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**Large-scale aggregation of humid heatwaves exacerbated by coastal
oceanic warming**

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Abstract

Large-scale concurrences of humid heatwaves substantially escalate the risks of heat-related mortality. However, quantifying the origins of these concurrent extremes remains challenging. Here we use a complex network approach applied to climate reanalysis data to show that the observed intensification of humid heatwaves is closely associated with coastal oceanic warming over the period 1982–2023. This linkage is more pronounced for the large-scale aggregation of extreme humid heatwaves than for the locally confined events. In particular, approximately 50% and 64% of the upward trends in humid heatwave frequency and spatial-aggregation strength over hotspot regions are linked to their adjacent oceans, respectively. These land–ocean linkages largely arise from tropical ocean-driven moisture transport towards land regions and from coupled terrestrial–oceanic warming in the mid-to-high latitudes associated with atmospheric Rossby waves. Compared with mid-to-high latitudes, the tropics encompass most high-risk areas and exhibit stronger land–ocean linkages, highlighting the critical role of tropical oceans. Climate model experiments further demonstrate the influence of tropical oceans on adjacent terrestrial humid heatwaves. Our study provides insights that coastal sea surface temperature can be a crucial precursor of the large-scale aggregation of humid heatwaves.

Compound humid and hot events pose a substantially higher risk for human health, compared with the extreme events of a single type^{1–3}. The heat stress of such compound events is widely indicated by wet-bulb temperature (T_w), which integrates the effects of both temperature and humidity^{4–8}. When T_w exceeds the critical survival threshold of 35 °C, it becomes fatal for humans and many other mammals^{6–8}. Even at considerably lower values, T_w can still lead to serious risks to human morbidity and mortality^{9–10}. Such heat stress caused by compound humid heatwaves has been rising rapidly over the past decades^{7,11–13}, and is projected to accelerate further in the future^{14–16}. A comprehensive investigation of humid heatwaves at the global scale, including the disentanglement of their underlying dynamics and drivers, is essential for developing efficient mitigation and adaptation strategies in response to climate changes.

Occurrences of humid heatwaves have been found to be modulated by atmospheric rivers^{17–19}, quasi-stationary planetary waves^{20–22}, light rain²³, land–atmosphere feedbacks^{24–25}, and oceanic variability^{13,22,26–27}. In particular, atmospheric rivers transport moisture and heat to terrestrial regions during humid heatwave occurrences^{17–19}, while light rainfall enhances local evaporation²³. Influence of the atmospheric Rossby waves involves large-scale moisture transport, warm air advection, and intensified solar radiation accompanied by heat-dome-like circulations^{20–22,28–29}. Coastal oceanic warming can exacerbate thermal discomfort in coastal areas by inducing changes in temperature, humidity, and wind speed²⁶. Moreover, ocean–atmosphere coupling modes, such as El Niño and the Indian Ocean Dipole, have been found to aggravate humid-heat risks by triggering atmospheric Rossby wave trains^{22,27}.

By contrast, terrestrial soil drought can mitigate the lethality of humid heatwaves through reducing surface evaporation²⁵, while agricultural irrigation exerts an opposite effect^{30–31}.

Compared with the well-documented humid heatwave events in individual areas, their nearly simultaneous occurrences across broad spatial domains remain poorly understood. Extreme events concentrated in both time (i.e., occurring simultaneously) and space (i.e., occurring geographically closely) are likely to amplify societal risks and pose greater challenges for disaster mitigations. It remains unclear over which regions the humid heatwaves tend to aggregate at a large scale. Identifying such hotspots considering both extreme intensity and spatial aggregation may help improve our understanding of heat stress more accurately and comprehensively. Furthermore, determining the spatial-aggregation strength with interannual variations and long-term trends, is essential for quantifying the drivers of large-scale concurrent humid heatwaves. Therefore, it is essential to apply advanced statistical techniques to effectively address these challenges.

Complex climate networks have been widely applied in analysis of extreme weather and climate, involving studies of remote connections in extreme rainfalls^{32–33}, droughts³⁴, heatwaves^{35–37}, and extreme atmospheric circulations^{35,38}. In this study, the spatial-aggregation strength of humid heatwaves is identified during 1982–2023 in a climate network framework established here (see Methods for details). This way, we can quantify the linkages between atmospheric–oceanic factors and concurrent humid heatwaves. We provide a flowchart that illustrates the key steps involved in the network

analysis of this study (Extended Data Fig. 1). Furthermore, the simulated adjacent land–ocean relationships are investigated using outputs from 30 models of the Coupled Model Intercomparison Project Phase 6 (CMIP6)³⁹, alongside additional numerical experiments conducted with the Community Earth System Model (CESM)⁴⁰.

Humid heatwaves triggered by onshore moisture transport

Humid heatwaves are identified based on the 95th-percentile threshold of standardized T_w (see Methods for details). These events exhibit higher T_w in the tropics and the subtropical monsoon regions, than in the mid- and high-latitudes (Fig. 1a). Lower T_w is observed over northwestern North America, the Tibetan Plateau, and northeastern Asia (Fig. 1a). The spatial pattern of humid-heat stress aligns more closely with the climatological pattern of summertime near-surface atmospheric specific humidity, compared with that of near-surface air temperature (Extended Data Figs. 2a–b).

