

Regional thermodynamic constraints on nighttime temperatures during heatwaves: heat retention under humid conditions and stronger cooling under dry conditions

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Research Article

Keywords: heatwave, warm night, nighttime minimum temperature, dew-point temperature, vapour pressure deficit, downward longwave radiation

Posted Date: September 15th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-11010756/v1>

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Additional Declarations: No competing interests reported.

1 Regional thermodynamic constraints on nighttime temperatures
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7 **Acknowledgements**

8 We thank the NOAA Physical Sciences Laboratory for providing CPC temperature data, and ECMWF
9 and NSF NCAR for providing ERA5 reanalysis data and related data services.

10 **Abstract**

11 Severe daytime heatwaves often come with warm nights, but it remains unclear whether the same
12 thermodynamic conditions limit nighttime cooling across regions. We compared 158 severe heatwaves
13 with seasonally matched non-heatwave periods in Europe, East Asia, Australia, and southern South
14 America during 1985–2024 using NOAA Climate Prediction Center (CPC) daily temperature and ERA5
15 hourly data. During days 0–5 after onset, regional-mean minimum temperature increased by 0.613–1.639
16 °C in all four regions, and land area above the local 90th (P90) and 95th (P95) percentiles of daily
17 minimum temperature also increased. Of 20 prespecified hourly links, only two met all false-discovery-
18 rate, same-year, bootstrap, and blocked-validation criteria. Higher onset dew point was followed by
19 stronger maintenance-period nighttime downward longwave radiation in Europe and East Asia, while
20 higher maintenance-period vapour pressure deficit (VPD) was associated with stronger nighttime cooling
21 in Australia and southern South America. In targeted follow-up tests, onset dew point predicted higher
22 day 4–5 ERA5 and CPC minimum temperature but not P90 warm-night area, whereas higher VPD
23 predicted lower minimum temperature and smaller P90 warm-night area. Held-out error decreased by
24 13.6–14.5% for the northern temperature models and 17.3% for the southern P90-area model. Similar
25 warm-night increases therefore do not imply the same local thermodynamic process: humid conditions
26 are more consistent with heat retention in Europe and East Asia, while drier conditions are linked to
27 stronger nighttime cooling in Australia and southern South America.

28 Keywords: heatwave; warm night; nighttime minimum temperature; dew-point temperature; vapour
29 pressure deficit; downward longwave radiation

30 **1 Introduction**

31 Heatwaves are becoming more frequent, longer, and more intense across many land regions, although
32 the size of the change differs from place to place (Perkins 2015; Perkins-Kirkpatrick and Lewis 2020).
33 Background warming shifts temperature distributions toward higher values (Domeisen et al. 2023).

Individual heatwaves also depend on atmospheric circulation. Blocking and subsidence, for example, can reduce ventilation and help regional heat persist (Pfahl and Wernli 2012; Horton et al. 2015).

High daytime temperature and weak nighttime cooling are different parts of heatwave severity. Warm nights extend heat exposure through the full day-night cycle and can carry heat into the next day (Wang et al. 2020; Wu et al. 2023). Because absolute minimum temperature depends on latitude, elevation, and background climate, local percentile thresholds are useful for comparing regions (Perkins and Alexander 2013). Warm-night area therefore provides a common measure of nighttime heat extent without assuming that every region reaches it through the same local conditions.

Previous studies often describe two broad local thermodynamic settings. In humid conditions, more near-surface water vapour and stronger downward longwave radiation can limit nighttime cooling (Wu et al. 2023). In drier conditions, less water is available for evaporation, more surface energy can go into sensible heating, and boundary-layer temperature and vapour pressure deficit can increase (Fischer et al. 2007; Seneviratne et al. 2010; Miralles et al. 2014). These settings are not mutually exclusive, and their importance can change with heatwave stage and regional background climate (Teuling et al. 2010; Hirsch and King 2020; Maraun et al. 2025).

Recent studies have grouped heatwave environments by surface-energy balance or moisture conditions (Tian et al. 2024; Saha et al. 2026). Two questions remain important here. First, do different regions show a similar increase in warm nights during severe heatwaves? Second, can moisture, radiation, or dryness relations seen in one region carry over to minimum temperature several days later and keep the same direction across time? Answering the second question requires hourly diagnostics for local nighttime and an independent daily minimum-temperature product, rather than only concurrent daily means or composites.

We use matched events from four continental regions to answer two main questions. First, are severe daytime heatwaves accompanied by higher nighttime minimum temperature and larger warm-night area in all four regions? Second, among 20 prespecified hourly links, which local variables are related to later nighttime conditions and still predict minimum temperature or warm-night area on days 4–5 after the preceding evening temperature is controlled? After these main tests, we use the first principal component (PC1) to summarize how dew point, downward longwave radiation, sensible-heat fraction, and VPD vary together, and to describe regional differences in that thermodynamic background. Event-control differences are treated as paired observational contrasts, not treatment effects. PC1 and the related clustering are exploratory and are not used to select the main links.

2 Data and methods

2.1 Study regions and analysis design

The analysis covers 1985–2024, with 1991–2020 as the threshold reference period. Four fixed regions and warm seasons are used: Europe (35°–70°N, 10°W–40°E) and East Asia (20°–55°N, 100°–145°E) from May to September; Australia (10°–45°S, 110°–155°E) and southern South America (15°–55°S,

285°–325°E, equivalent to 75°W–35°W) from November to March. Southern Hemisphere warm seasons are indexed by the year in which they end. Climate Prediction Center (CPC) regional metrics use valid land grid cells with cosine-latitude weights. ERA5 regional means use cosine latitude multiplied by the fractional land-sea mask, with weights renormalized over valid cells within each fixed region. The regional aggregation and binary-land-mask sensitivity are described below.

Fig. 1 shows the locations, coordinate bounds, warm seasons, and severe-heatwave sample sizes of the four study regions.

