

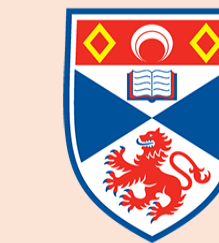
Understanding Extratropical Moist Heat Extremes: Evidence from Observation, Reanalysis and Models



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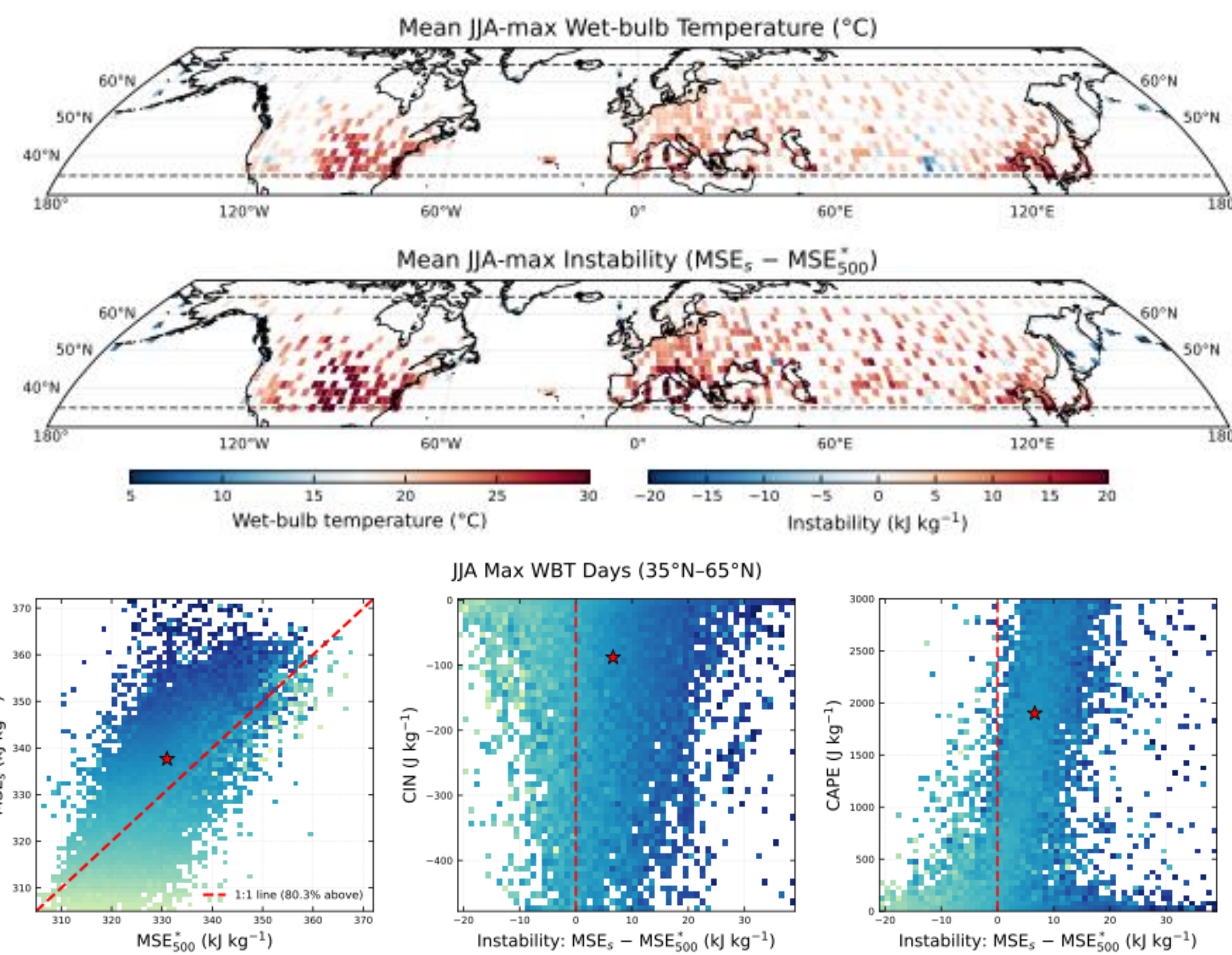
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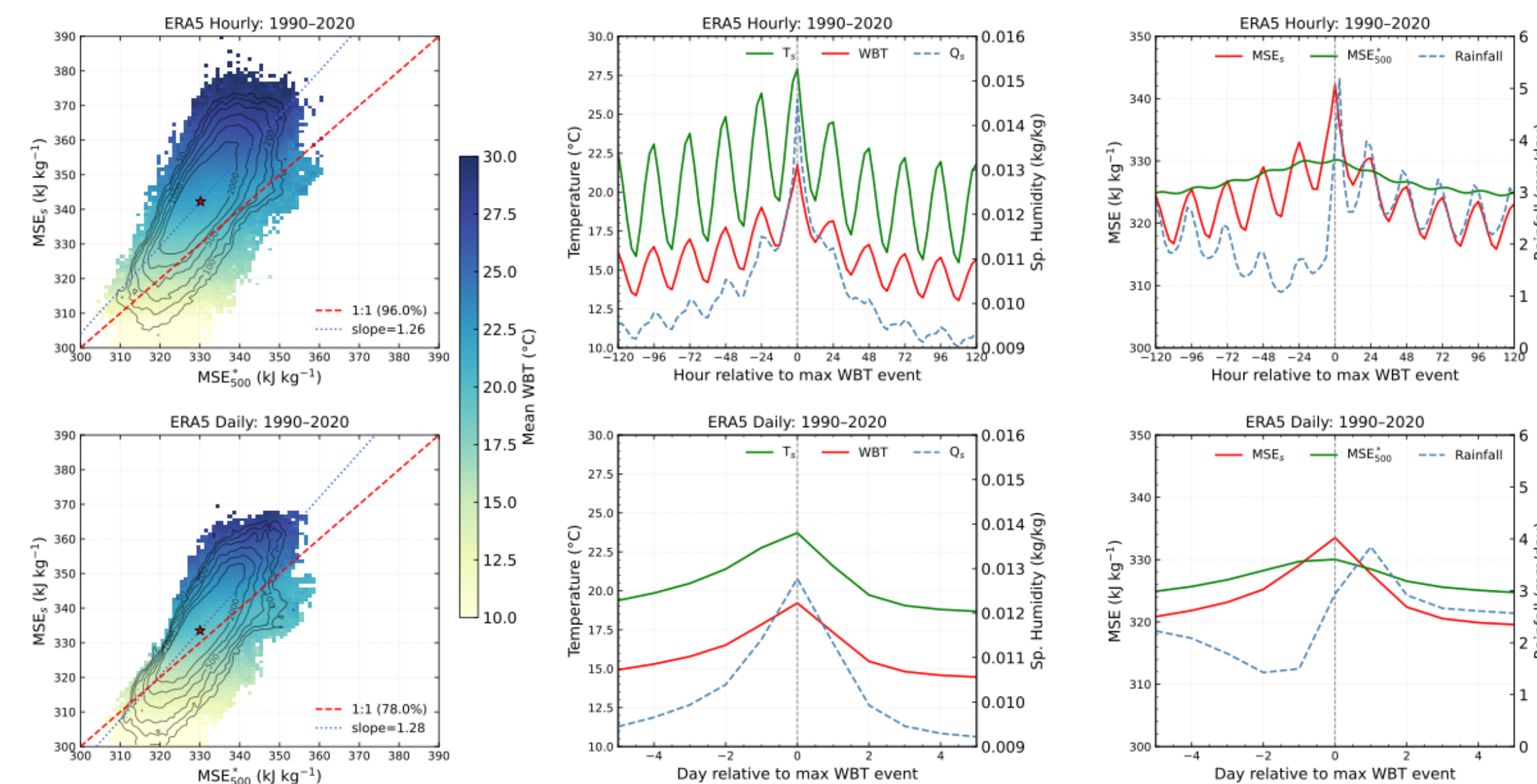
Moist Heat Extremes

