

El Niño amplifies subseasonal humid-heat risk across the tropics

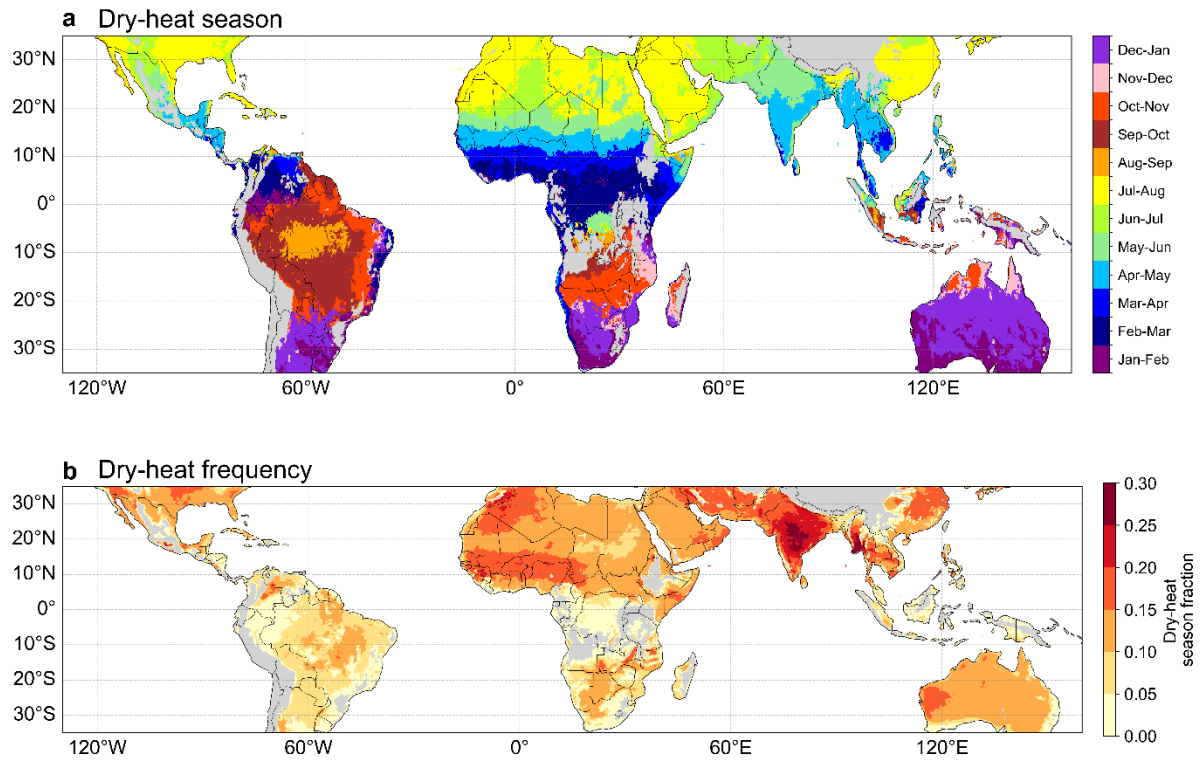
Supplementary Information

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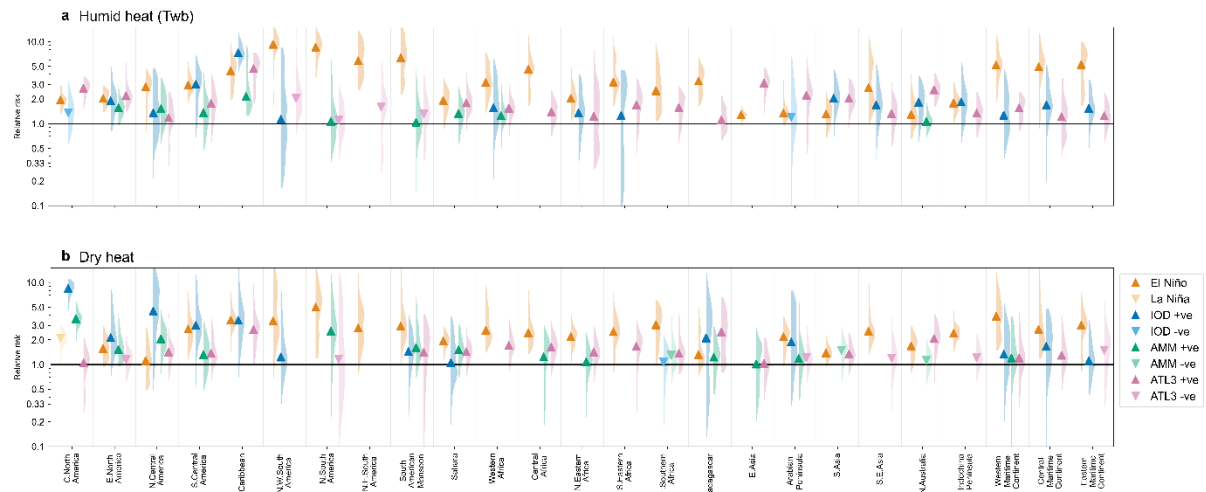
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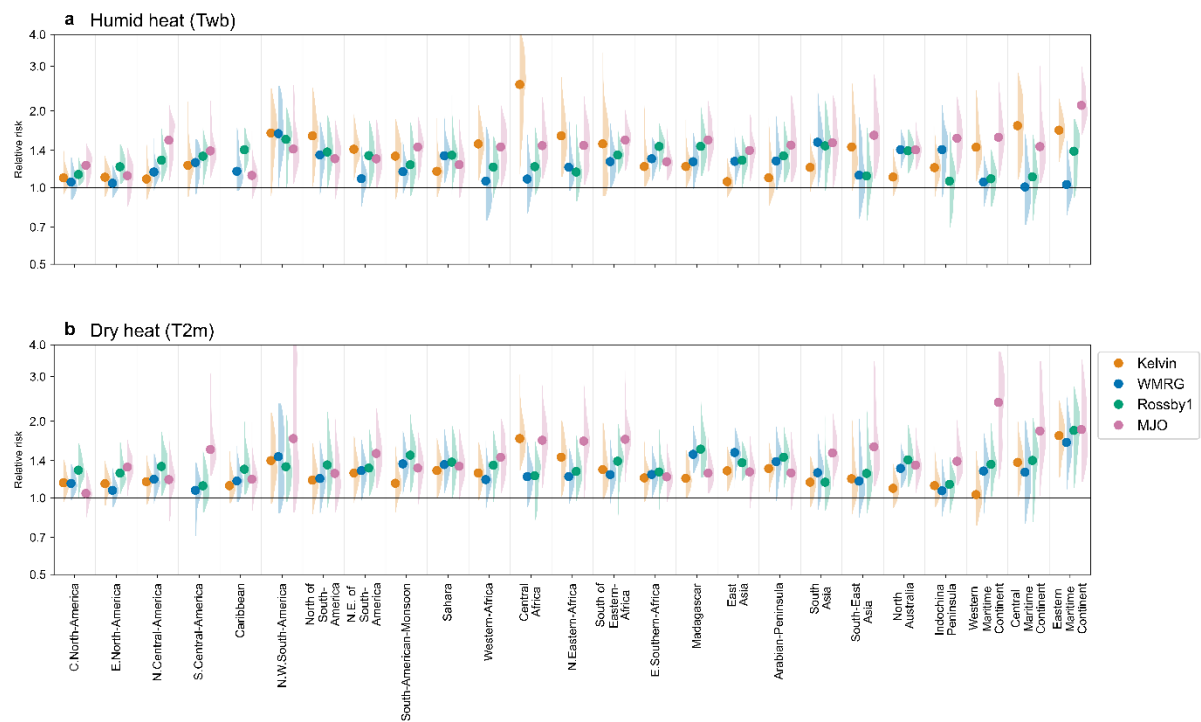
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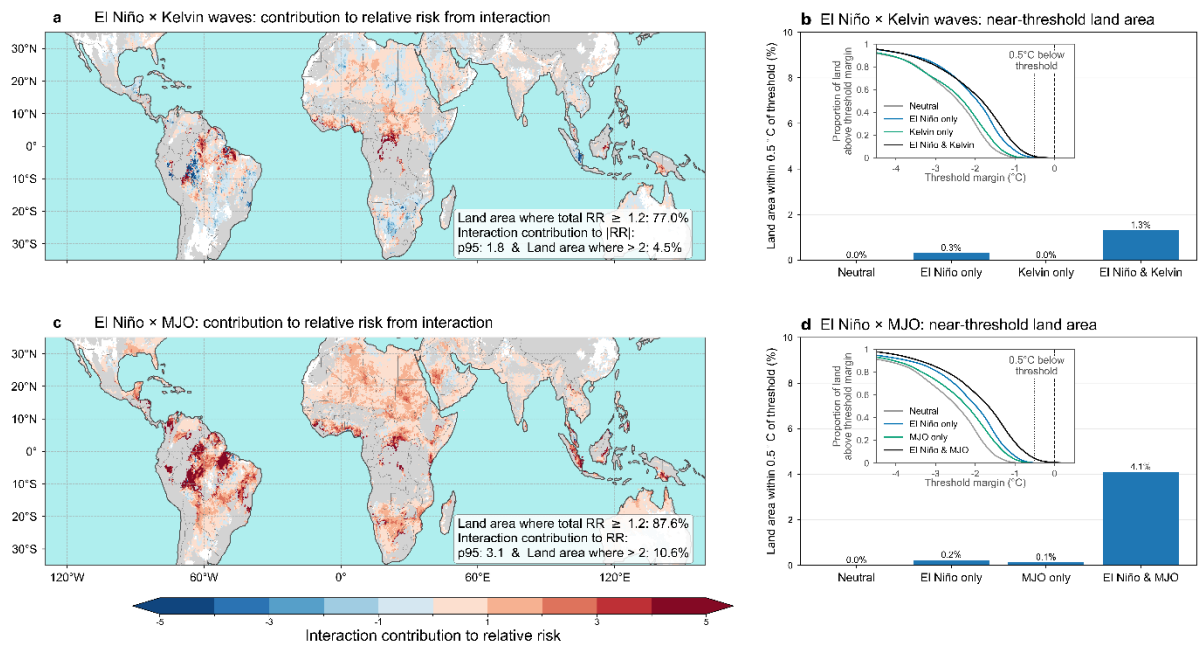
Supplementary Fig. 1 | Seasonality and frequency of dry heat. **a**, Dry-heat season, represented by the two-month period with the highest occurrence of dry-heat days. **b**, Frequency of dry-heat days during the local dry-heat season, expressed as the fraction of days classified as dry heat. Grey shading indicates where heatwave occurrence was absent or too infrequent for robust analysis. Dry-heat days are derived from ERA5 reanalysis and defined as days exceeding both a local 95th percentile threshold and an absolute global temperature threshold (Methods). These panels provide the dry-heat equivalents of Fig. 1b,d. Dry heat is most frequent in regions with pronounced seasonal cycles, although, unlike humid heat (Fig. 1), high frequencies are less closely associated with monsoon regions.