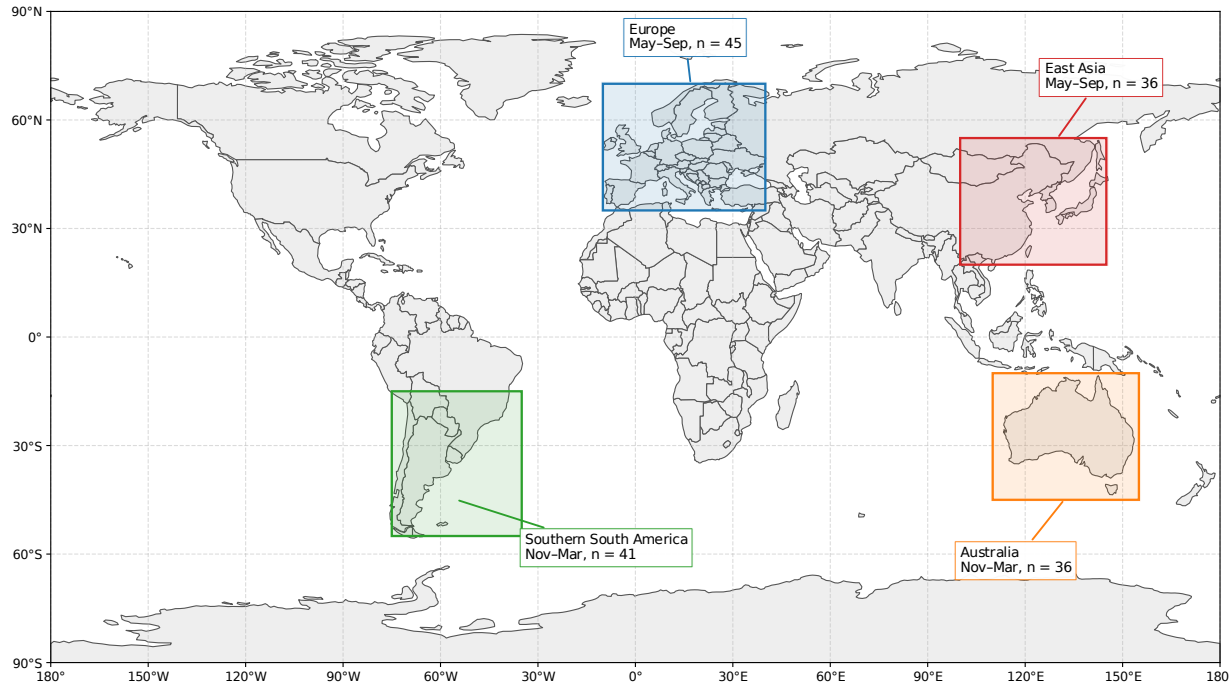


Fig. 1 Study regions and severe-heatwave sample sizes. Boxes show the four fixed study regions: Europe, East Asia, Australia, and southern South America. Warm seasons and numbers of severe heatwave events are indicated in the figure. Exact geographic bounds are given in Sect. 2.1.

The analysis has four steps. First, event-control differences are used to compare nighttime temperature and regional thermodynamic background. Second, 20 prespecified hourly links are tested in their time order. Third, only the two supported links are carried forward to tests of day 4–5 minimum temperature and warm-night area, including whether they reduce held-out error after preceding evening temperature, year, and region are controlled. Fourth, after the main results are known, PC1 is used to summarize common variation among four thermodynamic variables; regional slopes, clustering, and event evolution are kept as exploratory analyses.

The matched comparisons and the 20-link hourly audit use the same fixed set of 158 event-control pairs. N03 and S04 were identified by the hourly audit. The day 4–5 window and pass criteria were fixed before the follow-up models were run, but after N03 and S04 were known. This step is therefore a targeted follow-up, not an independently preregistered experiment. PC1 and clustering are interpreted as descriptive, exploratory results. Unsupported links, significant regional differences, and threshold-area results that fail the preset rule are all retained.

2.2 Data

The NOAA Climate Prediction Center Global Unified Temperature dataset provides 0.5° daily maximum and minimum temperature for heatwave and warm-night identification (NOAA Physical Sciences Laboratory n.d.). ERA5 provides 2 m air temperature and dew-point temperature, total-column water vapour, vertically integrated moisture transport, moisture-flux convergence, cloud fraction, layer-2 soil moisture, turbulent heat fluxes, and downward shortwave and longwave radiation (Hersbach et al. 2020). ERA5 surface sensible and latent heat fluxes are multiplied by -1 so that upward turbulent fluxes are positive; downward radiative fluxes keep their native positive sign.

The time-invariant ERA5 fractional land-sea mask comes from the 0.25° NSF National Center for Atmospheric Research (NCAR) archive (European Centre for Medium-Range Weather Forecasts 2019). Grid coordinates are checked explicitly against the mask for every variable. The 0.5° fields use coincident points from the 0.25° mask; this is nested-coordinate sampling, not conservative regridding of area means. Regional weights are $\cos(\text{latitude}) \times \text{land fraction}$ and are normalized over valid cells. The binary-mask sensitivity treats cells with land fraction ≥ 0.5 as land. Effective area and spatial coverage are reported in Online Resource 1, Table S7.

The archived daily ERA5 fields average 00, 06, 12, and 18 UTC samples and are used to describe regional thermodynamic background and the exploratory axis. The hourly-link audit uses complete hourly single-level fields on the native 0.25° grid and fixed-grid 850 hPa fields from relative day -7 to $+5$. Local solar time is calculated at each grid cell. Nighttime is defined as 18:00–06:00 local solar time and assigned to the date on which the night ends. Accumulated fluxes are converted to hourly rates from fixed forecast cycles. Hourly diagnostics and four-sample daily diagnostics are used for different analyses and are not mixed. Table 1 summarizes the data sources, event samples, and role of each product.

