



Contrasting drivers of hot extremes in observations and reanalysis over the Indo-Gangetic Plain

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Motivation

- ERA-5-Land exhibits large biases in capturing observed land surface conditions and Bowen ratios.
- However, ERA5-Land reproduces the air temperatures correctly.
- Question:** Does ERA5(-Land) reproduce hot extremes for the right physical reasons? We test this against flux-tower observations at Kanpur.

Data and Methods

- Observations:** INCOMPASS flux tower, Kanpur (26.51°N, 80.22°E), 2016-2017; ERA5-Land nearest 0.1° pixel (26.55°N, 80.25°E) plus ERA5 pressure-level fields.
- Heat-stress regimes:** $T_{\max} \geq 40^\circ\text{C}$ and $HI_{\max} < 45^\circ\text{C}$: Category 1, dry heat (**DH**).
 $T_{\max} < 40^\circ\text{C}$ and $HI_{\max} \geq 45^\circ\text{C}$: Category 2, moist heat (**MH**).
 $T_{\max} \geq 40^\circ\text{C}$ and $HI_{\max} \geq 45^\circ\text{C}$: Category 3, compound heat (**CH**).
- Temperature budget:** $\Delta T_{2m} = \Delta T_{adv} + \Delta T_{adi} + \Delta T_{dia}$ (advective, adiabatic, diabatic).
- Surface energy balance:** $K_r \Delta T_s = \Delta R_{s,net} + \Delta R_{id} - \Delta H - \Delta LE - \Delta G$, with $K_r = 4\sigma T_s^3$, each term is expressed as a temperature contribution.
- Longwave parameterization:** ΔR_{id} is split into atmospheric heat storage component and emissivity contributions from cloud (Δf_c) and humidity ($\Delta \epsilon_a$): $\Delta R_{id} = \sigma T_a^4 \Delta \epsilon_a + 4\sigma \bar{\epsilon}_a T_a^3 \Delta T_a$.