In the following, we examine the distance-dependent concurrences of humid heatwaves by a network analysis (see Methods for details). In particular, more than 35% of grid-cell pairs at distances below 1,500 km exhibit significant connections, indicating that large-scale aggregation of humid heatwaves is common (Fig. 1b). The proportion of significant connections decreases rapidly with increasing geographical distance from 0 to 2,000 km in both hemispheres (Fig. 1b). For longer distance, the proportion of significant links remains stable at around 20%, which is probably attributed to global-scale heatwave trends. A similar distribution is also found in the

significant connections between humid heatwaves and extreme wet events (Fig. 1b), indicating an essential role of large-scale moisture anomalies in modulating humid heatwave concurrences.

To further characterize these concurrent extremes, we identify their spatial-aggregation strengths which measures the extent to which the humid heatwaves at a grid cell occur simultaneously with neighboring humid heatwaves within 2,000 km (see Methods for details). Pronounced spatial-aggregation strengths are observed over southern Australia, southern South America, and tropical Africa (Fig. 1c). Despite this, the tropics encompass most high-risk regions, which experience both high wet-bulb temperature and strong spatial aggregation. The large-scale concurrence of humid heatwaves is closely associated with large-scale humid events (Figs. 1c versus 1d), rather than with large-scale heat events (Fig. 1c versus Extended Data Fig. 2c). In other words, large-scale moisture aggregation is critical for concurrent humid heatwaves.

Typically, in addition to locally recycled water vapor, humid air primarily originates from ocean evaporation and subsequent onshore moisture transport, which can modulate the occurrence of humid heatwaves over land. Hereafter, we quantify the synoptic signal flow of wet events from oceanic and terrestrial regions (four groups of grid cells; Fig. 2a), to terrestrial humid heatwaves (see Methods for details). In particular, we aggregate the strengths of significant links at different lags in the HW–W networks, to quantify changes in the contribution of atmospheric-moisture signals. For terrestrial humid heatwaves, preceding moisture signals strengthen over the oceans but weaken over land at 5-day lead relative to 0-day lead (Figs. 2b–c and 2d–g). This

pattern is consistent with ocean-to-land moisture transport from oceans to land linked to humid heatwaves. In particular, for terrestrial humid heatwaves, more than 62% of preceding wet-event signals are predominantly observed over adjacent oceans, rather than over land (Figs. 2d–g). In other words, terrestrial humid heatwaves are likely driven by processes originating over adjacent oceans. Therefore, we investigate in more detail the possible mechanistic influence of coastal oceanic warming on the occurrence of humid heatwaves in the following section.

Adjacent land–ocean linkage

Variations of precipitable water and large-scale moisture transport are strongly linked to underlying sea surface temperature (SST) anomalies^{41–42}. To assess oceanic impacts, we investigate the significant linkages between terrestrial extremes (including humid heatwaves and wet events) and oceanic warming events (see Methods for details). We find that in the tropics, nearly all (>90%) pairs of adjacent (<2,000 km) terrestrial and oceanic grid cells are significantly connected (Fig. 3a). By contrast, approximately 80% and 60% of the adjacent land–ocean pairs are significant in the subtropics and temperate zone, respectively. In addition to latitudinal differences, substantial land–ocean links are identified at short distances, probably within a 1,000 km radius (Fig. 3b). Conversely, fewer than 20% of grid-cell pairs are significantly correlated at distances exceeding 2,500 km. This widespread linkage between terrestrial humid heatwaves and adjacent oceans along global coastlines is mediated by moisture-related signals (Fig. 3b).

In particular, composite significant warming in the tropical Indian Ocean coincides with regional humid heatwaves over both South and Western Asia (Figs. 3c–d, Extended Data Fig. 3), supporting the dominant adjacent linkages revealed by the network analysis (Fig. 3b). Enhanced evaporation of warmer oceans typically leads to higher atmospheric humidity (Fig. 3e). Simultaneously, warming in Indian Ocean induces a low-level cyclonic circulation anomaly over the Arabian Sea, enhancing moisture convergence and intensifying humid heatwaves in adjacent regions, including South and Western Asia (Figs. 3d–e, Extended Data Fig. 3). This land–ocean linkage is also evident in historical simulations from CMIP6 models (Figs. 4a–b). Intensified summer humid-heat risks over South and Western Asia are tightly coupled to Indian Ocean warming, which strengthens low-level cyclonic circulation over the Arabian Sea and facilitates moisture transport toward the land (Figs. 4a–c), reproducing patterns found in observational data (Figs. 3c–e). Nevertheless, these statistical relationships in both observational data and model simulations may be obscured by remote oceanic variability. To explicitly elucidate the influence of tropical adjacent oceanic warming, we conduct additional model experiments using the CESM model. Specifically, observed SST anomalies in the tropical North Indian Ocean derived from observational data are prescribed in the NIO_warming experiment (Figs. 3c and 4d; see Methods for details). A cyclonic circulation anomaly over the Arabian Sea, closely resembling observed pattern, emerges in response to the North Indian Ocean warming (Figs. 4f versus 3e). Through enhanced onshore moisture transport and convergence, humid-heat risks over South and Western Asia are consequently aggravated (Figs. 4d–f).

A similar adjacent land–ocean linkage is observed near northern South America. Both composite analysis and CESM experiments suggest that tropical North Atlantic warming triggers a low-level cyclonic anomaly to its west, which subsequently intensifies onshore moisture transport and exacerbates the humid-heat risks over northern South America (Extended Data Fig. 4). Therefore, warming of the tropical oceans drives increases in humid heat over adjacent land regions in the tropics, which cover most high-risk areas. Conversely, the physical mechanisms differ in extratropical regions. Different atmospheric Rossby waves along the westerly jet stream facilitate humid heatwaves over northeastern Asia, the southeastern United States, and eastern Europe, respectively (Extended Data Fig. 5). These wave patterns also contribute to concurrent warming in the adjacent oceans (Extended Data Fig. 5). These results align with previous study, indicating that tropical atmospheric circulation primarily controlled by SST, while mid-latitude SST exert a much weaker effect⁴³. Nevertheless, coastal extratropical oceanic warming accompanied by increased atmospheric humidity may further intensify onshore moisture transport, yet its quantitative impact requires further study.