Table 1 Fixed data sources, event definitions, and analysis roles

Component	Definition or source	Period / window	Analysis role
Temperature	NOAA CPC 0.5° daily Tmax and Tmin	1985–2024; reference 1991–2020	Heatwave identification and warm-night metrics
Thermodynamic background	ERA5; fractional land $\times$ cosine-latitude weights; four UTC samples per day	Days -20 to $+10$	Paired background and exploratory PC1
Hourly process fields	ERA5 0.25° surface fields and fixed-grid 850 hPa fields; local solar time	Days -7 to $+5$	Nighttime radiation, cooling, and 20 prespecified tests
Severe-event sample	Upper within-region quartile of cumulative area-days	158 event-control pairs	Fixed sample for matched comparisons and main hourly audit
Controls	Same region and similar warm-season timing; no heatwave from day -7 to $+10$	126 same-year; 32 cross-year	Matched comparison and same-year sensitivity

Component	Definition or source	Period / window	Analysis role
Day 4–5 outcomes	ERA5 local-night minimum; CPC Tmin and P90 area	Nights/days 4–5	Continuous minimum temperature and P90 warm- night-area tests

Note. Tmax and Tmin denote daily maximum and minimum temperature, respectively. P90 denotes the local calendar-day 90th percentile.

2.3 Heatwaves, warm nights, and matched controls

Grid-cell heatwave thresholds are the local calendar-day 90th percentile of NOAA CPC daily maximum temperature, estimated over 1991–2020 with a 15-day moving window. Leave-one-year-out estimation is used within the reference period. A regional heatwave day requires at least 10% of valid land area to exceed the local threshold, and at least three consecutive regional heatwave days define a P90-D3 heatwave (Perkins and Alexander 2013). We identify 625 eligible events and retain events in the upper within-region quartile of cumulative area-days, including ties. This gives 158 severe heatwaves: 45 in Europe, 36 in East Asia, 36 in Australia, and 41 in southern South America. Severe-event selection uses only daytime heatwave area and duration.

Each heatwave is anchored at onset (day 0) and matched to a non-heatwave period in the same region with similar warm-season timing and no regional heatwave from relative day –7 through +10. Same-year controls within ± 45 seasonal days are preferred and provide 126 pairs. The remaining 32 events use controls from other years within 7 seasonal days. These 32 pairs are retained in the 158-pair descriptive and exploratory analyses, while a 126-pair same-year analysis checks sensitivity to cross-year matching. Warm nights use the local calendar-day P90 of NOAA CPC daily minimum temperature. The main outcome is the regional land fraction above that threshold during days 0–5. P95, area-duration combinations, and a days 0–10 window are sensitivity checks; the daytime heatwave sample is not reidentified. The fixed north-minus-south regional contrasts keep the same direction in the days 0–5 and 0–10 windows, although the extended-window downward-longwave interval crosses zero ($q=0.0760$; Online Resource 1, Fig. S1).

2.4 Event-control variables and phase definitions

Event-relative time is divided into four phases: background (days –20 to –8), preconditioning (–7 to –1), onset (0 to 2), and maintenance (3 to 5). For event-control pair i , variable X , and phase p , the paired difference is

$$\Delta X_{i,p} = \overline{X}_{i,p}^{event} - \overline{X}_{i,p}^{control} \quad (1)$$

The overbar denotes the phase mean. A positive value means that X is higher during the heatwave event than during its matched control, in the original unit of X .

The daily sensible-heat fraction is calculated only when the regional daily mean upward sensible plus latent heat flux exceeds 10 W m^{-2} :

$$f_{H,i,d} = \frac{H_{i,d}}{H_{i,d} + LE_{i,d}} \quad (2)$$

Here H and LE are land-weighted regional means of upward sensible and latent heat flux, and d is the event-relative day. The ratio is calculated day by day for both the event and control, then averaged over the phase, and finally differenced using Eq. (1). It is therefore neither a ratio of phase-mean fluxes nor a mean of grid-cell ratios. Vapour pressure deficit (VPD) is also calculated first at the original grid cell and sampled time, before temporal and spatial averaging:

$$\begin{aligned} v_{g,d,\tau} &= \max\{0, e_s(T_{g,d,\tau}) - e_s(T_{dew,g,d,\tau})\} \\ e_s(x) &= 0.6108 \exp\left(\frac{17.27x}{x + 237.3}\right) \\ VPD_{r,d} &= \frac{\sum_{g \in r} w_g \frac{1}{4} \sum_{\tau \in U} v_{g,d,\tau}}{\sum_{g \in r} w_g}, \quad w_g = \cos(\varphi_g) f_g \end{aligned} \quad (3)$$

In Eq. (3), v is vapour pressure deficit at one grid cell and time; g , r , and d index grid cell, region, and day; τ is the sampled UTC time; T is 2 m air temperature; and the subscript dew denotes dew-point temperature. Temperatures are converted from kelvin to °C. The saturation-vapour-pressure function $e_s(x)$ follows Allen et al. (1998), with pressure in kPa. U contains 00, 06, 12, and 18 UTC; f is the fractional land mask, φ is latitude, and w is the land-area weight. Only valid land-weighted cells are used. VPD is therefore calculated at each grid cell, averaged over the four times, and then land-weighted across the region. It is not calculated from regional-mean air and dew-point temperature. VPD describes atmospheric moisture demand, not soil dryness.

2.5 Prespecified hourly links and the day 4–5 temperature test

We prespecified 20 hourly links in three branches: humid-radiative, dry-sensible, and 850 hPa dynamical. Models use standardized event-control differences, control for year and region, and include region $\times$ predictor interactions. Uncertainty is estimated with heteroskedasticity-consistent type 3 (HC3) covariance. The fixed 20-test family is adjusted with the Benjamini–Hochberg false discovery rate (FDR) procedure (Benjamini and Hochberg 1995). A link is called robust only if it remains supported in the same-year refit, 5000 region-stratified event bootstraps, 5000 season-year cluster bootstraps, and three blocked time validations. N03 tests onset dew-point temperature against maintenance local-night downward longwave radiation in Europe and East Asia. S04 tests maintenance daytime VPD against maintenance nocturnal cooling in Australia and southern South America.