Results and Discussions

1. Heat Extreme Regimes

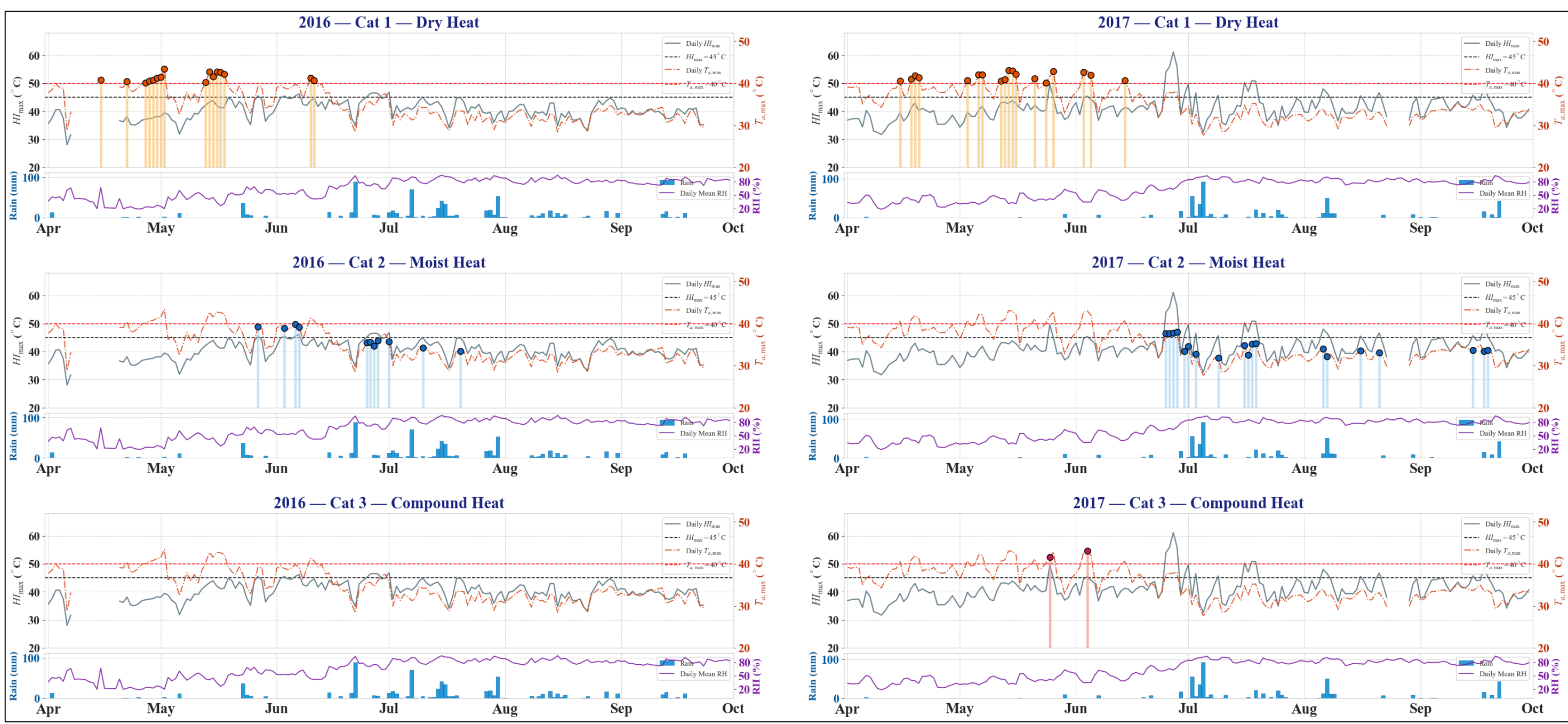


Figure 1. Classification of heat-extreme days into dry (Cat 1), moist (Cat 2) and compound (Cat 3) heat; their occurrence in 2016–2017 relative to rainfall and RH.

2. Bowen Ratio and Temperature Comparisons

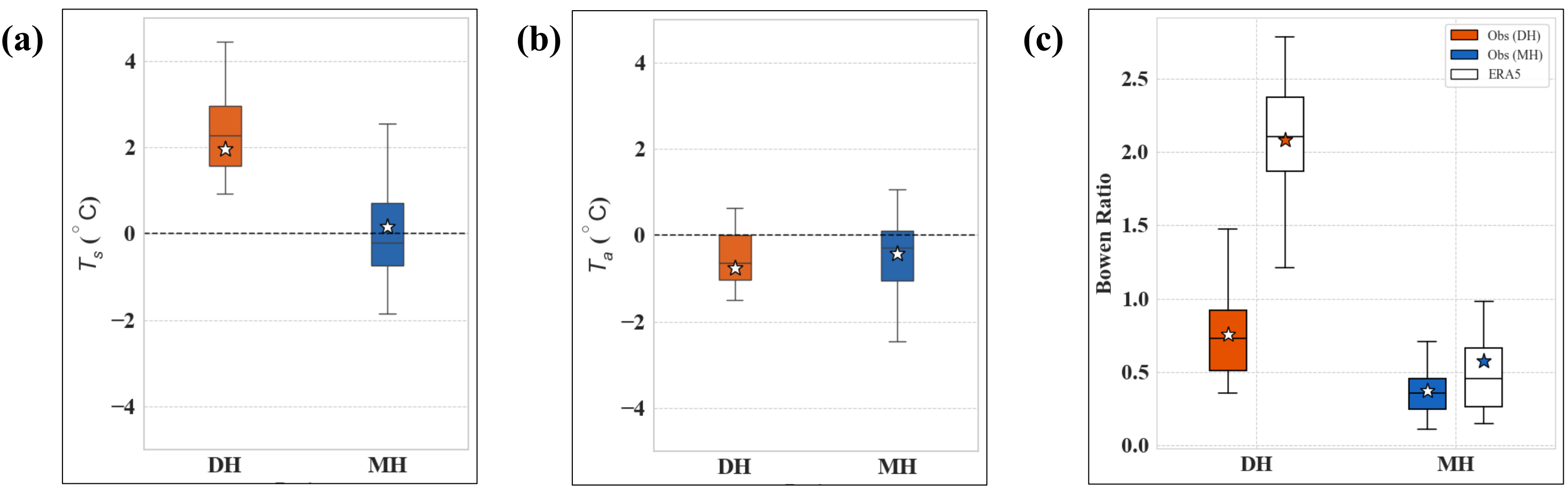


Figure 2. ERA5-Land minus observed bias T_s (a) and T_a (b) on DH and MH days. Daily mean Bowen ratio of DH and MH days for ERA5-Land and observation (c).

- Ts:** DH bias $\approx +2^\circ\text{C}$ (ERA5-Land warmer); MH bias $\approx 0^\circ\text{C}$.
- Ta:** small cold bias of $\leq +1^\circ\text{C}$ in both DH and MH.
- Residuals of only $\approx 1\text{--}2^\circ\text{C}$, so temperature is reasonably well captured in both regimes.
- DH:** median Bowen ratio ≈ 0.7 (observed) vs ≈ 2.1 (ERA5-Land), nearly $3\times$ too high.
- MH:** ≈ 0.4 vs ≈ 0.5 , close agreement; the bias grows with dryness.
- Offset is present from day -7: a persistent dry surface state, not an event response.
- VPD is reproduced, so the error lies on the **surface supply side, not atmospheric demand**.