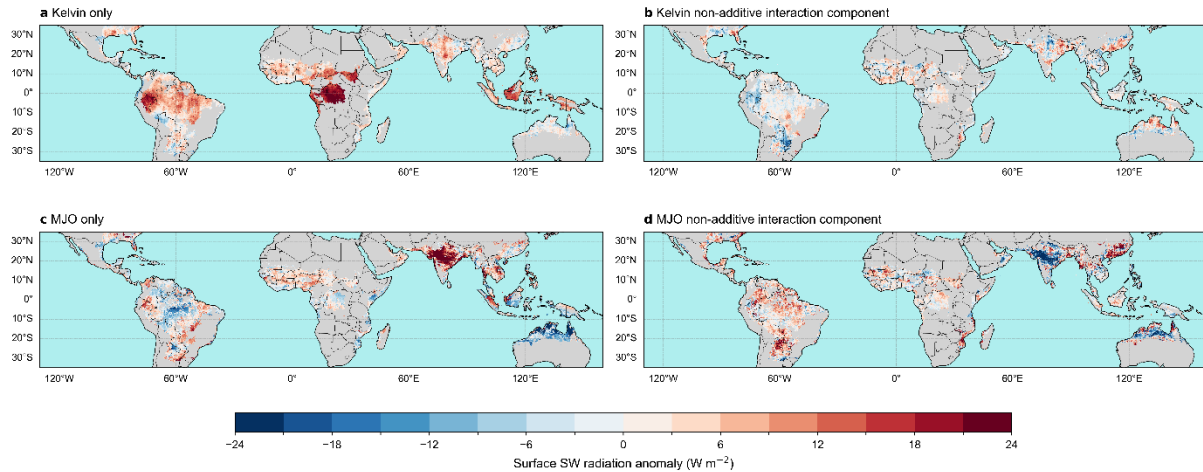
Supplementary Fig. 2 | Regional modulation of humid- and dry-heat risk by interannual tropical variability. Relative risks (RR) of **a**, humid-heat and **b**, dry-heat occurrence associated with ENSO, the Indian Ocean dipole (IOD), the Atlantic Meridional Mode (AMM), and ATL3 (an index of equatorial Atlantic SST variability) for all tropical and subtropical regions. Markers indicate regional median RR and shaded envelopes show the 95th percentile range across grid cells within each region. A representative subset of these regions is presented in Fig. 2c,d.