Long-term trend linked to coastal oceanic warming

In this section, we quantify the extent to which the interannual variability and long-term trend of humid heatwave frequency are linked to adjacent oceanic signals, which are identified based on the most-connected oceanic grid cell within 3,000 km for each terrestrial grid cell (see Methods for details). Specifically, the adjacent oceans explain over 30% of the interannual variance in humid heatwave frequency over South Asia,

tropical Africa, Greenland, northern South America, northeastern Asia, and northwestern North America (Fig. 5a). Similar hotspots are observed for spatial-aggregation strengths, but with higher explained variances (Figs. 5b versus 5a), suggesting that oceanic warming exhibits a stronger linkage with the large-scale concurrences of humid heatwaves than the occurrence at individual grid cell level.

Long-term trends are further investigated. Over the past four decades, humid heatwaves have exhibited pronounced upward trends worldwide (Fig. 5c). Significant increases are observed over South Asia, Southeast Asia, the Arabian Peninsula, tropical western Africa, eastern Europe, northern South America, North America, and northeastern Asia, while modest reductions are observed over the Iranian Plateau and tropical eastern Africa (Fig. 5c). The increased frequency over these hotspots is predominantly associated with strengthened moisture advection from adjacent oceans (Fig. 5c). Moreover, the spatial-aggregation strengths of extreme T_w also exhibit accelerated trends over these hotspots (Fig. 5d), similar to the pattern observed for humid heatwave frequency.

Hereafter, we estimate the trends in humid heatwaves linked to adjacent oceanic signals using a linear regression model (see Methods for details). Nearly all hotspots, and the weakening trends observed over the Iranian Plateau and tropical eastern Africa, are captured by the estimated trends of humid heatwave frequency linked to adjacent oceans (Fig. 5e versus 5c). In particular, approximately half of the observed upward trends in humid heatwave frequency over the hotspots are linked to adjacent oceanic warmings, with strong associations over northeastern Asia and eastern Europe (>55%),

and relatively lower values over Africa and America (~40%). It is noteworthy that higher proportion of trends in spatial-aggregation strengths is estimated by adjacent oceans, compared with that in frequency (Fig. 5f versus 5e). Overall, approximately 64% of the observed trends in spatial-aggregation strengths are linked to adjacent oceanic warmings in the hotspots (Fig. 5f). This suggests that coastal oceanic warming is more strongly linked to the spatial aggregation of humid heatwaves than to the extreme frequency at individual grid cells.

Based on a complex network analysis, our study highlights a crucial role of adjacent SST warming in large-scale concurrences of terrestrial humid heatwaves. However, the present study does not focus on the remote influences of oceanic modes, such as El Niño, on humid heatwaves, as these influences are slightly weaker than those associated with adjacent oceanic warming (Extended Data Fig. 6). It should be noted that these remote impacts can extend well beyond 1,500 km via atmospheric teleconnections^{21,28,35}, which our network analysis may not fully capture given the climate system's nonlinearity. By the end of the century, El Niño-like SST changes are projected as remarkable global oceanic signals by climate models^{38,44–45}, which could accelerate future heatwave changes over Western Asia and western North America⁴⁴. Nevertheless, the heat stress probably mediated by moisture changes remains far from being understood and deserves further investigations. In addition, enhanced moisture transport onto land may promote convection and alleviate surface extreme temperature. This competing effect may be modulated by rainfall intensity, as light rain has been shown to exacerbate humid-heat risks²³. Elucidating the mechanisms that increase

moisture without coincident heavy rainfall is crucial for identifying precursors of extreme humid heatwaves, yet it remains an open question. Furthermore, humid heatwaves may also be accelerated by global warming-induced increases in specific humidity with enhanced moisture-holding capacity of the atmosphere over many regions. However, the relative contributions of such thermodynamic effects versus the dynamic transport processes discussed in the present study, to the long-term trends of humid heatwaves, remain unclear and warrant further investigations. Addressing these questions may advance our understanding of the complex climate system and strengthen our capacity to mitigate and adapt to future thermal risks.

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Author Contributions

F.C. and T.Z. conceived and designed the study. F.C. conducted the analysis and drafted

260 the manuscript. T.Z. and J.K. supervised the research. D.G., K.Z., and S.Y. provided
261 important comments and revised the manuscript. All authors discussed the scientific
262 interpretation of the results, and reviewed the manuscript.