Key Conclusions

- ERA5 (Land) reproduces observed air temperature anomalies but misrepresent the underlying surface energy balance. It underestimates radiative heating (clouds, humidity, antecedent heat storage) and compensates for it with weaker turbulent cooling and excess sensible heating.
- Temperature agreement does not guarantee correct process attribution within data assimilation frameworks.** Understanding heatwave drivers over under-sampled regions therefore requires expanding observations and careful interpretation of reanalysis datasets.

References

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- Saha, M., Dixit, V., & Karthikeyan, L. (2026). Local land-atmosphere interactions precondition moist and dry heatwaves under large-scale subsidence over the Indo-Gangetic Plains. *Geophysical Research Letters*, 53, e2025GL118998.
- Chakraborty, T., Sarangi, C., Krishnan, M. *et al.* Biases in Model-Simulated Surface Energy Fluxes During the Indian Monsoon Onset Period. *Boundary-Layer Meteorol* **170**, 323–348 (2019).

3. Diabatic Heating dominates, but through different terms

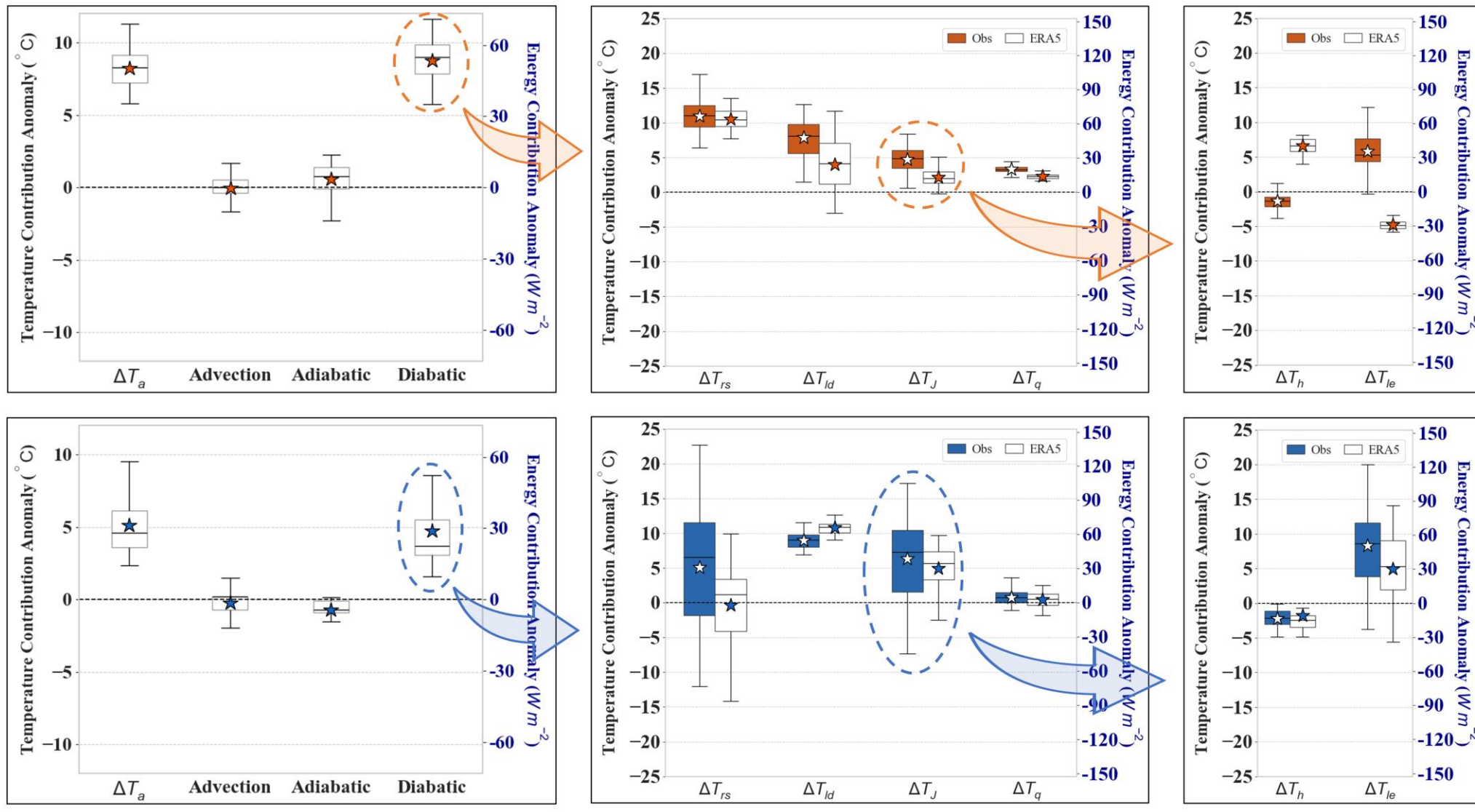


Figure 3. Decomposition of the T_a anomaly into advection, adiabatic and diabatic terms (left), the diabatic part into radiative and surface-flux terms (middle), and turbulent fluxes into H and LE (right), for DH (orange) and MH (blue).

4. Understanding Biases in Downward Longwave Heating

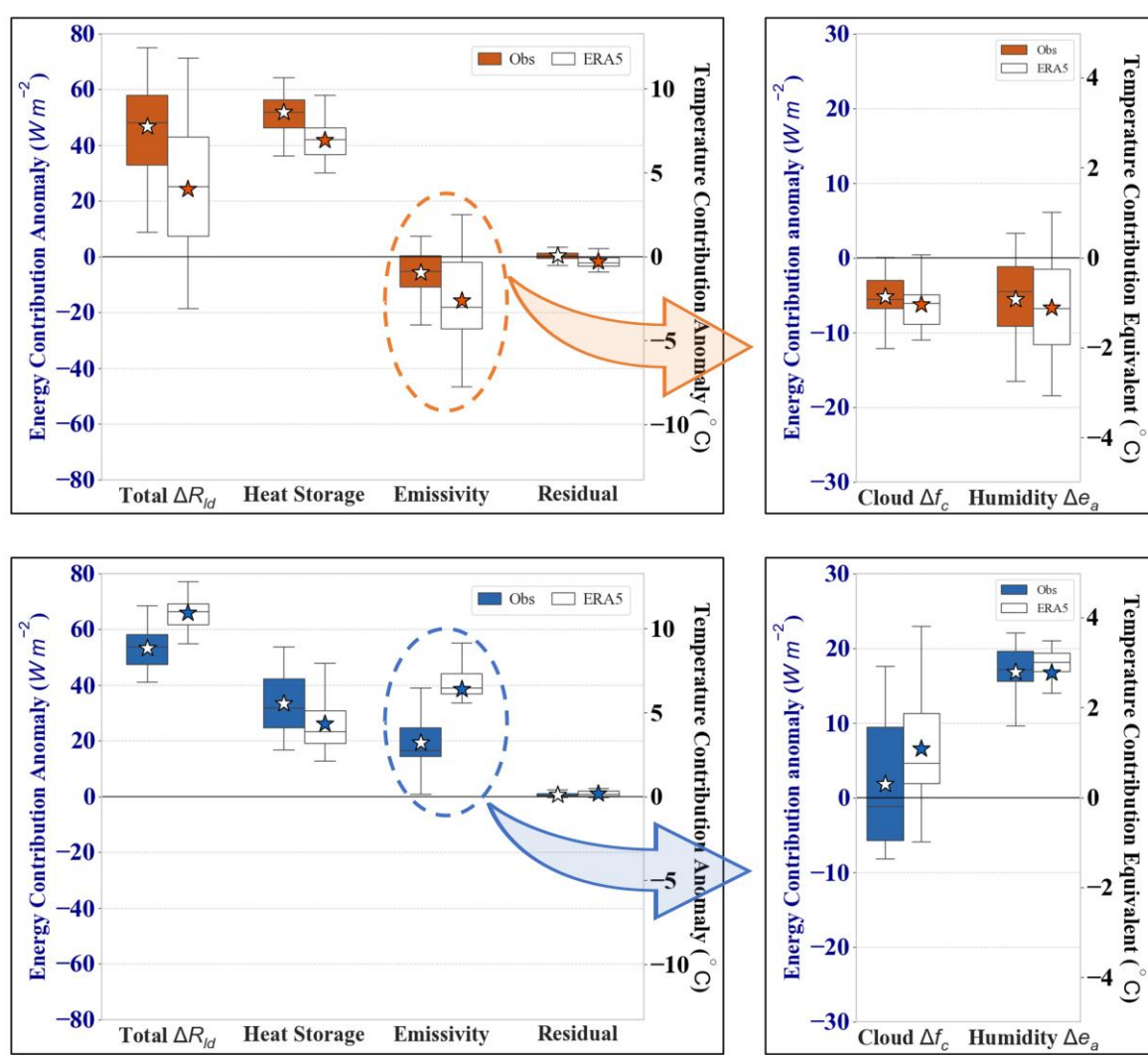


Figure 4. Decomposition of ΔR_{ld} into heat storage and emissivity (cloud, humidity) for DH (top) and MH (bottom).