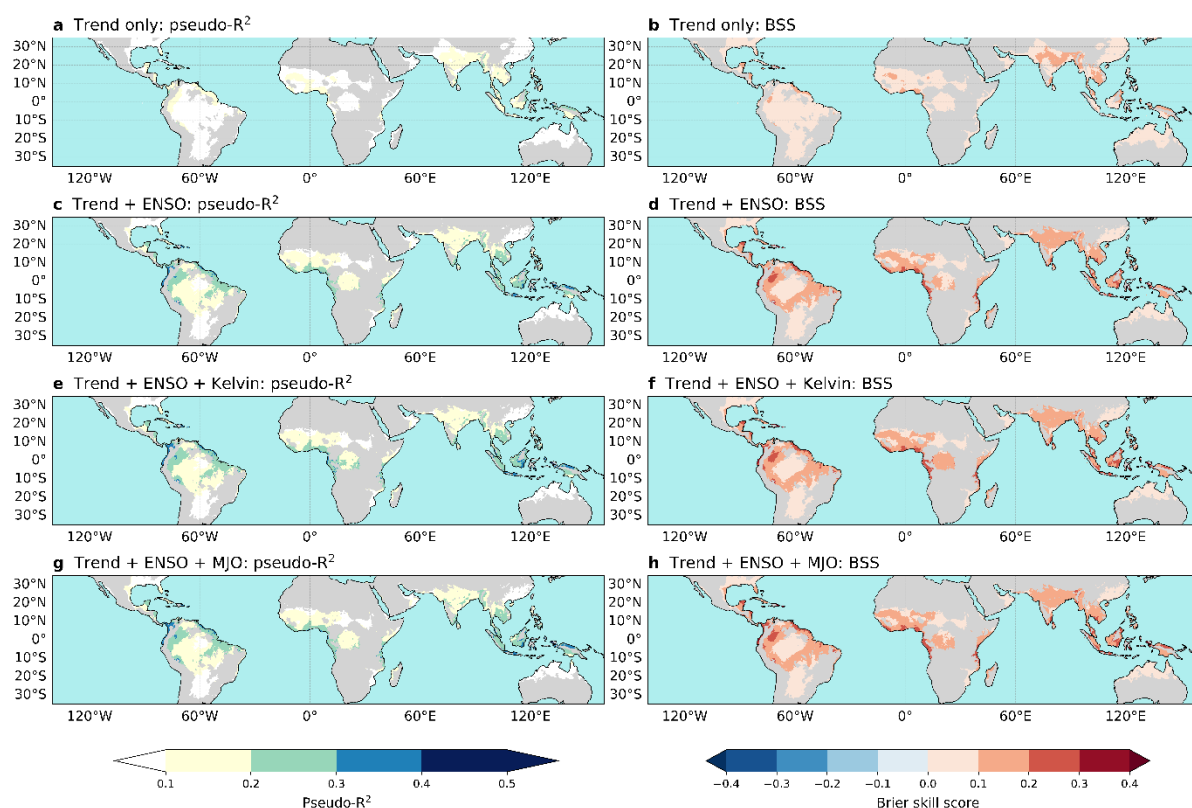
Supplementary Fig. 3 | Regional modulation of humid- and dry-heat risk by subseasonal tropical variability. Relative risks (RR) of **a**, humid-heat and **b**, dry-heat occurrence associated with the enhancing phases of Kelvin waves, westward mixed Rossby–gravity (WMRG) waves, first-baroclinic Rossby (Rossby1) waves and the Madden–Julian Oscillation (MJO) for all tropical and subtropical regions. Circles indicate regional median RR and shaded envelopes show the 95th percentile range across grid cells within each region. A representative subset of these regions is presented in Fig. 3c,d.