- During moist heat extremes, near-surface moist static energy (MSE_s) frequently surpasses the moist convective threshold defined by MSE_{500}^* , implying a breakdown of moist convective neutrality over extratropical land in summer [Li & Tamarin-Brodsky, (2026); Duan et al, (2024)]
- The breakdown of moist neutrality has been attributed to entrainment of dry air and CIN-related energy barriers during moist heat extremes [Nicolas & Hotz, (2025); Li & Tamarin-Brodsky, (2026), Jha & Byrne, (2026)]
- Here we combine observations, reanalysis, global coarse-resolution models (CMIP6), and global storm-resolving simulations (IFS and ICON) to diagnose extratropical moist heat extremes in the historical climate and assess how their thermodynamic structure respond to anthropogenic warming



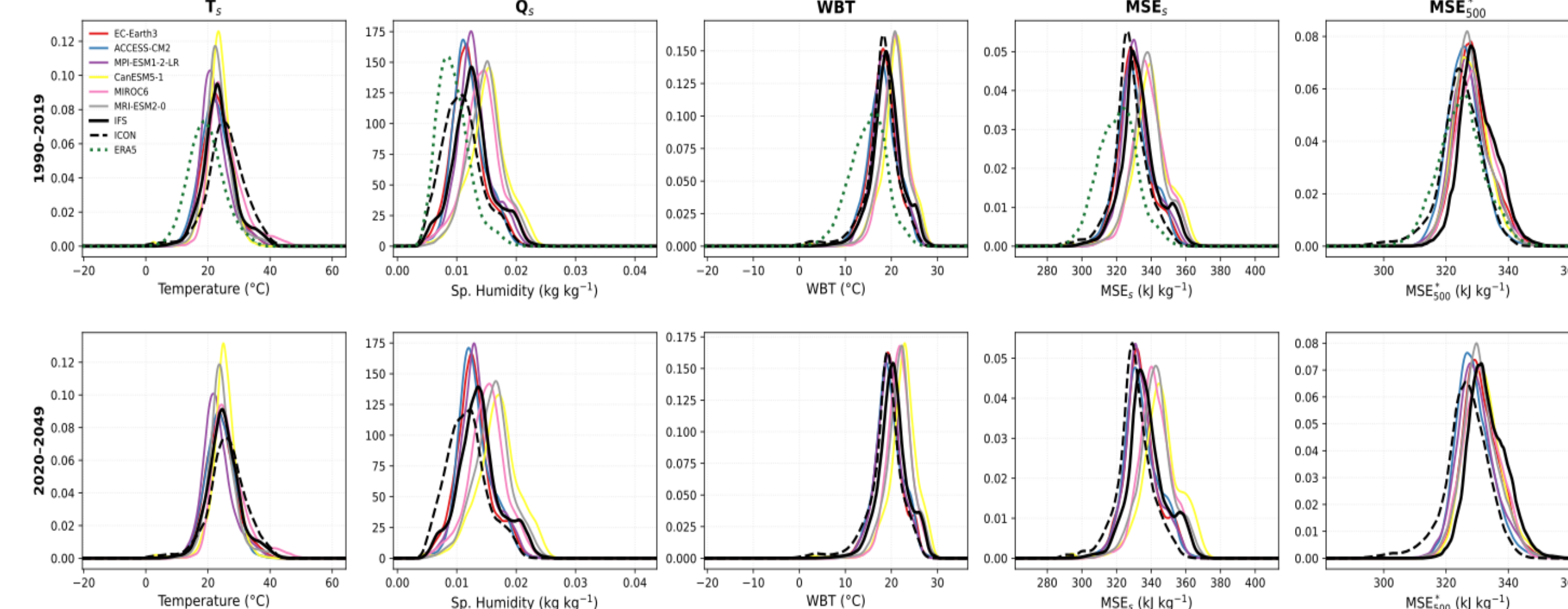
IGRA2 Radiosonde data suggests JJA maximum wet-bulb temperature hotspots coincide with positive boundary-layer instability with varying level of CIN values

