

Supplementary Information

Physical Regimes and Lifecycle Evolution of Global Heatwaves

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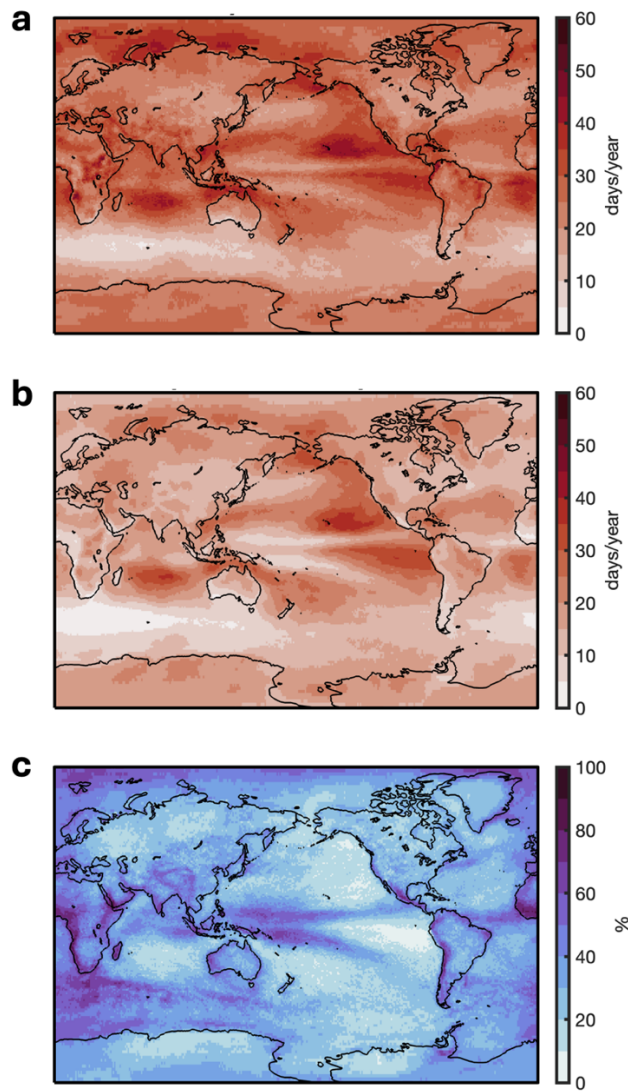
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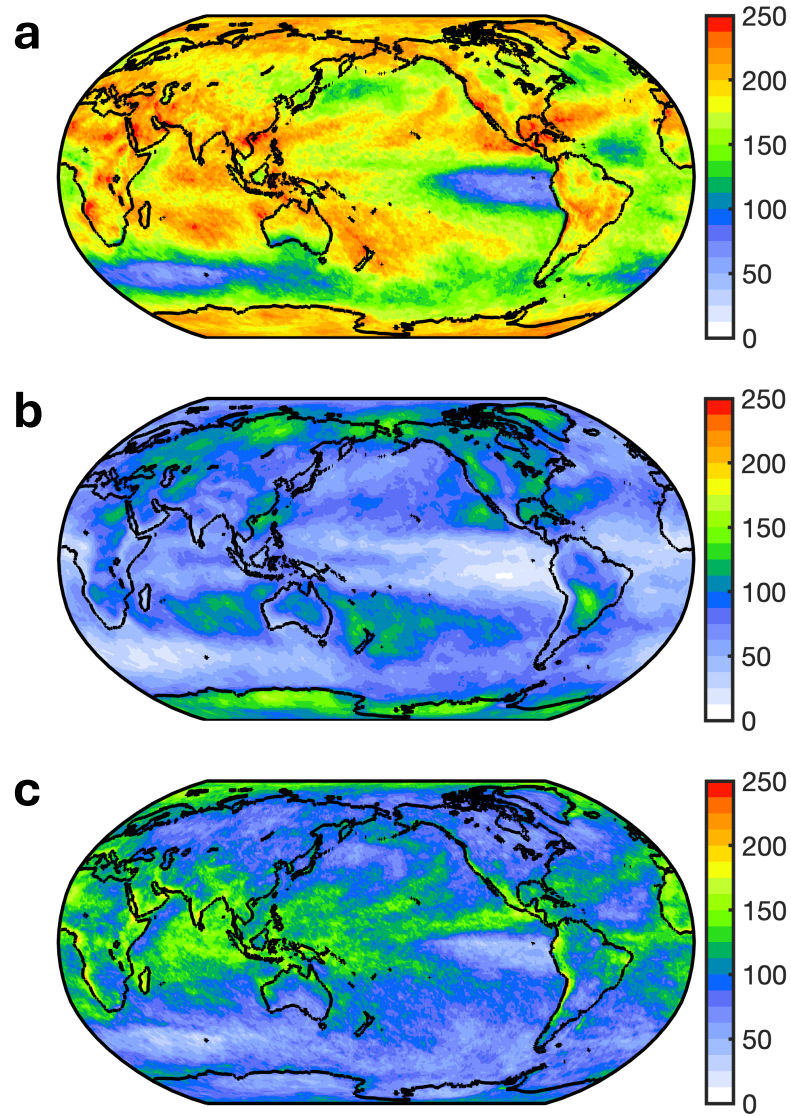
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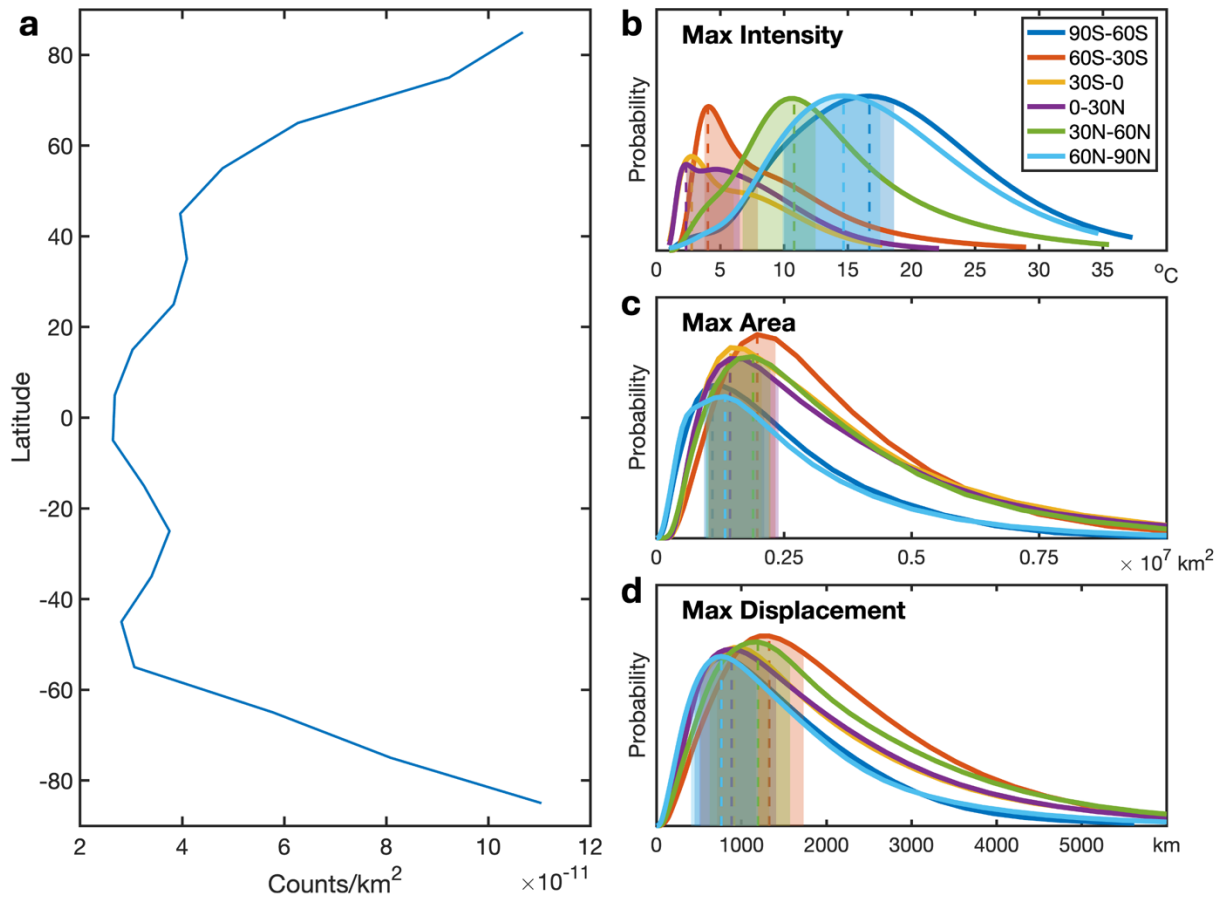