263 **Competing Interests**

264 The authors declare no competing interests.

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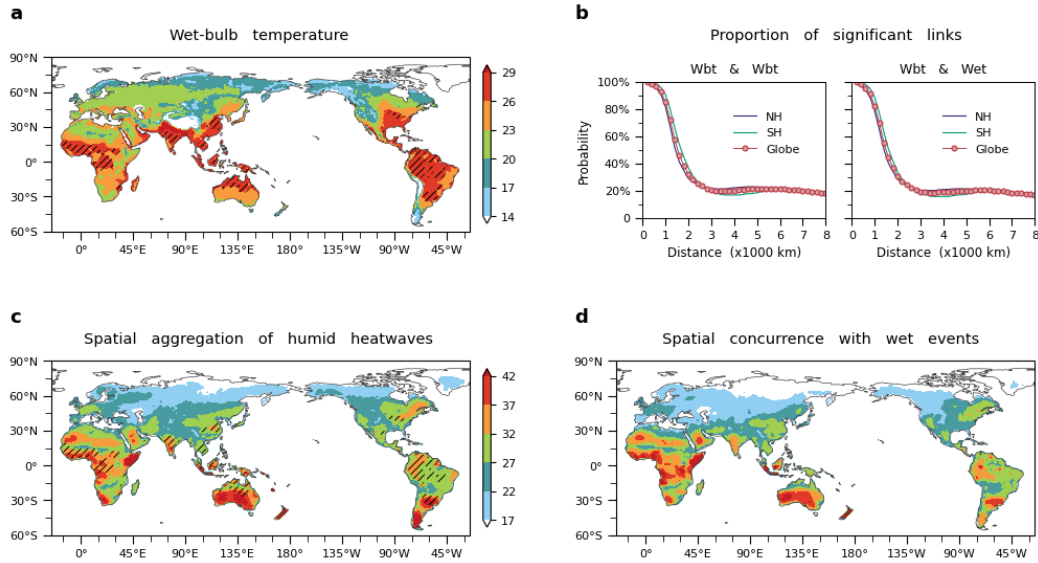


Fig. 1 | Extreme humid heatwaves and their spatial concurrences. **a**, Composite wet-bulb temperature (°C) for humid heatwaves during 1982–2023. **b**, Distance distribution of the proportion of significant links in HW–HW networks (left), and HW–W networks (right), across the globe (red circles), Northern Hemisphere (purple lines), and Southern Hemisphere (green lines). **c–d**, Spatial-aggregation strengths between humid heatwaves and neighboring humid heatwaves (**c**), and between humid heatwaves and neighboring wet events (**d**). The black hatched areas in (**a**, **c**) indicate the hotspots where both (**a**) and (**c**) exceed the 66.6th percentile across global land areas.

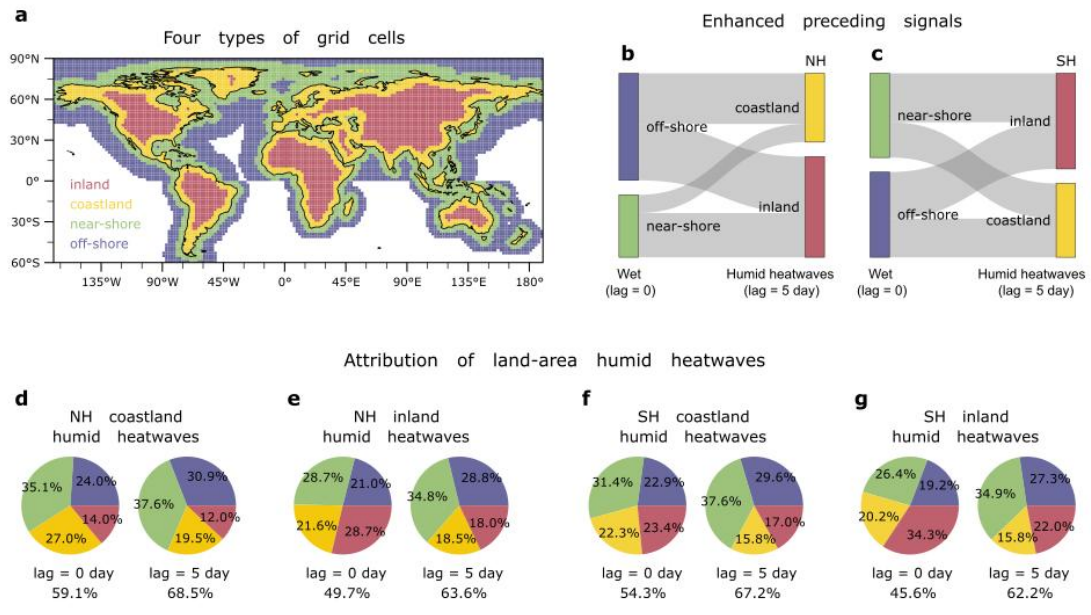


Fig. 2 | Terrestrial humid heatwaves influenced by moisture transport from adjacent oceans. a, Four groups of grid cells: inland (red), coastland (yellow), near-shore (green), and off-shore (blue). **b–c**, Enhanced preceding signal flow of HW–W networks (5-day lag minus 0-day lag) among the four groups for the Northern Hemisphere (**b**), and Southern Hemisphere (**c**). No enhanced signal flow from land is shown in (**b–c**), because terrestrial moisture signals are weaker at 5-day lead times than at 0-day lead. **d–g**, The contributions of four-group wet events with 0-day lead (left) and 5-day lead (right), to terrestrial humid heatwaves over two land groups in the Northern and Southern Hemispheres. The accumulated contributions of oceanic regions (i.e., near-shore and off-shore) are shown at the bottom of panels (**d–g**).