ERA5 Reanalysis

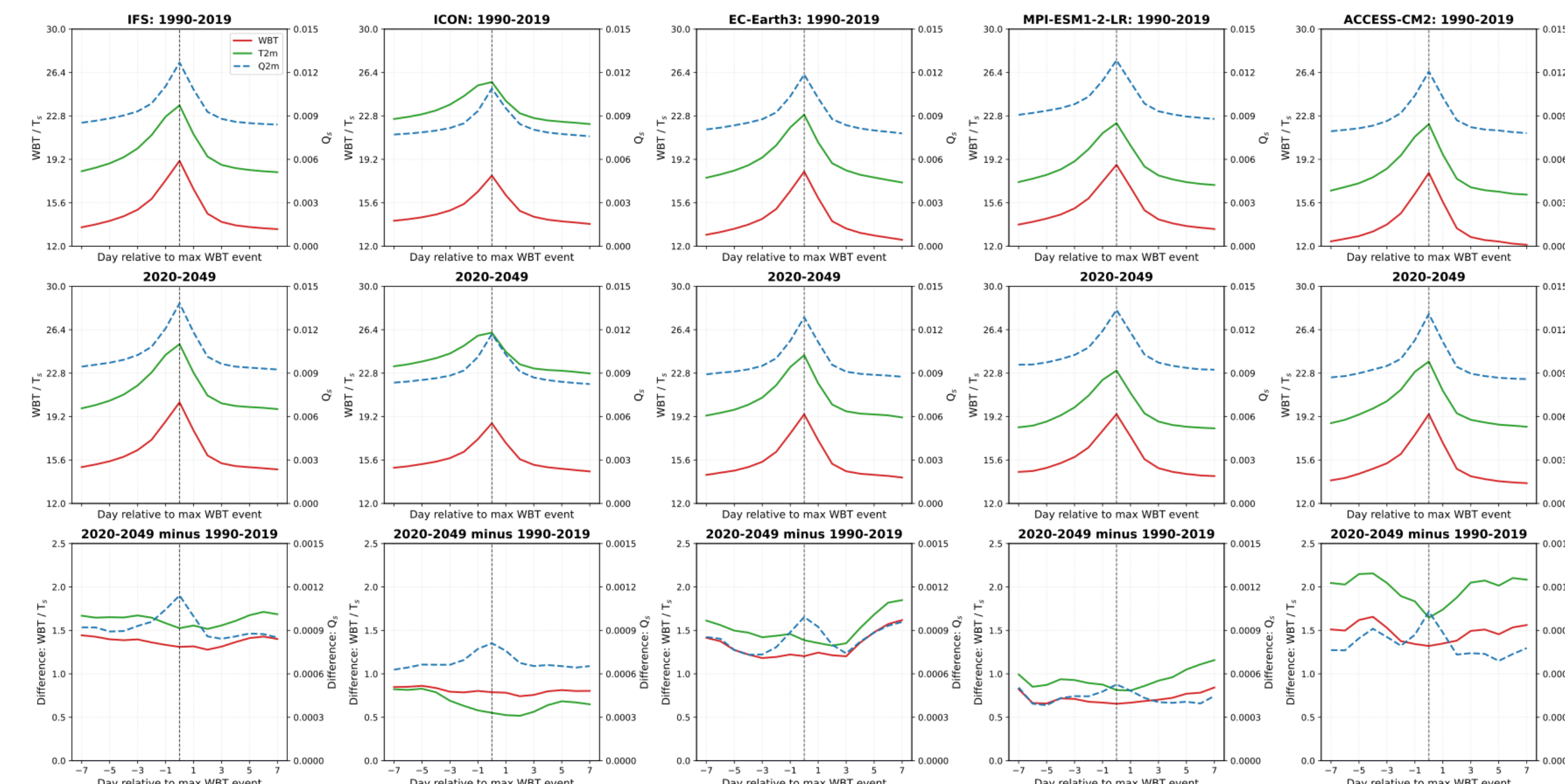


During extreme-WBT events, $MSE_s > MSE_{500}^*$, with an unstable boundary layer causing increase in WBT and is quickly followed by increased rainfall