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22 **Supplementary Figure 1** | Effect of $5^\circ \times 5^\circ$ spatial smoothing on heatwave (HW) day patterns. (a)
 23 annual mean number of HW days from the raw dataset, (b) annual mean number of HW days after
 24 retaining only events that are part of tracked HW objects, defined as those with a spatial extent
 25 larger than $5^\circ \times 5^\circ$ after smoothing and persisting for more than five consecutive days. (c)
 26 fractional difference between (a) and (b).

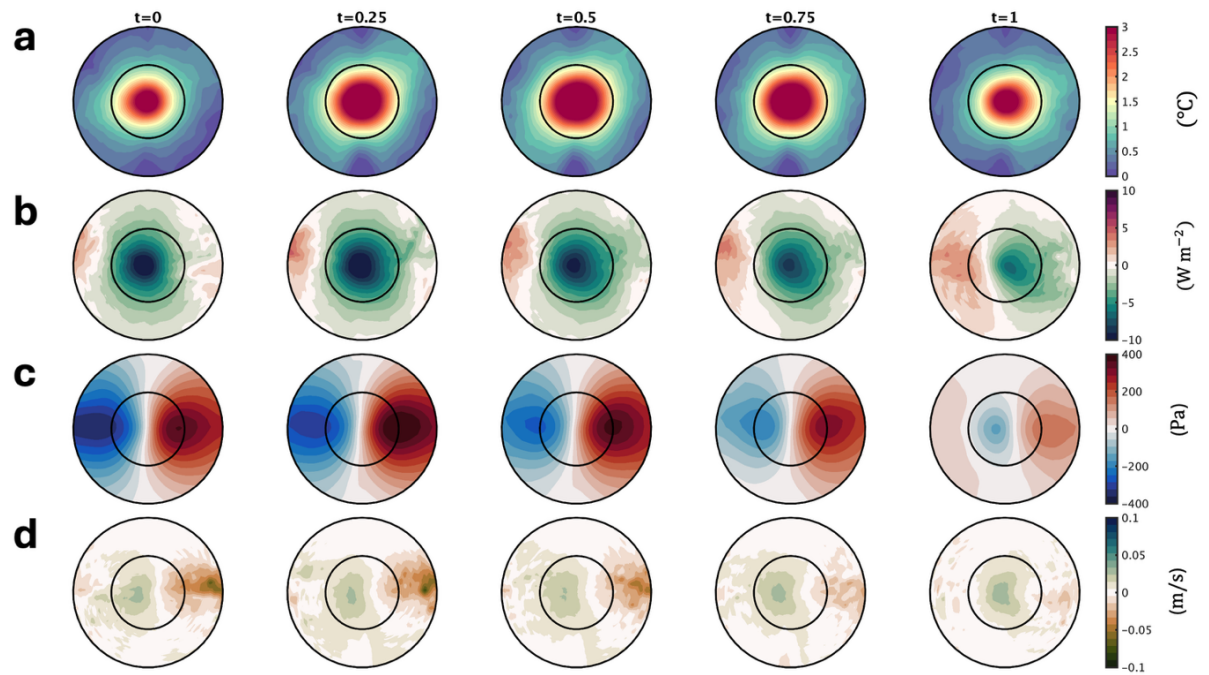


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28 **Supplementary Figure 2**| Global pattern of number of HWs at local grid in (a) Eulerian
 29 perspective, (b) semi-Lagrangian perspective (same as Fig. 1a), and (c) the difference between