Only N03 and S04 are carried forward to the day 4–5 nighttime test. In Europe and East Asia, days 0–2 dew point predicts night-minimum temperature for nights ending on days 4–5. In Australia and southern South America, daytime VPD on days 3–4 predicts the following nights ending on days 4–5. Each model controls for year, region, the immediately preceding evening temperature, and the prespecified branch covariate; interactions of predictor and control variables with region are retained. The two branches are each tested against ERA5 night-minimum temperature, independent CPC minimum temperature, and CPC P90 warm-night area, giving six tests. A link passes only if the full and same-year

samples pass the six-test FDR family, both bootstrap schemes support the expected direction, the regional interaction is not significant, pooled held-out RMSE improves by more than 2%, and at least two time blocks improve. Earlier four-UTC-sample daily local relations are kept in Online Resource 1, Table S4 as an exploratory sensitivity and are not used to select N03 or S04.

2.6 Exploratory thermodynamic axis

To place the two main links in a broader thermodynamic background, the exploratory analysis uses four variables: onset dew-point temperature, maintenance downward longwave radiation, onset sensible-heat fraction, and maintenance VPD. The first two represent the more humid-radiative side and the last two the drier-sensible side. The four event-control differences are standardized across the 158 pairs and then entered into principal component analysis (PCA). These four features were chosen after the main hourly results were known, to summarize the sample background; they were not used to select N03 or S04. For pair i ,

$$P_i = \sum_{j=1}^4 l_j z_{i,j}; \quad S_i = \frac{P_i - \bar{P}}{s_P} \quad (4)$$

Here j indexes the four features, z is the feature difference standardized by the mean and sample standard deviation of the 158 pairs (denominator $n-1$), and l is the unit-length first-component loading vector. P is the unscaled first principal component (PC1) score, $\bar{P}$ and s_P are its sample mean and standard deviation, and S is the score in standard-deviation units. For easier interpretation, the whole loading vector is sign-flipped if needed so that its dot product with $(1, 1, -1, -1)$, in the listed feature order, is positive. Individual loadings are not flipped separately. The positive PC1 direction therefore broadly corresponds to higher dew point and downward longwave radiation and lower sensible-heat fraction and VPD, although every training subset is not forced to keep the same four signs. Warm-night area is not used in PCA or clustering. Because feature selection occurred after the main results were known, this analysis is interpreted as exploratory.

The k-means groups and their event-relative evolution do not determine any main result. Grouping methods, stability checks, and event-evolution plots are moved to Online Resource 1. They are used only to show whether a hard classification mainly reflects regional composition, not to define universal heatwave types.

PC1 time-block and leave-one-region-out consistency checks are also kept as exploratory robustness results in Online Resource 1. The time blocks are 1986–2010, 2011–2018, and 2019–2024. These checks assess whether the thermodynamic axis is stable; they are not independent prediction or causal evidence. Leave-one-region-out and time-block consistency results are given in Online Resource 1, Table S5, and the fixed spatial-mask and dew-point/VPD deletion sensitivities are given in Online Resource 1, Table S3.

2.7 Exploratory relation between the thermodynamic axis and warm-night area

To test whether the relation between PC1 and warm-night area is regionally consistent, the exploratory analysis first estimates a pooled trend with ordinary least squares and HC3 covariance, then adds PC1 $\times$ Region interactions to test whether regional slopes differ (MacKinnon and White 1985):

$$\Delta WN_i = \alpha + \beta S_i + \gamma Year_i + \sum_{r=2}^4 \delta_r I_{i,r} + \varepsilon_i \quad (5)$$

Here i indexes event-control pairs, ΔWN is the event-minus-control P90 warm-night area during days 0–5, S is PC1 in standard-deviation units, $Year$ is standardized warm-season year, and I is a region indicator. The pooled coefficient is used only to summarize the current sample and does not assume a common regional slope. Overall and within-region Spearman correlations are descriptive checks. Full-refit bootstrap and same-year results are reported in Online Resource 1. The two full-refit bootstrap results are in Online Resource 1, Table S1, and region-specific Spearman correlations are in Online Resource 1, Table S6.

Blocked validation compares a Year + Region model with a Year + Region + PC1 model. Each training fold supplies its own standardization parameters, PCA loadings, and regression coefficients before the held-out observations are predicted. Root-mean-square error (RMSE) is calculated across all held-out observations. This measures out-of-sample error change, not external validation or forward forecasting (Roberts et al. 2017; Online Resource 1, Table S2).

Regional differences are tested directly with PC1 $\times$ Region interactions. The model keeps region intercepts and a common year coefficient. A three-degree-of-freedom HC3 Wald F test evaluates whether the four regional slopes are equal, and all regional slopes and pairwise contrasts are reported; the pairwise contrasts form a separate Benjamini–Hochberg family. This analysis was carried out after the main hourly results were known and is exploratory. Full results are in Online Resource 1, Table S8.

2.8 Software and reproducibility

Analyses used Python 3.12.14, NumPy 2.5.2, pandas 3.0.5, SciPy 1.18.0, statsmodels 0.14.6, xarray, and Matplotlib. The random seed for the 20-link hourly audit is 20260904, and the seed for the day 4–5 follow-up is 20260908. All 3588 hourly input files passed the integrity checks. The derived local-day table contains 3741 unique region-date records, and the event-control table contains 158 pairs. The two follow-up bootstrap schemes produced 180000 stored slope estimates with no failed repetitions. Input identities, processing parameters, and SHA-256 hashes are retained with the outputs. OpenAI ChatGPT and Codex were used to assist with manuscript editing, code development and inspection, data-processing checks, and reproducibility review. The source observations and ERA5 fields were not AI-generated; all statistical estimates were produced by the documented scripts and reviewed by the author. The derived data, analysis outputs, and reproducible code are archived on Zenodo (Tang 2026).

3 Results

3.1 Severe heatwaves have warmer nights and larger warm-night area in all four regions

Fig. 2 first compares severe daytime heatwaves with matched non-heatwave periods. The result is straightforward: during days 0–5 after heatwave onset, regional-mean minimum temperature is higher in all four regions, by 0.613–1.639 °C (Fig. 2a). P90 and P95 warm-night area also increase, and the region-stratified 95% bootstrap intervals exclude zero in all four regions (Fig. 2b,c). The event-control difference in occurrence is also positive under the P90 A10-D3, P95 A10-D3, and P90 A10-D5 definitions (Fig. 2d–f). Thus, all four regions show stronger nighttime heat during severe daytime heatwaves. These paired differences show that the event and control periods differ; they do not show that daytime heat directly caused the nighttime anomaly or that all four regions share one local thermodynamic process.