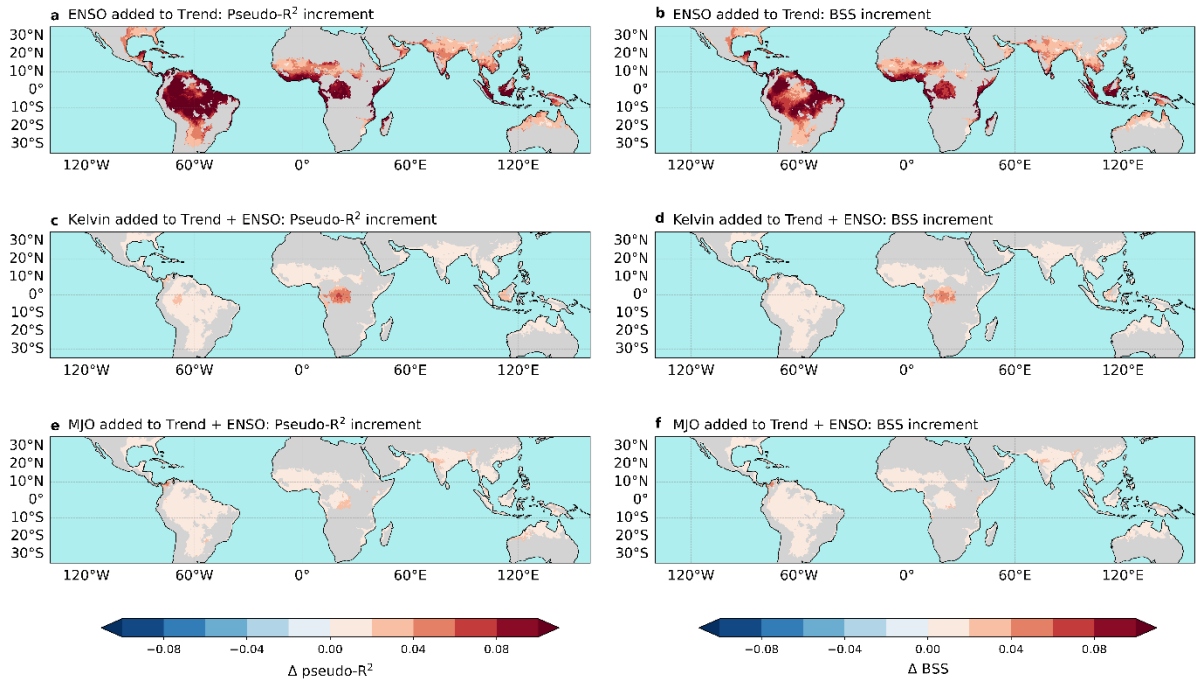
Supplementary Fig. 4| Contributions to relative risk of dry heat from interactions between Kelvin waves and the MJO with El Niño. a, Contribution to RR of dry heat from interactions between El Niño and Kelvin wave phase 5. Grey shading indicates where heatwave occurrence was absent or too infrequent for robust analysis. Grid cells with total RR less than 1.2 are shaded white. **b,** Threshold proximity, the proportion of dry-heat prone land within 0.5 °C of the local dry-heat threshold for neutral conditions (neutral ENSO and Kelvin waves not in phase 5), El Niño conditions, Kelvin-wave phase 5 under ENSO-neutral conditions, and concurrent El Niño and Kelvin-wave phase 5 conditions. The inset shows the proportion of dry-heat prone land within a given threshold margin (x-axis). **c,** Contribution to RR of dry heat from interactions of El Niño and the MJO phase with peak local RR. **d,** As c except for the MJO.



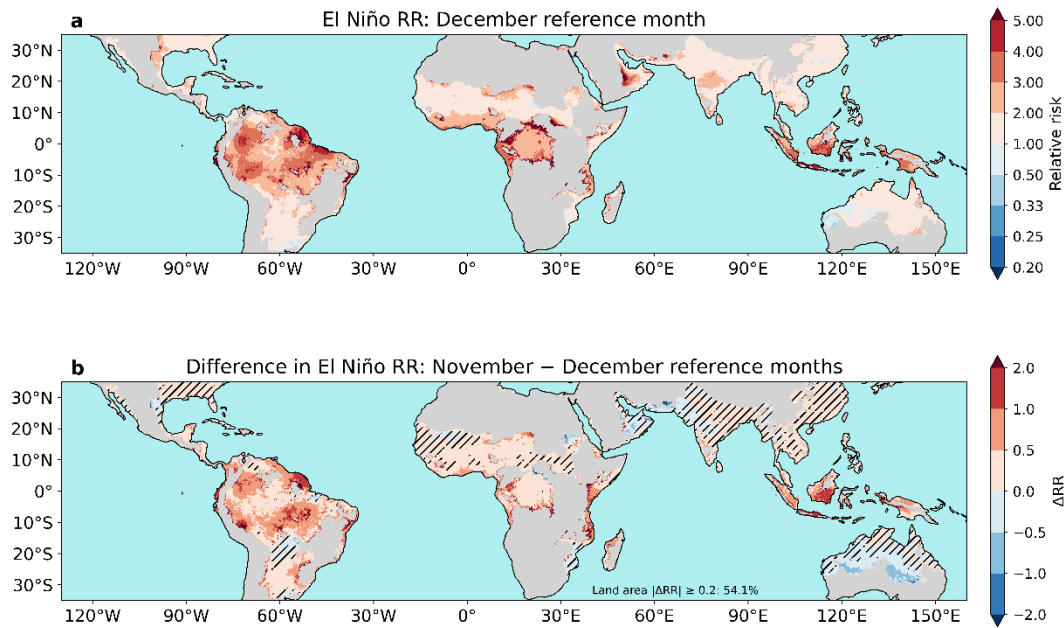
Supplementary Fig. 5 | Surface shortwave radiation anomalies associated with Kelvin waves, the Madden–Julian Oscillation (MJO) and their interactions with El Niño. Composite anomalies in downward surface shortwave radiation. **a**, Kelvin wave phase 5 during ENSO-neutral conditions. **b**, Non-additive interaction component for El Niño and Kelvin wave phase 5, calculated as the anomaly during concurrent El Niño and Kelvin-wave events minus the sum of the individual El Niño and Kelvin-wave anomalies. **c,d**, As in **a,b**, but for the local MJO phase associated with the maximum humid-heat relative risk. Grey shading indicates where heatwave occurrence was absent or too infrequent for robust analysis. Kelvin waves are associated with widespread positive shortwave radiation anomalies over regions exhibiting strong Kelvin-wave modulation of humid heat, supporting solar radiative heating as an important mechanism by which Kelvin-wave phase evolution promotes humid-heat occurrence. In contrast, the interaction components are generally weak relative to the Kelvin-wave anomalies, indicating that El Niño produces little additional modification of the shortwave-radiation response. The MJO exhibits a more spatially heterogeneous shortwave-radiation response, implying that its influence on humid heat is less directly attributable to a single radiative mechanism. Together, these results support the interpretation that the enhanced humid-heat risk during concurrent El Niño and Kelvin-wave (or MJO) events arises primarily from the threshold-proximity effect (Fig. 4), rather than from substantially stronger meteorological forcing.