 30 Eulerian and semi-Lagrangian perspective.



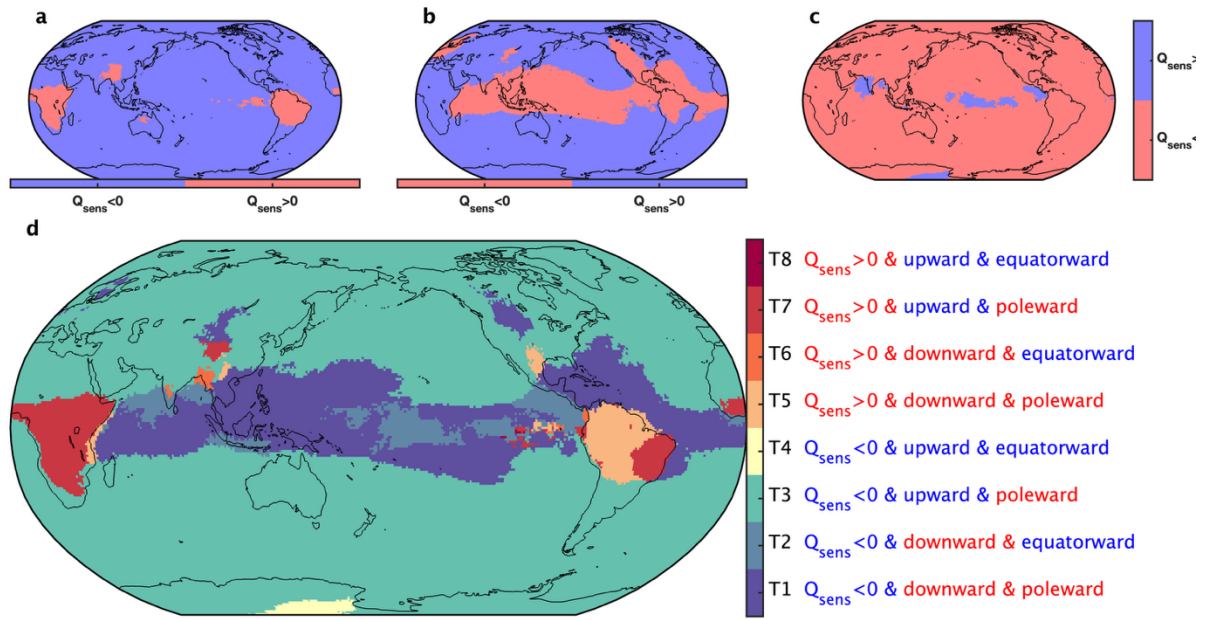
Supplementary Fig. 3 | HW properties across latitudes. (a) Zonal mean HW density as a function of latitude. (b–d) Probability distributions of maximum intensity, maximum area, and maximum displacement for HWs originating in different latitude bands, corresponding to Fig. 1h–m.