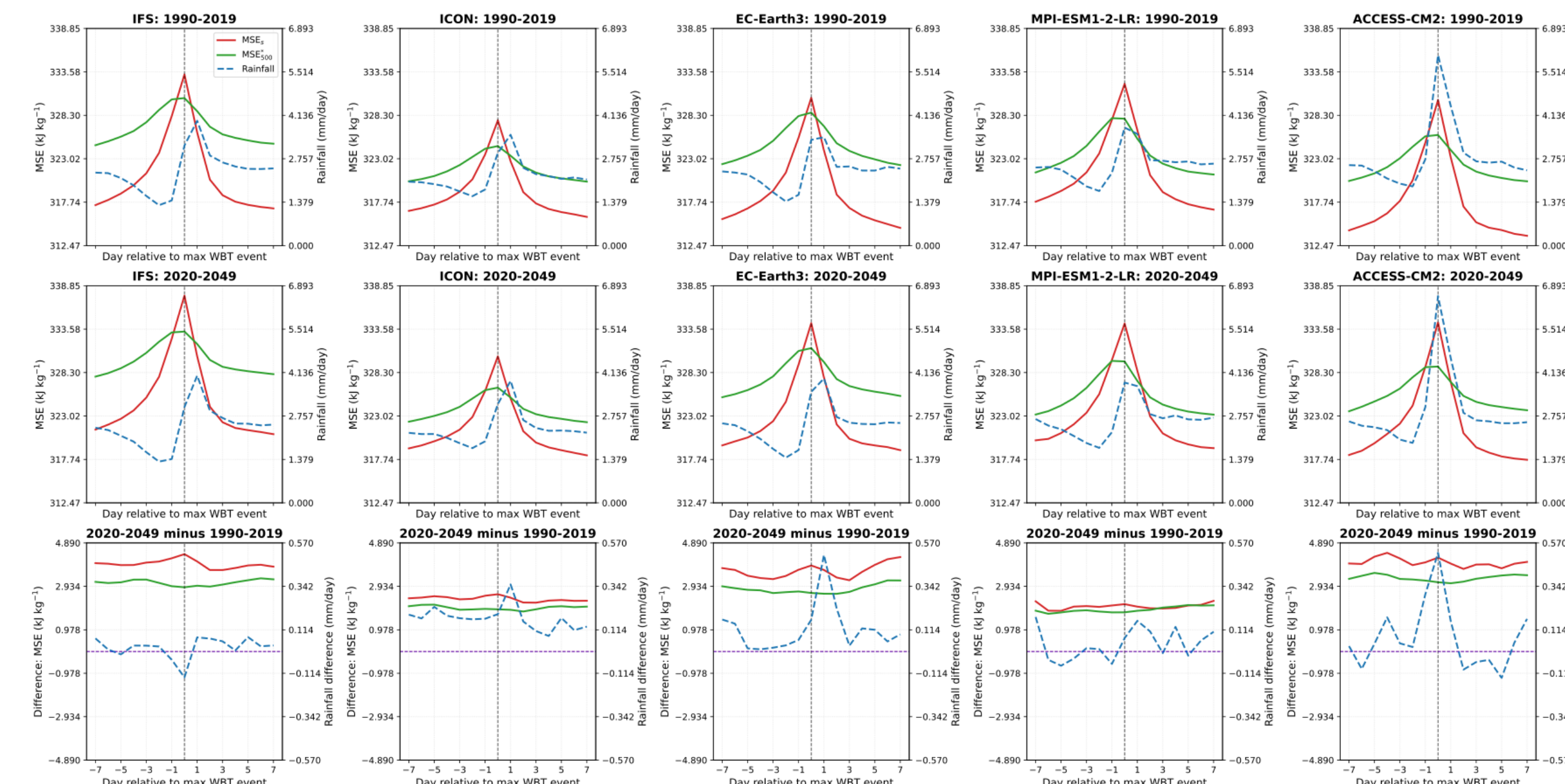
Model Comparison (1990-2019 and 2020-2049)



Inter-model differences in moist-heat extremes (WBT) are driven much more by near-surface thermodynamics than by variations in the free-tropospheric saturation, MSE_{500}^*