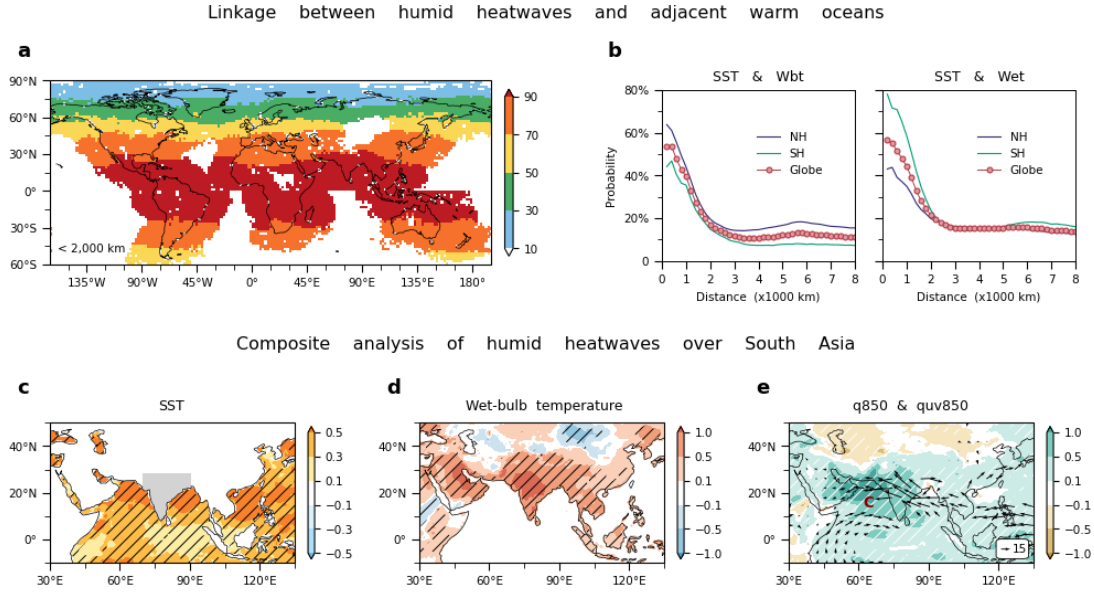


Fig. 3 | Observed linkages among humid heatwaves, warm SST, and wet events at synoptic scales. a, Proportions (%) of grid cells exhibiting significant links within 2,000 km in the HW–OW networks. **b**, Distance distribution of significant links for the HW–OW networks (left), and OW–W networks (right), across the globe (red circles), Northern Hemisphere (purple lines), and Southern Hemisphere (green lines). **c–e**, Composite anomalies of SST (K) (**c**), near-surface wet-bulb temperature (K) (**d**), and 850-hPa specific humidity (q850; g kg⁻¹), and 850-hPa moisture transport (quv850; g kg⁻¹ m s⁻¹) (**e**) during regional humid heatwaves over South Asia. Anomalies significant at $P < 0.05$ (two-sided t -test) are indicated by hatching and vectors in (**c–e**).

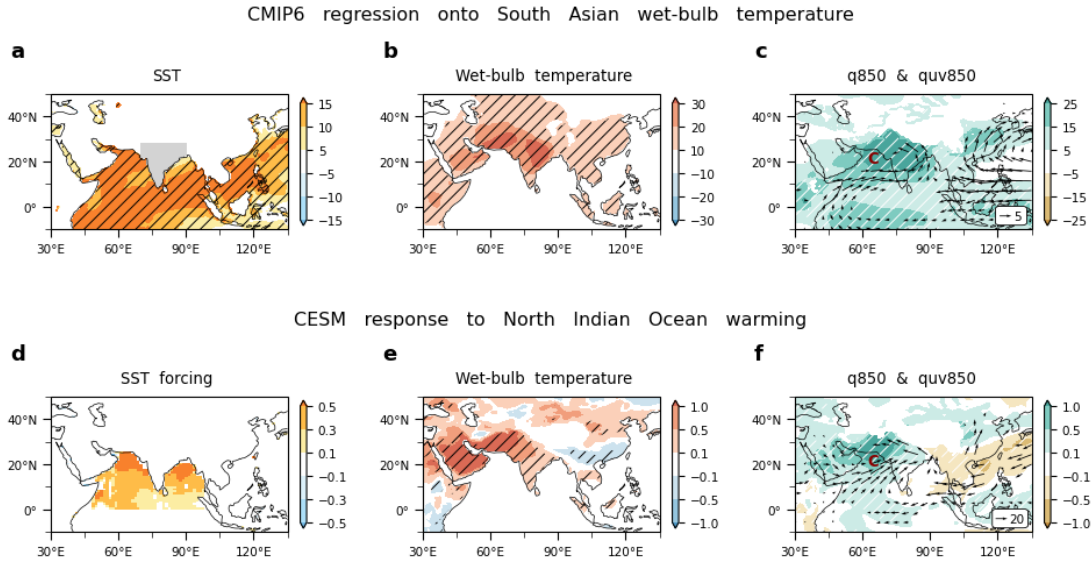


Fig. 4 | North Indian Ocean warming exacerbates humid-heat risks over South and Western Asia. **a–c**, Regression coefficients of SST (10^{-2} K) (**a**), wet-bulb temperature (10^{-2} K) (**b**), and specific humidity at 850 hPa (q850; 10^{-2} g kg $^{-1}$), and moisture transport at 850 hPa (quv850; 10^{-2} g kg $^{-1}$ m s $^{-1}$) (**c**), onto the regional mean wet-bulb temperature over South Asia, during 990 summers (1982–2014) simulated by 30 climate models. **d–f**, Differences in SST forcing (K) (**d**), wet-bulb temperature (K) (**e**), and q850 (g kg $^{-1}$) and quv850 (g kg $^{-1}$ m s $^{-1}$) (**f**) between the NIO_warming and CTL runs of the CESM model. Only significant values ($P < 0.05$; two-sided t -test) are shown by hatching and vectors in **a–f**.