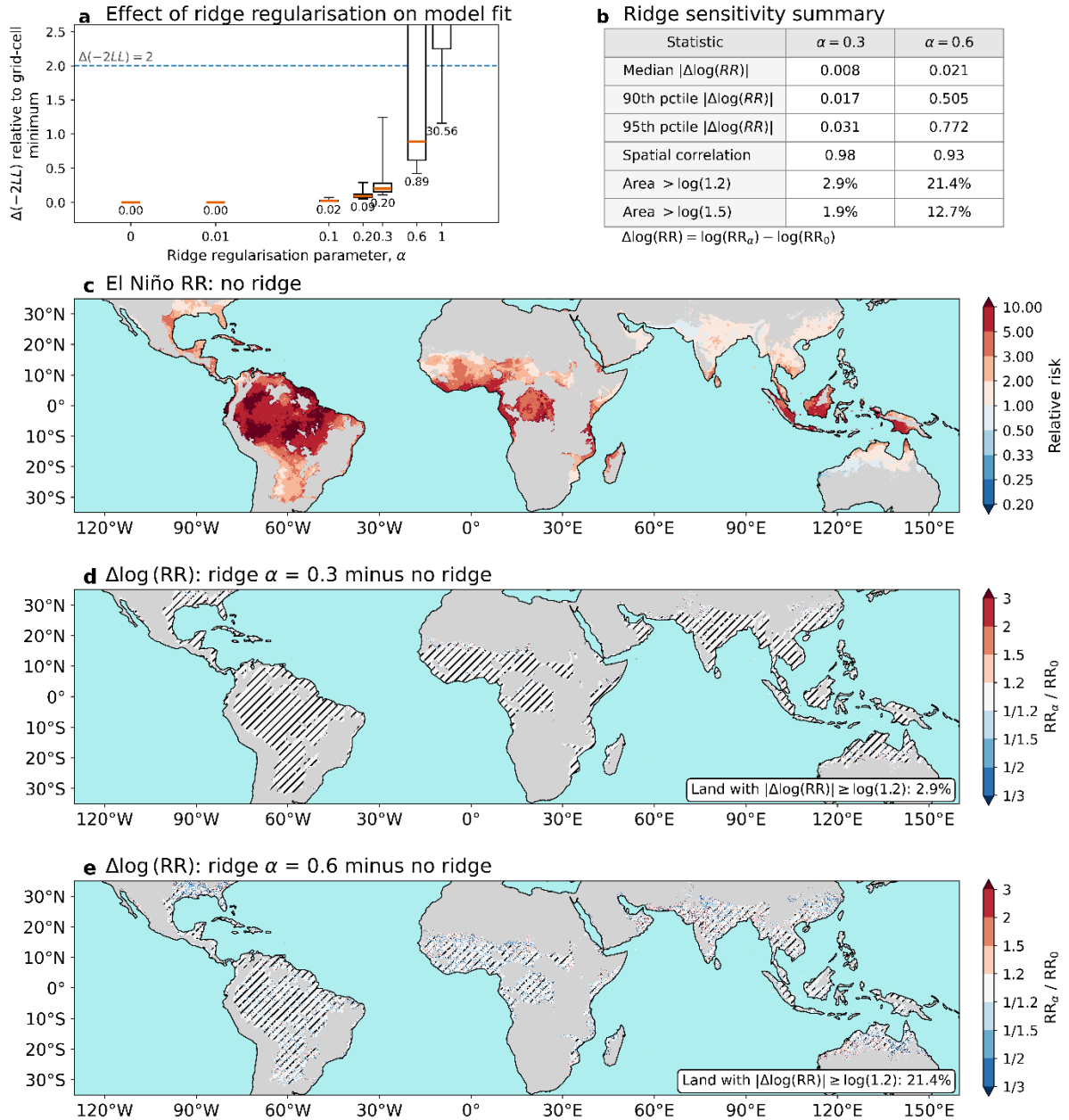
Supplementary Fig. 6 | Absolute model performance for logistic regression models of humid-heat occurrence. McFadden's pseudo- R^2 (left) and Brier skill score (BSS; right) for logistic regression models of humid-heat occurrence with increasing model complexity. **a,b**, Linear trend only. **c,d**, Trend + ENSO. **e,f**, Trend + ENSO + Kelvin waves. **g,h**, Trend + ENSO + Madden–Julian Oscillation (MJO). Grey shading indicates where heatwave occurrence was absent or too infrequent for robust analysis. Both performance metrics show that models including ENSO substantially outperform the trend-only model across much of the tropics, whereas the addition of intraseasonal variability produces more localised improvements, particularly over equatorial Africa for Kelvin waves. McFadden's pseudo- R^2 is not directly comparable to the coefficient of determination from ordinary least-squares regression; values of approximately 0.2–0.4 are generally regarded as indicating excellent model fit for logistic regression¹.