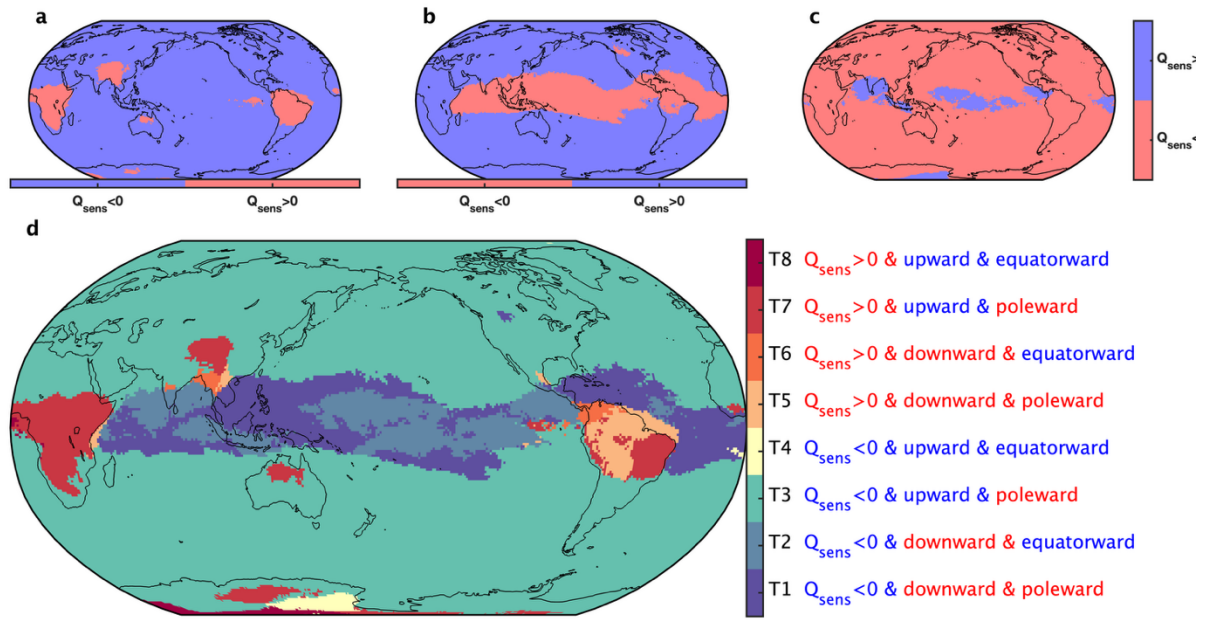
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37 **Supplementary Figure 4 | Mean CELL patterns of global HWs (count 20023 in total) at**
 38 **different lifetime stages. Panels show (a) HW intensity, (b) surface sensible heat flux anomalies**
 39 **(SHA), (c) surface pressure anomalies (SPA), and (d) vertical velocity anomalies at 850 hPa**
 40 **(W850), evaluated at five normalized time points ($t = 0, 0.25, 0.5, 0.75, 1$; left to right).**

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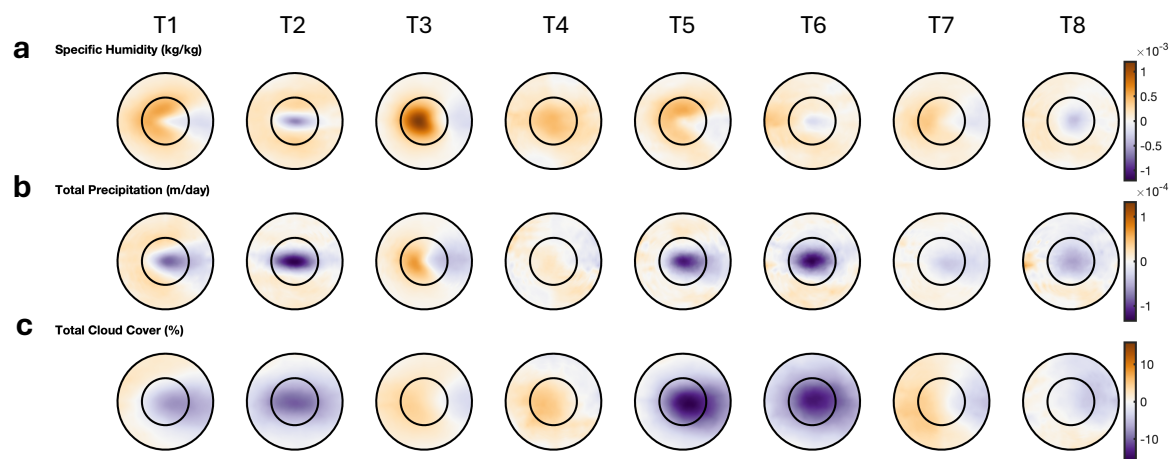
Supplementary Figure 5 | Global distribution of dominant HW types during the growing phase. Similar to Figure 3, but calculated for the growing phase of HWs, defined as $t = 0-0.5$. (a) Predominant sign of the composite sensible heat flux anomaly (SHA), determined by comparing the number of HWs associated with positive versus negative SHA anomalies. Red indicates net surface heating, while blue indicates net surface cooling. (b) Predominant sign of the composite vertical-motion