When the definition is tightened to P90 A20-D3, the four regions are no longer fully consistent. A20 means that at least 20% of regional land area reaches the P90 warm-night threshold; the Australian interval includes zero. A positive response under the main definitions therefore does not mean that every area-duration definition gives the same result.

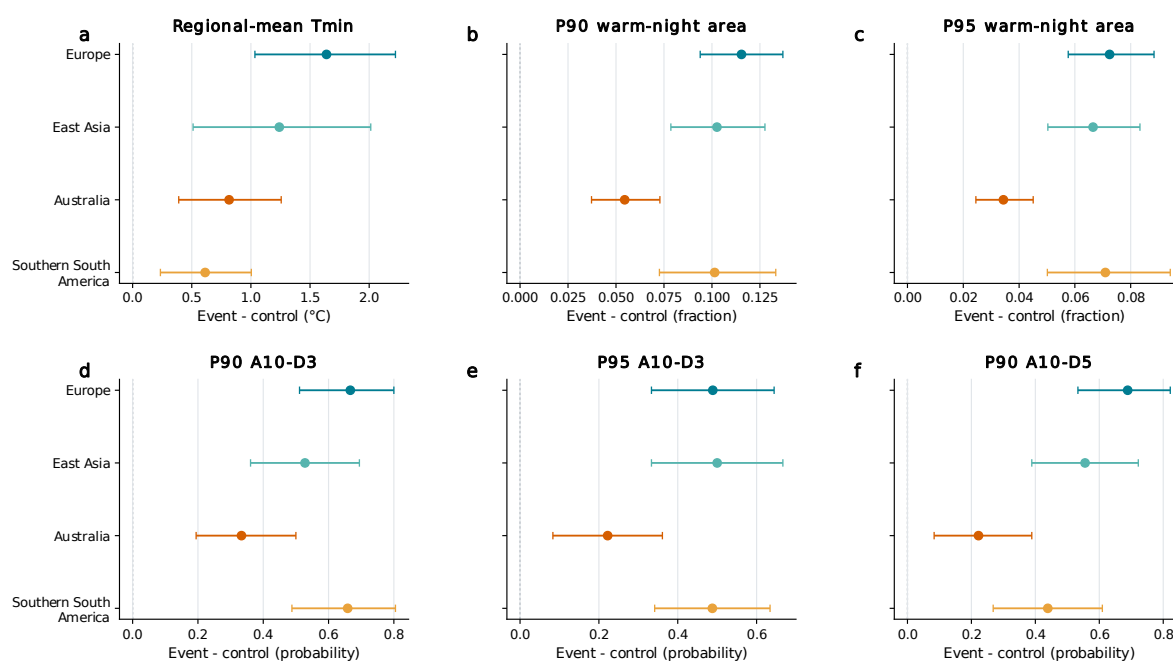


Fig. 2 Nighttime-temperature differences between severe heatwaves and matched non-heatwave periods, with sensitivity tests. Event-minus-control differences are shown for (a) regional-mean daily minimum temperature, (b) local P90 warm-night area, (c) local P95 warm-night area, (d) P90 A10-D3 occurrence, (e) P95 A10-D3 occurrence, and (f) P90 A10-D5 occurrence. Points are regional means and horizontal bars are region-stratified bootstrap 95% confidence intervals. A10 means that at least 10% of regional land area reaches the threshold; D3/D5 require at least 3/5 consecutive qualifying days within days 0–5. All panels use the same severe daytime-heatwave sample. P90 and P95 are the local 90th and 95th percentiles of daily minimum temperature

3.2 Higher dew point is followed by stronger nighttime longwave radiation in Europe and East Asia, while higher VPD is linked to stronger nighttime cooling in Australia and southern South America

In Europe and East Asia, higher onset dew point is followed by stronger maintenance-period local-night downward longwave radiation (Fig. 3a, N03). The standardized slopes are 0.215 and 0.239, respectively; the FDR q value for the 20-test family is 1.13×10^{-24} , the same-year q value is 2.61×10^{-15} , and the region interaction is $P=0.859$. Adding dew point reduces pooled held-out RMSE by 3.63%, with improvement in two of the three time blocks. Both bootstrap schemes support a positive mean slope across the two regions. The Europe-only HC3 interval crosses zero, so the single-region estimate is less precise there. The regional point estimates are close and the interaction is not significant, so the data do not support different slopes between Europe and East Asia.

In Australia and southern South America, higher maintenance daytime VPD is associated with stronger nighttime cooling during the same phase (Fig. 3a, S04). The standardized slopes are 0.820 and 0.840, respectively; the FDR q value for the 20-test family is 2.21×10^{-30} , the same-year q value is 2.78×10^{-27} , and the region interaction is $P=0.920$. Adding VPD lowers pooled held-out RMSE in all three time blocks, by 41.55% overall. Thus, in these two regions, higher VPD is linked to stronger nighttime heat loss rather than stronger warm nights. None of the 20 tested links forms a stable chain from upstream conditions to CPC P90 warm-night area, and the 850 hPa branch is not supported as a common four-region pathway.

3.3 Dew point predicts higher day 4–5 minimum temperature in Europe and East Asia, while VPD predicts lower minimum temperature in Australia and southern South America

In Europe and East Asia, onset dew point still predicts higher day 4–5 nighttime minimum temperature after the preceding evening temperature and onset cloud fraction are controlled (Fig. 3b,d). Standardized slopes for ERA5 night minima are 0.266 in East Asia and 0.277 in Europe; slopes for independent CPC Tmin are 0.289 and 0.279. For both temperature outcomes, the six-test FDR q values are below 1.2×10^{-7} and the same-year q values are below 9.8×10^{-6} ; the region interactions are not significant ($P=0.911$ and 0.929). Adding dew point reduces pooled held-out RMSE by 14.50% for ERA5 and 13.57% for CPC, with improvement in all three time blocks.