Supplementary Fig. 7 | Incremental improvements in model performance associated with tropical modes. Changes in McFadden's pseudo- R^2 (left) and Brier skill score (right) resulting from the sequential addition of individual predictors. **a,b**, Increment associated with adding ENSO to the trend-only model. **c,d**, Increment associated with adding Kelvin waves to the trend + ENSO model. **e,f**, Increment associated with adding the Madden-Julian Oscillation (MJO) to the trend + ENSO model. Grey shading indicates where heatwave occurrence was absent or too infrequent for robust analysis. ENSO provides the largest improvement in model performance across extensive regions of the tropics, while Kelvin waves and the MJO contribute smaller, regionally confined increases in predictive skill, consistent with their more localised influence on humid-heat occurrence.

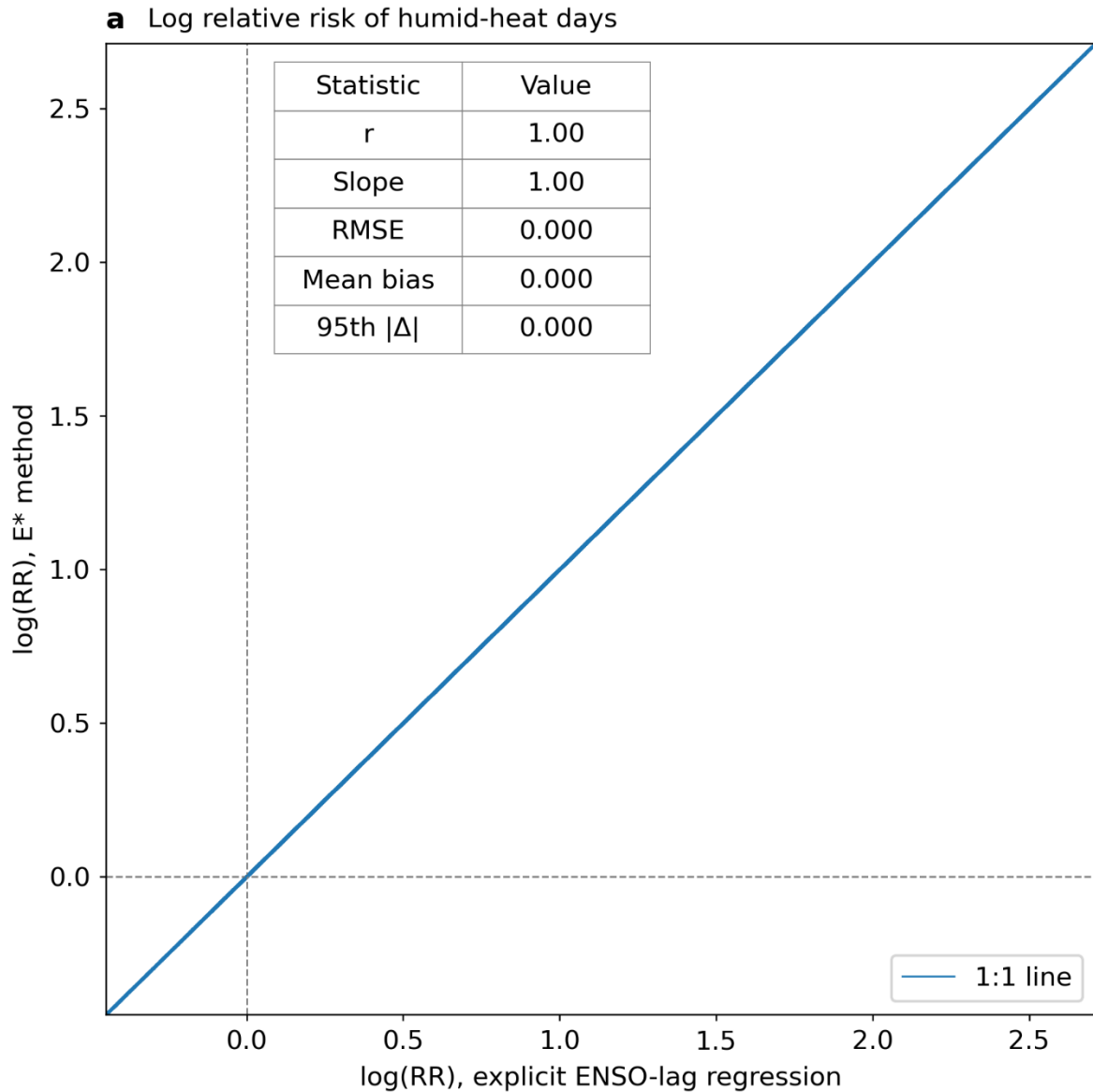


Supplementary Fig. 8 | Sensitivity of ENSO relative-risk estimates to the choice of reference month. **a**, Relative risk (RR) of humid-heat days during El Niño estimated using a reference-month approach, a commonly used approximation for representing lagged ENSO influences, in which the ENSO index is assumed constant between successive reference months and updated annually after the selected reference month (December). **b**, Difference in RR obtained by changing the reference month from December to November (November – December). Hatched regions indicate $|\Delta RR| < 0.2$. Grey shading indicates where heatwave occurrence was absent or too infrequent for robust analysis. More than half of tropical land exhibits RR differences of at least 0.2 when the reference month is changed, demonstrating that regional daily RR estimates are sensitive to the choice of reference month. This sensitivity motivated the use of distributed ENSO lags (1–11 months) in the main analyses, which avoid the need to specify a single reference month.