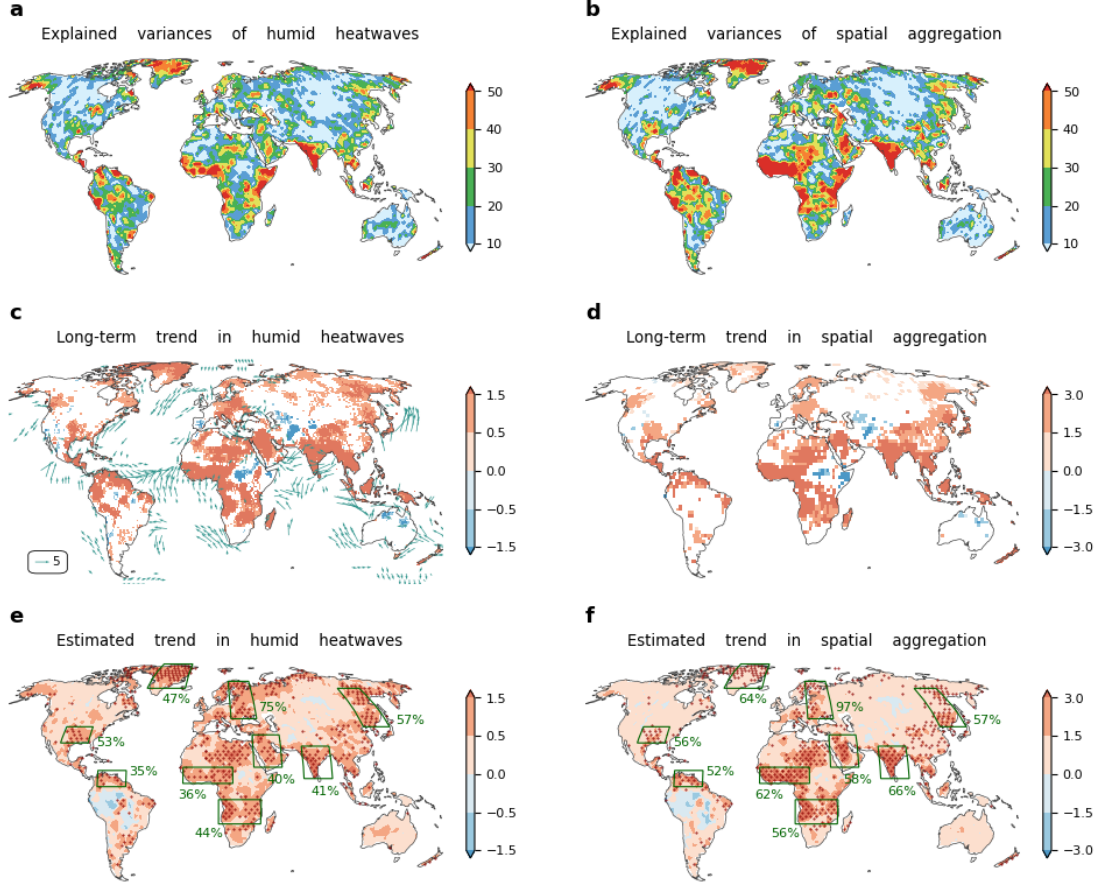


Fig. 5 | Observed and estimated trends in humid heatwaves. **a–b**, Explained variance (%) between the most-connected warm SST event frequency and humid heatwave frequency (**a**), and spatial-aggregation strength of humid heatwaves (**b**) on interannual timescales. **c–d**, Observed trends in humid heatwave frequency (shadings; $P < 0.05$, two-sided t -test; decade⁻¹) and near-surface moisture transport (vectors; $P < 0.05$, two-sided t -test; g kg⁻¹ m s⁻¹ decade⁻¹) (**c**), and spatial-aggregation strength of humid heatwaves ($P < 0.05$, two-sided t -test; 10⁻¹ decade⁻¹) (**d**) during 1982–2023. **e–f**, Estimated trends by the most-connected warm SST events for humid heatwave frequency (decade⁻¹) (**e**), and for its spatial-aggregation strength (10⁻¹ decade⁻¹) (**f**), with red dotted areas indicating where more than 30% of observed trends are estimated. The

domains of hotspots (see Methods for details) are outlined by green boxes and the corresponding estimated trend ratio are shown in (e–f).

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Methods

Datasets. Hourly air temperature at 2m (T_{2m}), dew point temperature at 2m, and surface pressure, used for calculating wet-bulb temperature, are obtained from the ERA5 reanalysis dataset⁴⁶. Daily maxima of both hourly T_{2m} (T_{max}) and wet bulb temperature (T_w) are calculated for further identification of heatwaves and humid heatwaves. Multi-level atmospheric specific humidity is also derived from the ERA5 reanalysis dataset⁴⁶. Near-surface specific humidity (q) is calculated from the dew point

temperature at 2m and surface pressure. Hourly near-surface specific humidity is averaged into daily means for identifying wet events. Daily SST is derived from OISST dataset⁴⁷. The analyzed period is June–July–August (December–January–February) of 1982–2023 for Northern (Southern) Hemisphere, and the analyzed latitude range is limited to 60°S–90°N, excluding the Antarctic continent due to its low population density.

In additional to the ERA5 reanalysis and OISST data, the historical simulations during the period 1982–2014 from 30 CMIP6 models are also analyzed in this study³⁹ (see Supplementary Table S1). Daily near-surface air temperature and relative humidity in the CMIP6 model output are employed to derive T_w . To simplify the calculation process, we analyze the summer-mean T_w for model outputs.