The northern dew-point relation does not extend to P90 warm-night area (Fig. 3c,d). The East Asian and European slopes have opposite signs, the six-test FDR q value is 0.550, and adding dew point increases pooled held-out RMSE by 0.67%. Dew point therefore contains information about later continuous minimum temperature, but not about how much land area crosses the P90 warm-night threshold.

In Australia and southern South America, higher VPD on days 3–4 predicts lower ERA5 and CPC minimum temperature on days 4–5 (Fig. 3b,d). ERA5 standardized slopes are -0.913 and -0.469 , and CPC slopes are -0.888 and -0.510 , respectively. FDR correction, the same-year sample, both bootstrap

schemes, and held-out prediction support the negative direction, but the regional interactions are significant ($P=0.0026$ and 0.0169). The direction is the same in both regions, while the continuous-temperature response is larger in Australia.

The VPD relation with P90 warm-night area meets all preset criteria (Fig. 3c,d). Standardized slopes are -0.500 in Australia and -0.591 in southern South America; the six-test FDR q value is 0.000325 , the same-year q value is 0.00254 , and the region interaction is $P=0.788$. Pooled held-out RMSE improves in all three time blocks, by 17.31% overall. The Australia-only HC3 interval crosses zero, so the single-region evidence is clearer in southern South America. Overall, the northern and southern region pairs differ not only in the direction of the relation but also in which nighttime-temperature metric carries the strongest signal.

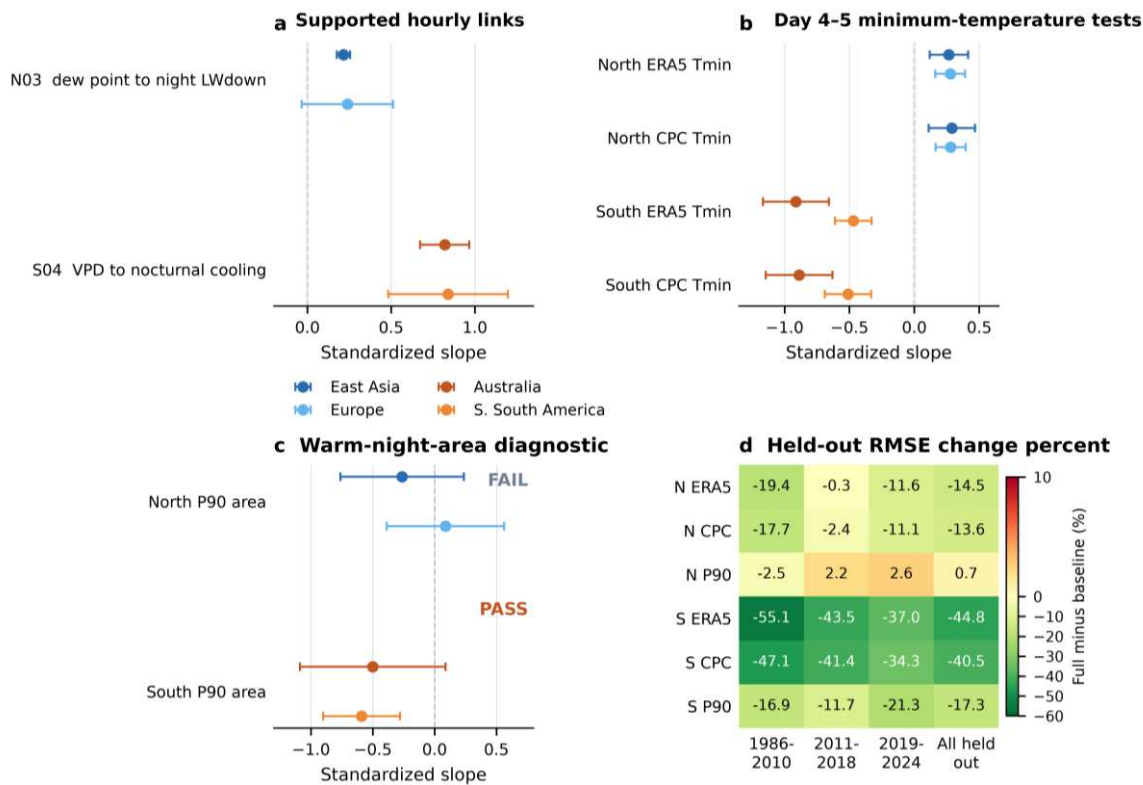


Fig. 3 The two main hourly links and their translation to day 4–5 nighttime temperature. (a) Region-specific standardized slopes and HC3 95% intervals for the two links supported by the 20-test hourly audit: N03, onset dew point to maintenance nighttime downward longwave radiation; and S04, maintenance VPD to nocturnal cooling. (b) Slopes for day 4–5 ERA5 local-night minimum temperature and independent CPC daily minimum temperature. (c) CPC P90 warm-night-area results. (d) RMSE change relative to the fixed baseline in each time block and across all held-out observations; negative values mean lower error. Predictors are standardized within region, and models control for year, region, preceding evening temperature, and the prespecified branch covariate. The Europe–East Asia dew-point relation passes the continuous-temperature test but not the P90-area test. The Australia–southern South America continuous-temperature slopes share a direction but differ in magnitude, while the P90-area relation meets all preset criteria. These are observational associations and held-out predictions, not causal effects

Table 2 summarizes the key effect sizes and statistical limits for the two main hourly links and the day 4–5 results.