Supplementary Fig. 9 | Sensitivity of ENSO relative-risk estimates to ridge regularisation. **a**, Change in log-likelihood relative to the unregularised model as a function of the ridge regularisation parameter (α). The dashed line indicates $\Delta(-2LL)=2$, a commonly used threshold for a meaningful improvement in model fit. **b**, Summary statistics comparing relative risks (RR) estimated with ridge regularisation ($\alpha=0.3$ and 0.6) against the unregularised model. **c**, Relative risk of humid-heat days during El Niño estimated using the unregularised trend + ENSO logistic regression. **d,e**, Difference in log relative risk between ridge-regularised and unregularised models for $\alpha=0.3$ and 0.6 , respectively. Grey shading indicates where heatwave occurrence was absent or too infrequent for robust analysis. Hatching indicates regions where $|\Delta \log(RR)| < \log(1.2)$, corresponding to changes in RR of less than 20% indicating that most land areas experience negligible changes in estimated RR. Moderate ridge regularisation produces

only minor changes in model fit and relative-risk estimates, demonstrating that the distributed-lag ENSO formulation is robust despite the inclusion of 11 monthly lag predictors.



Supplementary Fig. 10 | Validation of the E* metric as a low-dimensional representation of distributed ENSO lags. Comparison of predicted log relative risks (RR) of humid-heat days from the full distributed-lag logistic regression model, which includes ENSO lags spanning 1–11 months, and the corresponding E*-based regression. The E* predictor is derived from the distributed-lag ENSO coefficients, providing a single predictor that preserves the influence of the full lag structure while substantially reducing model dimensionality. The points represent land grid cells and are not visible because they lie on or very close to the 1:1 line. This near-perfect agreement, together with the summary statistics, demonstrates that E reproduces the distributed-lag model with negligible error, supporting its use as a computationally efficient surrogate for the full distributed-lag representation in the interaction regressions and thermodynamic pathway analyse

References for Supplementary Information

1. McFadden, D. Conditional logit analysis of qualitative choice behavior. in *Frontiers in Econometrics* 105–142 (Academic Press, New York, 1974).