anomaly associated with HWs. Red denotes anomalous downward motion, consistent with subsidence-induced heating, while blue denotes anomalous upward motion. (c) Predominant direction of composite near-surface wind-stress anomalies, used here as a proxy for the direction of lower-tropospheric air-mass transport. Red indicates poleward transport, associated with warming, whereas blue indicates equatorward transport, associated with cooling. (d) Regional distribution of dominant HW types, defined as the most frequently occurring HW type at each location during the growing phase. Colors denote the combination of the three diagnostic indicators defining each type; label colors indicate their inferred thermal effect, with red representing warming and blue representing cooling.



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58 **Supplementary Figure 6 | Global distribution of dominant HW types during the decaying**

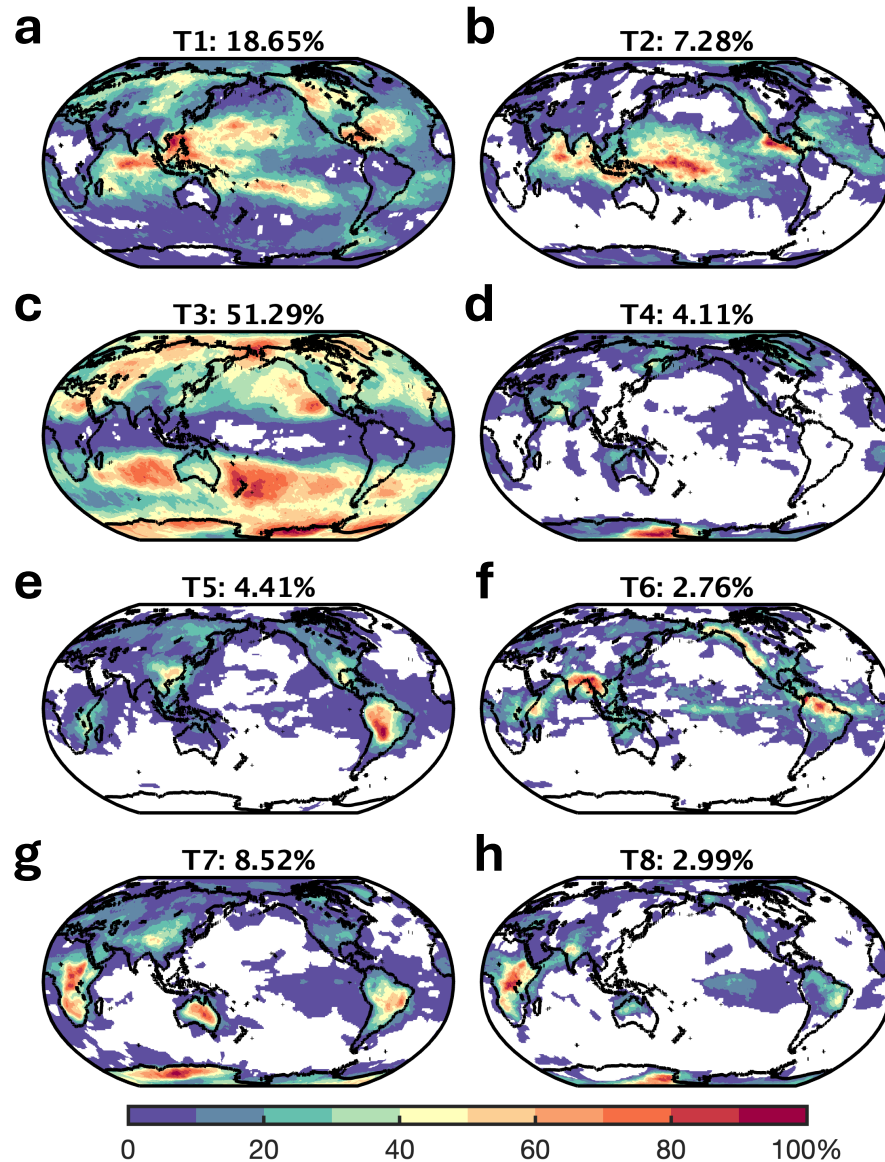
59 **phase.** Similar to Figure 3, but calculated for the growing phase of HWs, defined as $t = 0.5-1$.