Table 2 Main results and their statistical limits

Main result	n	Estimate	Main statistical result	Interpretation
P90 warm-night area in all four regions	158	Positive in all four regions	Region-bootstrap 95% intervals all exclude zero	Warm nights intensify in all four regions
Europe and East Asia: dew point → nighttime downward longwave (N03)	81	East Asia 0.215; Europe 0.239	20-test FDR $q=1.13 \times 10^{-24}$; held-out RMSE -3.63%	Same direction; Europe-only interval crosses zero
Australia and southern South America: VPD → nocturnal cooling (S04)	77	Australia 0.820; southern South America 0.840	20-test FDR $q=2.21 \times 10^{-30}$; held-out RMSE -41.55%	Higher VPD is linked to stronger cooling in both regions
Europe and East Asia: day 4–5 T _{min}	81	ERA5 0.266/0.277; CPC 0.289/0.279	Both temperature outcomes $q<1.2 \times 10^{-7}$; held-out RMSE $-14.50\%/-13.57\%$	T _{min} supported; P90 area not supported
Australia and southern South America: P90 area	77	Australia -0.500 ; southern South America -0.591	$q=0.000325$; held-out RMSE -17.31%	Meets preset rule; Australia-only interval crosses zero

Note. Slopes are standardized within each model sample. N03 and S04 come from the prespecified 20-link hourly audit. The day 4–5 follow-up uses a six-test FDR family. Negative RMSE change means lower held-out error. CPC P90 is the local calendar-day 90th percentile of daily minimum temperature. All reported relations are observational associations or prediction results and do not establish causal mediation.

3.4 The exploratory thermodynamic axis overlaps across regions, but the warm-night relation is not the same

After the main hourly tests, Fig. 4 uses the same four variables to summarize the thermodynamic background of the sample. Onset dew point and maintenance downward longwave radiation load positively on PC1, while onset sensible-heat fraction and maintenance VPD load negatively. PC1 explains 59.8% of the standardized variance (Fig. 4a). Regional scores overlap substantially. Australia extends furthest toward the lower-score, drier-sensible end, while Europe and East Asia are more concentrated toward higher scores (Fig. 4b).

Further exploratory analysis shows that the PC1–P90 warm-night-area slopes differ across regions (HC3 Wald $P=0.0000561$; Online Resource 1, Table S8), so the main text no longer emphasizes one pooled regression line. The k-means groups are also strongly shaped by regional composition: 18 of the 20 low-score events are Australian, so they cannot define a stable cross-region heatwave type. The pooled relation, grouping results, and event-relative evolution are therefore kept in Online Resource 1. The descriptive k-means grouping and pooled PC1–warm-night relation are shown in Online Resource 1, Fig. S2, and the event-relative evolution of the descriptive groups is shown in Online Resource 1, Fig. S3.

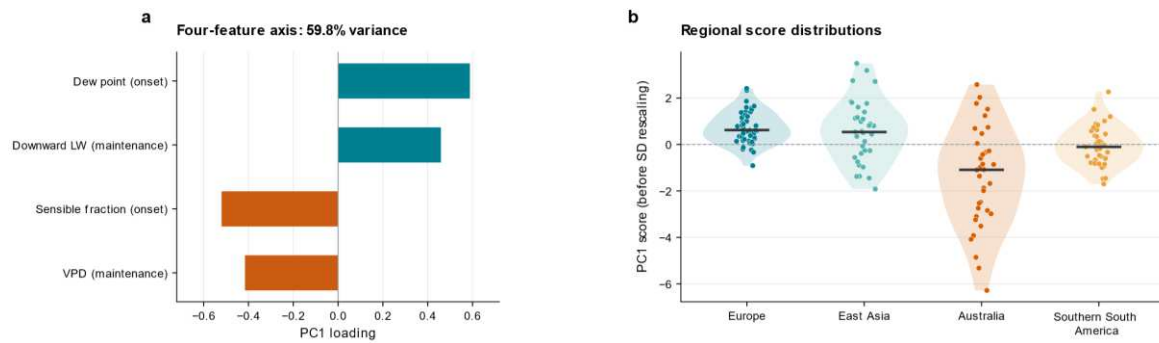


Fig. 4 Loadings and regional distribution of the exploratory thermodynamic axis. (a) PC1 loadings for four standardized event-control variables: onset dew point, maintenance downward longwave radiation, onset sensible-heat fraction, and maintenance VPD. Onset is days 0–2 and maintenance is days 3–5; PC1 explains 59.85% of the variance. (b) Unscaled PC1 scores for the four regions; points are events, density shapes show the distributions, and horizontal marks are medians. PC1 was constructed after the main hourly results were known to summarize sample thermodynamic background; it was not used to select N03 or S04. Regional PC1–P90 slopes, k-means groups, and event evolution are reported in Online Resource 1

4 Discussion

4.1 Warm nights intensify in all four regions, but the local thermodynamic constraints differ

All four regions show the same broad temperature outcome: severe daytime heatwaves have higher nighttime minimum temperature and larger warm-night area. The hourly analysis, however, does not identify one local thermodynamic relation that applies to all four regions. In Europe and East Asia, higher dew point is linked to higher continuous minimum temperature several days later. In Australia and southern South America, higher VPD is linked to stronger nighttime cooling, lower day 4–5 minimum temperature, and smaller warm-night area. Treating either relation as a global mechanism would go beyond the evidence. The more defensible interpretation is that heat retention under humid conditions and stronger cooling under drier conditions represent different regional constraints.

The exploratory PC1 is used only to show how four thermodynamic variables vary together and how the regions are distributed along that axis. Because regional slopes differ, PC1 cannot replace the main hourly relations or serve as a common predictor for all four regions. The main evidence still comes from the prespecified hourly links, the independent CPC minimum-temperature product, and held-out results across time blocks.

4.2 Europe and East Asia: dew point is consistently linked to later minimum temperature, but not to P90 warm-night area

Europe and East Asia show two results with the same direction but different evidence levels. Higher onset dew point is followed by stronger maintenance nighttime downward longwave radiation, and onset dew point also predicts higher minimum temperature on days 4–5 after the preceding evening temperature and onset cloud fraction are controlled. ERA5 and independent CPC minimum temperature agree in direction, and held-out error decreases in all three time blocks. Previous work shows that humid near-surface air and stronger downward longwave radiation often occur together with weaker nighttime cooling (Wu et al. 2023), so our result is consistent with the physical idea that humid air can help retain

nighttime heat. However, the full link from downward longwave radiation to later cooling is not supported here, so downward longwave radiation should not be described as an identified complete mediator.