Extreme weather events. At first, T_{max} , T_w , near-surface q , and SST are standardized. Then, we calculate the 95th-percentile threshold of the standardized variables over the entire summer (June–July–August for Northern Hemisphere and December–January–February for Southern Hemisphere). Days when T_{max} , near-surface q , T_w , or SST exceeds their 95th-percentile threshold, are recognized as the occurrences of heatwaves, wet events, humid heatwaves, or oceanic warming events, respectively. Approximately 193 (189) days of each type of extreme events are identified during the June–July–August (December–January–February) of 1982–2023 for Northern (Southern) Hemisphere. Humid heatwave frequency and oceanic warming event frequency are calculated as the number of corresponding extreme events during each summer.

Network analysis. To investigate the relationships among humid heatwaves, wet

events, and oceanic warming events, we design five kinds of networks between: (1) humid heatwaves and humid heatwaves (HW–HW networks), (2) humid heatwaves and wet events (HW–W networks), (3) humid heatwaves and oceanic warming events (HW–OW networks), (4) wet events and wet events (W–W networks), and (5) oceanic warming events and wet events (OW–W networks). The strength of a link between grid cells i and j is identified as $L_{(i,j)}$ for each network. $L_{(i,j)}$ is determined as the total number of concurrent days (i.e., event coincidence; see Supplementary Fig. S1), when an extreme weather event occurs over i and another one occurs over j simultaneously, referred to previous studies^{35–36,48}. Zero-lag (i.e., time lag = 0) networks are performed for all five kinds of networks. Additionally, we also construct lead–lag networks with a time lag of 5 days, for HW–W networks, to investigate the lead–lag impacts of onshore moisture transport on terrestrial humid heatwaves. To identify the significance level of extreme event coincidence, we calculate the threshold using the corresponding shuffled data. In particular, we shuffle the time series of daily events (presence as 1 or absence as 0) 1,000 times, and then calculate the 99th-percentile threshold of $L_{(i,j)}$ from the 1000 shuffled values^{35,48}. When the real $L_{(i,j)}$ is no less than the 99th-percentile threshold of the shuffled data, this link is identified as significant and will be preserved.

Spatial-aggregation strength. Weighted degree centrality of humid heatwaves inside humid heatwaves with a distance less than 2,000 km is identified as spatial-aggregation strength:

$$D_i = \sum_{distance(i,j) < 2,000km} (L_{(i,j)} * W_{(i,j)}) / \sum_{distance(i,j) < 2,000km} (A_{(i,j)} * W_{(i,j)})$$

where $L_{(i,j)}$ represents the link strength of HW–HW networks, $W_{(i,j)}$ is the latitude weighted matrix identified as $\cos((|latitude_i| + |latitude_j|)/2)$, and $A_{(i,j)}$ indicates pairs of two terrestrial grid cells (i.e., $A_{(i,j)} = 1$ if a and b are both terrestrial grid cells, and otherwise $A_{(i,j)} = 0$ if i or j is oceanic grid cell). D_a indicates to what extent the humid heatwaves at a grid cell occur simultaneously with the humid heatwaves over the neighboring region ($<2,000$ km). In addition to the total strengths over 1982–2023, we also partition the 42-year spatial-aggregation strength (in Fig. 1c) into an interannual time series at each grid cell, with each yearly value representing the number of neighboring concurrences observed in that year. In this way, we can quantify the interannual relationships between warm SST event frequency and spatial-aggregation strength of humid heatwaves.

Signal flow between oceans and land. At first, we categorize the grid cells into four groups: inland, coastland, near-shore, and off-shore regions, for both Northern and Southern Hemispheres. Specially, land-area grid cells are classified as either inland or coastland, based on their distances from the coastline, with a threshold of 500 km. Similarly, oceanic grid cells are divided into near-shore and off-shore categories using the same threshold of 500 km. Oceanic grid cells located more than 1,800 km (1,000 km) from the coastline in the Northern (Southern) Hemisphere are excluded, to ensure a balanced distribution of the four grid cell types (see Supplementary Table S2).

The contributions of wet events over the four regions to terrestrial humid heatwaves are quantified by accumulating the strengths of significant links. For instance, the 5-day–lead signal flow from near-shore regions (wet events) to coastland regions (humid

heatwaves) is given by:

$$F_{(lag=5\text{ days}, near-shore \rightarrow coastland)} =$$

$$\sum_{i \in near-shore, j \in coastland} L_{(i,j), lag=5\text{ days}} / \sum_{i \in all, j \in coastland} L_{(i,j), lag=5\text{ days}}$$

where $L_{(i,j), lag=5\text{ days}}$ represents the link strength in the HW–W networks, considering a time lag of 5 days. $F_{(lag=5\text{ days}, near-shore \rightarrow coastland)}$ represents the contribution of near-shore wet events to coastland humid heatwaves at a 5-day lag.

Subsequently, the enhanced signal flow is calculated as:

$$\Delta F_{(near-shore \rightarrow coastland)} =$$

$$F_{(lag=5\text{ days}, near-shore \rightarrow coastland)} - F_{(lag=0\text{ days}, near-shore \rightarrow coastland)}$$

ΔF can be positive or negative. In Figs. 2b–c, we show only positive ΔF , corresponding to enhanced signals at 5-day lead relative to 0-day lead. Detailed contributions of moisture signals across different lags and regions are also shown in Figs. 2d–g.

