing the manuscript.

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Data availability The datasets analyzed in this study are available in the following websites:
- ERA5 hourly single-level: https://cds.climate.copernicus.eu/datasets/reanalysis-era5-single-levels?tab=overview.
- ERA5 monthly single-level: https://cds.climate.copernicus.eu/datasets/reanalysis-era5-single-levels-monthly-means?tab=overview.
- CRU TS4.08 https://crudata.uea.ac.uk/cru/data/hrg/.

Declarations

Competing interests The authors have no competing interests.

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