Dew point predicts continuous minimum temperature but not P90 warm-night area, and these results are not contradictory. Regional minimum temperature mainly describes the overall nighttime temperature level. P90 warm-night area also depends on how many land grid cells cross their own local calendar-day thresholds, how far each cell lies from its threshold, and whether warming is spatially coherent enough to push many cells across it. A higher regional-mean temperature therefore does not have to produce a larger threshold-exceedance area. The Europe-only HC3 interval for N03 crosses zero, which means the European estimate is less precise. But the European and East Asian point estimates are similar and their interaction is not significant, so the current data do not support the claim that the pooled relation is mainly driven by East Asia.

4.3 Australia and southern South America: VPD is linked to stronger cooling, but continuous-temperature sensitivity differs

In Australia and southern South America, higher VPD is followed by stronger nighttime cooling, lower later minimum temperature, and smaller P90 warm-night area after the preceding evening temperature is controlled. Continuous-temperature slopes are larger in Australia and the regional interactions are significant. By contrast, the two P90-area point estimates are similar and the current sample does not detect a clear regional difference in those slopes. These two outcome types should be interpreted separately: continuous temperature describes the magnitude of temperature change, while threshold area also depends on local threshold position and spatial coverage. A regional difference in the first outcome therefore does not have to appear in the second in the same proportion.

Previous work shows that Australian heatwaves often occur with a dry land-atmosphere background and marked changes in surface-energy partitioning (Hirsch and King 2020; Miralles et al. 2014). This provides physical context for the VPD–cooling relation, but it does not explain why the continuous-temperature slope is larger in Australia. Background humidity, cloud, boundary-layer structure, and surface-energy partitioning could all contribute, and this study does not separate them. The safer conclusion is that VPD acts as a dry-condition constraint associated with nighttime heat loss in these two southern regions, not as one proven causal mechanism.

4.4 Cross-region comparisons should not rely on warm-night frequency alone

A model can reproduce warm-night frequency and still misrepresent the local thermodynamic relations that shape those temperatures. It may produce a similar warm-night area while missing the dew-point–heat-retention relation in Europe and East Asia, the VPD–cooling relation in Australia and southern South America, or the different way these relations translate to continuous T_{min} and threshold area. The slopes and held-out errors reported here can be used as regional process checks, although this study does not directly evaluate a climate model or attribute trends.

4.5 Limitations

This study covers four broad regions and only severe heatwaves in the upper within-region quartile of cumulative area-days, so the results do not represent all land climates or weaker heatwaves. CPC is a gridded temperature analysis and ERA5 is a reanalysis. Thirty-two event-control pairs use controls from other years, although the direction and FDR decision of every day 4–5 result are rechecked in the 126 same-year pairs. Event matching, year adjustment, and blocked held-out tests cannot remove all synoptic-scale confounding.

Dew point and VPD are both thermodynamically related to air temperature, and controlling the preceding evening temperature cannot fully separate common air-mass influences. The day 4–5 follow-up was specified after N03 and S04 were known, so it is a targeted follow-up rather than an independent preregistration. The failed northern P90-area result, significant regional differences in southern continuous-temperature slopes, unsupported 850 hPa branch, and other failed hourly links all limit generalization. Controlled perturbation experiments in radiation, moisture, or land-surface conditions would be needed to identify causal mediation or make climate-change attribution claims.

5 Conclusions

Severe daytime heatwaves in Europe, East Asia, Australia, and southern South America are all accompanied by higher nighttime minimum temperature and larger warm-night area, but the local thermodynamic constraints on later nighttime temperature differ. In Europe and East Asia, higher onset dew point is followed by stronger maintenance nighttime downward longwave radiation and higher ERA5 and CPC minimum temperature several days later, but dew point does not predict P90 warm-night area. In Australia and southern South America, higher early-maintenance VPD is linked to stronger nighttime cooling, lower later minimum temperature, and smaller P90 warm-night area; the VPD relation with continuous minimum temperature is stronger in Australia. The 850 hPa branch is not supported as a common four-region pathway, and no complete common chain from upstream conditions to P90 warm-night area is established. Overall, the evidence supports different regional constraints—heat retention under humid conditions in Europe and East Asia, and stronger cooling under drier conditions in Australia and southern South America—rather than one mechanism that applies to all four regions. These findings are observational associations and held-out predictions; they do not by themselves establish causal mediation.

Supplementary Information

Online Resource 1 contains Figs. S1–S3 and Tables S1–S8, covering the fixed-region event-window sensitivity, full-refit resampling and blocked validation of the exploratory thermodynamic axis, spatial and feature sensitivities, four-UTC-sample daily exploratory local relations, axis consistency, spatial support, regional PC1 slope differences, the descriptive k-means grouping, the pooled PC1 relation, and event-relative group evolution.

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Statements and Declarations

Funding The author declares that no funds, grants, or other support were received during the preparation of this manuscript.

Competing interests The author has no relevant financial or non-financial interests to disclose.

Author contributions Shulin Tang: Conceptualization; Methodology; Software; Validation; Formal analysis; Investigation; Data curation; Visualization; Writing – original draft; Writing – review & editing.

Data availability NOAA CPC temperature data are available from the NOAA Physical Sciences Laboratory, and ERA5 is available from ECMWF and the NCAR Geoscience Data Exchange (European Centre for Medium-Range Weather Forecasts 2019). The data and code archive supporting this study is available on Zenodo (Tang 2026): <https://doi.org/10.5281/zenodo.22692192>. Source CPC and ERA5 files are not redistributed.

Code availability The reproducible workflow includes land-weighted hourly extraction, local-solar-time nighttime diagnostics, VPD and cooling metrics, the prespecified 20-link hourly audit, two bootstrap schemes, same-year refits, the day 4–5 follow-up, and blocked time validation. Analysis scripts and derived outputs are available in the same Zenodo archive (Tang 2026).

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [OnlineResource1Source.docx](#)