5. Build-up to the event (day –7 to +5)

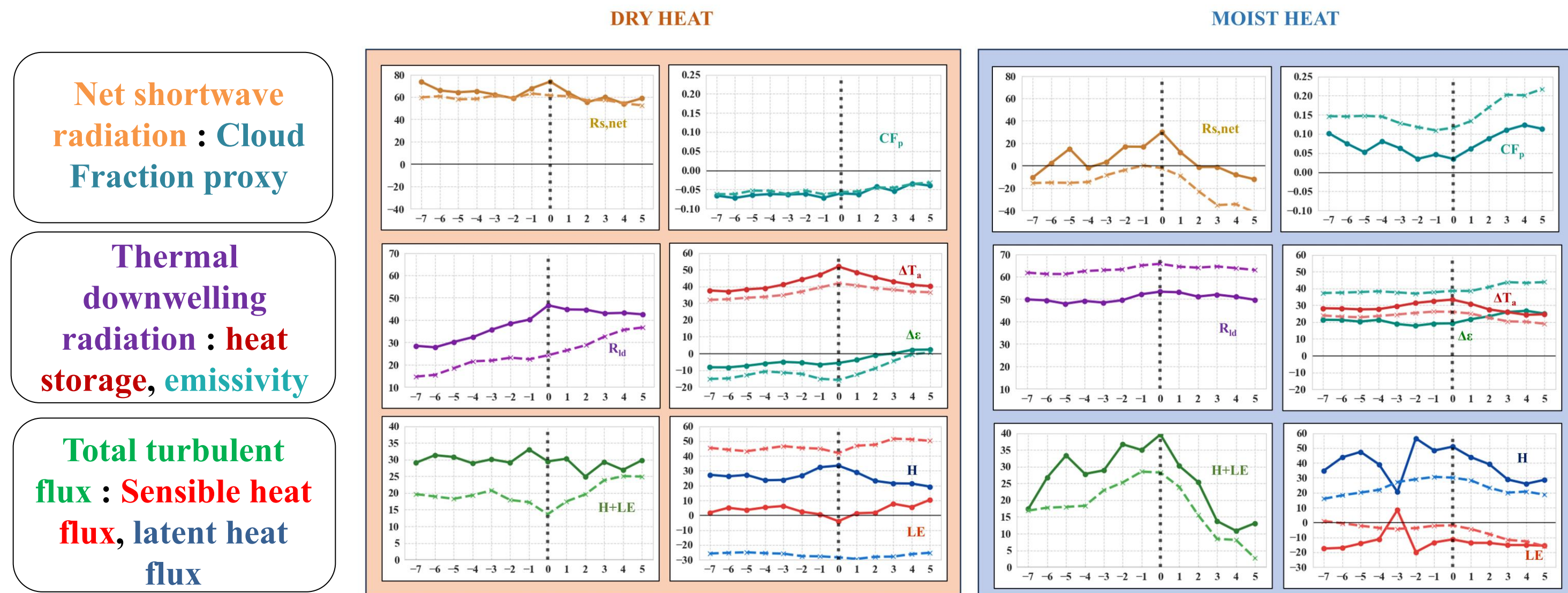


Figure 5. Event-centred composites of anomalies of net shortwave, downwelling longwave and turbulent-flux anomalies, with cloud proxy, heat storage/emissivity and H/LE , for observations and ERA5.

- DH:** preceded by clear skies; ERA5-Land overestimates cloud by a very small margin on day 0 and misses the shortwave peak.
- MH:** smaller $R_{s,net}$ anomaly under positive cloud anomaly; ERA5-Land underestimates the peak and misses the multi-day build-up.
- ERA5-Land tend to overestimate the cloud-cover.
- ERA5-Land follows the shape of the R_{id} build-up but misses the day 0 peak (too low in DH, too high in MH).
- DH:** heat-storage peak is captured but weak, and a strongly negative emissivity term cancels it.
- MH:** the positive R_{id} bias comes from overestimated cloud fraction, not heat storage.
- DH turbulent flux:** H of ERA5-Land is heavily overestimated and LE is not reproduced.
- MH turbulent flux:** shape is reproduced but magnitude is low, as the LE underestimate exceeds the opposite H bias.



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