Estimation of humid heatwave trends by adjacent oceans. Following previous study³⁵, we employ a network-searching method to estimate the trends of humid heatwave frequency linked to adjacent oceanic warmings. In the HW–OW networks, we search for the strongest adjacent link (i.e., the highest concurrences within 3,000 km) to each humid heatwave grid cell. In this way, for each humid heatwave grid cell, the most-connected adjacent oceanic grid cell is identified as adjacent oceanic signals (<3,000 km). Hereafter, we estimate the trends of humid heatwave frequency related to the corresponding oceanic warming frequency at the most-connected adjacent oceanic grid cell. Specially, the estimation of trends in humid heatwave frequency

($Trend_{(HHWs, \text{estimated})}$) is based on a linear regression model:

$$Trend_{(HHWs, \text{estimated})} = RC_{(Oceanic \text{ warming, } HHWs)} \times Trend_{Ocean \text{ waming}}$$

where $Trend_{Ocean \text{ waming}}$ is the temporal trends in the most-connected adjacent oceanic warming frequency, and RC is the regression coefficient between the detrended yearly time series of the oceanic warming frequency at the most connected grid cell and humid heatwave frequency.

Regional observed and estimated trends of humid heatwave frequency and spatial aggregation are compared over northern South America (3°–13°N, 75°–55°W), southeastern United States (30°–40°N, 105°–85°W), the Greenland (65°–85°N, 55°–20°W), eastern Europe (45°–75°N, 20°–40°E), tropical western Africa (5°–15°N, 15°W–20°E), subtropical southern Africa (40°–5°S, 10°–40°E), Western Asia (15°–35°N, 35°–55°E), South Asia (8°–28°N, 70°–90°E), and northeastern Asia (40°–65°N, 120°–140°E). The ratios of estimated trends to observed trends over these regions are shown in Figs. 5e–f.

Regional humid heatwave events. To elucidate the physical processes underlying large-scale humid heatwaves, we conduct a regional composite analysis for multiple regions: South Asia, Western Asia, northern South America, eastern Europe, northeastern Asia, and the southeastern United States. For each terrestrial region, we calculate the daily anomaly of wet-bulb temperature averaged over the region. Regional humid heatwave events are identified when the regional wet-bulb temperature anomaly exceeds the 90th-percentile threshold during the summer season. Specifically, approximately 387 days are identified from a total of 3,864 summer days for each

region. Differences in physical variables are calculated by comparing the mean of the selected days and the climatology of all days, and statistical significance is assessed using a Student's *t*-test. The composite results are presented in Figs. 3c–e and Extended Data Figs. 3–5.

Numerical model experiments. We have designed numerical model experiments using the Community Earth System Model (CESM) version 2.1.5⁴⁰. The atmospheric model used in the CESM is the Community Atmosphere Model version 6 (CAM6)⁴⁰ with a finite-volume dynamical core, a nominal 1° horizontal resolution ($0.9^\circ \times 1.25^\circ$), and 32 vertical hybrid levels. The experiments used historical SST and sea ice forcings, which were 2005–2015 climatological mean from the NOAA Optimum Interpolation SST version 2⁴⁷. We conducted three model experiments: 1) a control run (CTL) forced by climatological SST; 2) a sensitivity run (NIO_warming) forced by prescribing SST anomalies during June–July–August in the North Indian Ocean (0° – 30° N, 48° – 99° E; Fig. 4d) derived from the composite analysis of regional humid heatwaves over South Asia (Fig. 3c); and 3) a sensitivity run (TNA_warming) forced by prescribing SST anomalies in the tropical North Atlantic (6° – 20° N, 69° – 40° W; Extended Data Fig. 4d) derived from the composite analysis of regional humid heatwaves over northern South America (Extended Data Fig. 4a). The model integrated 30 years, with the first 10 years excluded as a spin-up period, and the results of final 20 years were analyzed. The anomalies in the NIO_warming (TNA_warming) simulation relative to the CTL simulation are presented in Figs. 4d–f (Extended Data Figs. 4d–f).

Sensitivity test in network results. To investigate the phase synchronization between

terrestrial humid heatwaves and adjacent oceanic warming, we use the Hilbert-transformed time series of wet-bulb temperature and SST. The complex correlation coefficient is calculated between each pair of grid cells. Strong links are identified using different thresholds (i.e., 0.2, 0.3, and 0.4) for computing the distance distribution. We find that the local phase synchronization is dominant (see Supplementary Fig. S2), which is consistent with the patterns obtained from the networks based on event coincidence analysis (Figs. 1b and 3b).

Cluster coefficients. The cluster coefficients ($<2,000$ km) of HW–HW networks are also calculated (see Supplementary Fig. S3). The spatial distribution of the cluster coefficients resembles that of large-scale aggregation except for the polar region (Supplementary Fig. S3 versus Fig. 1a), with high values in southern Australia, South Asia, the Maritime continent, tropical Africa, southern part of South America. Well-clustered extremes in a relatively small group over Greenland and the Arctic regions may be attributed to phase-locked Rossby waves; However, these patterns do not connect a substantial number of grid points within 2,000 km, resulting in relatively low spatial aggregation in these regions.

Data Availability

The dataset of ERA5 single-level and multi-level variables are provided at <https://doi.org/10.24381/cds.adbb2d47> and <https://doi.org/10.24381/cds.bd0915c6>, respectively. The OISST dataset is provided at <https://psl.noaa.gov/data/gridded/data.noaa.oisst.v2.highres.html>. The outputs of

CMIP6 simulations could be freely obtained from <https://esgf-node.llnl.gov/search/cmip6/>. The processed data generated in this study are available in the Zenodo database: <https://zenodo.org/records/18086860>.

Code Availability

The code used to generate the results of this study is available at https://github.com/FenyngCai/humid_heatwaves_ocean_networks/. The CESM code is publicly available at <https://github.com/ESCOMP/CESM>.

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