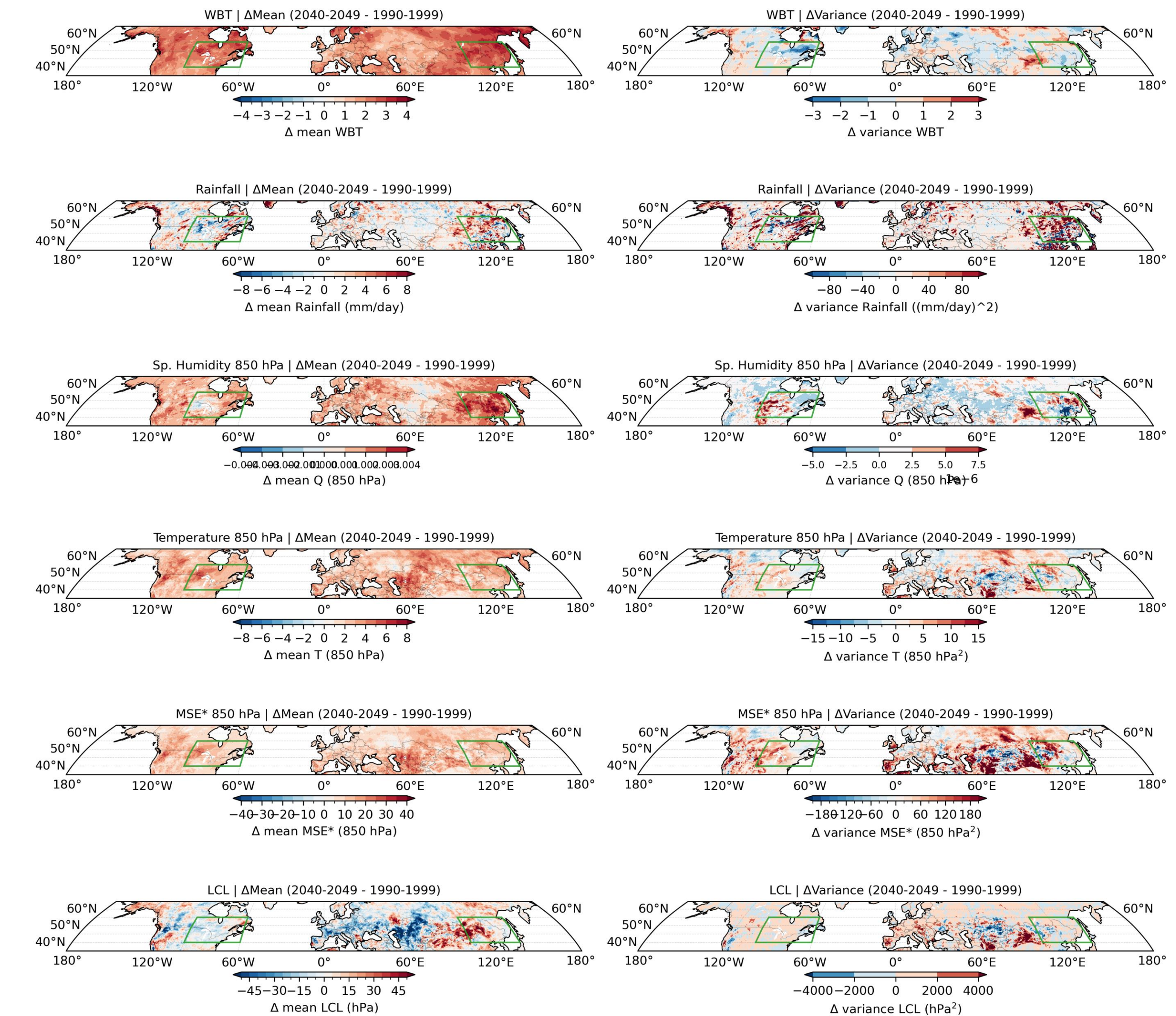


Across the GSRMs (IFS, ICON) and CMIP models, future changes in peak WBT around extreme events are largely driven by increases in near-surface temperature and humidity



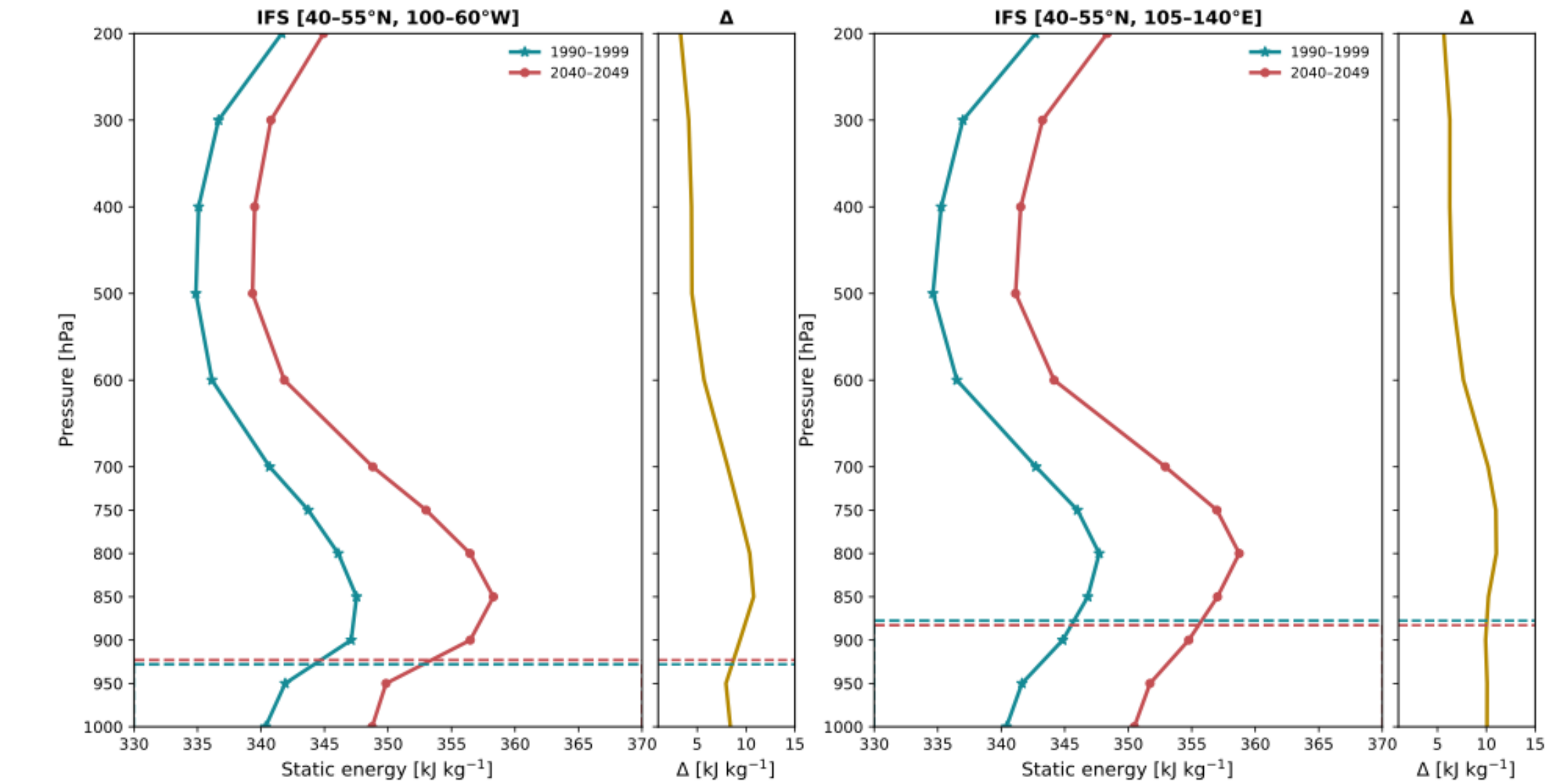
Future extreme-WBT events are consistently associated with increases in both MSE_s and MSE_{500}^* , but IFS stands out by showing a reduction in coincident rainfall

IFS: Response to warming



Amplified moist heat over Eastern North America and Northern China emerges where enhanced low-level MSE^* co-occurs with substantial changes in LCL height, but the sign of the LCL response differs between regions, implying distinct controls on boundary-layer humidity and convective efficiency

IFS: Changes in Static Energy Profile



In IFS, static energy increases throughout the column during future extreme-WBT events over both Eastern North America and Northern China, with the largest absolute increases in the lower to mid troposphere and a modest enhancement near the surface

References

- Duan, S.Q., Ahmed, F. & Neelin, J.D., Moist heatwaves intensified by entrainment of dry air that limits deep convection. *Nat. Geosci.* **17**, 837–844 (2024).
- Jha, R., & Byrne, M.P., Entrainment-based framework for understanding extratropical moist heat extremes. *ESS Open Archive* (2026).
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- Nicolas, Q., & Hotz, B., Dry and moist convective upper bounds for near-surface temperatures, *Weather Clim. Dynam.*, **7**, 843–856 (2026).

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