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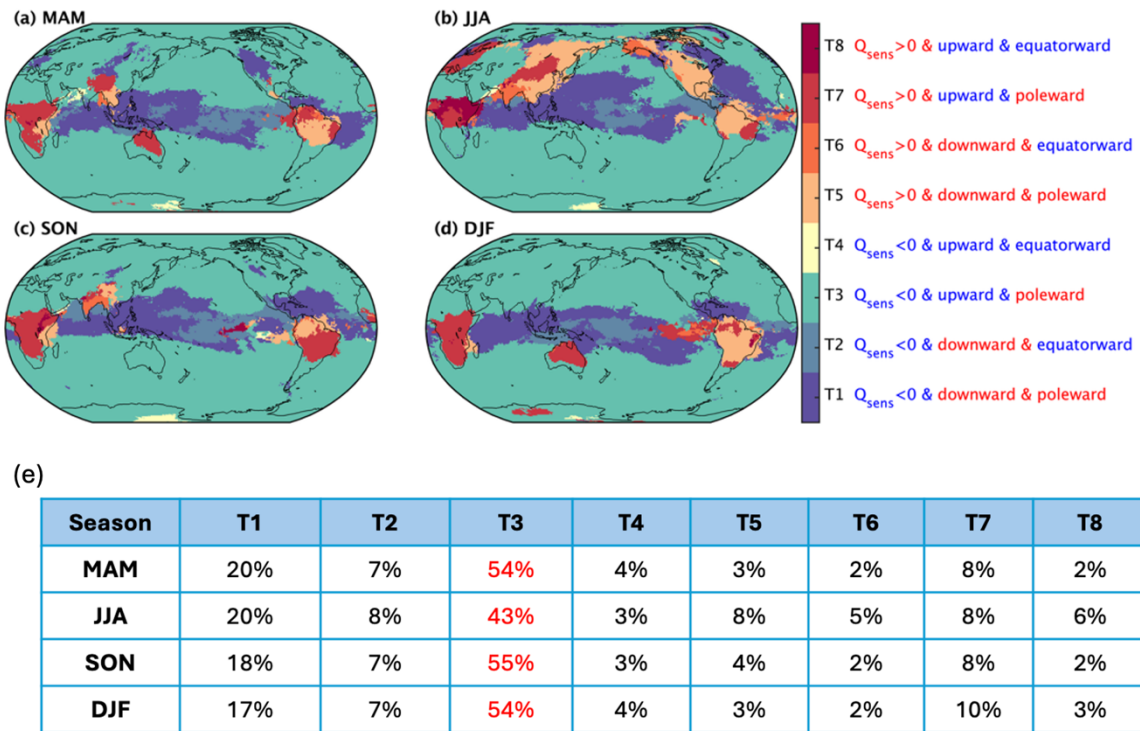
61 **Supplementary Figure 7** | CELL pattern of anomalous of (a) humidity, (b) precipitation, and
 62 cloud coverage ratio (between) of HWs in Type 1 to Type 8 (from left to right).

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65 **Supplementary Figure 8** | Spatial distribution of individual HW types, with panels (a–h)
 66 corresponding to Types 1–8, respectively. The number in each panel title indicates the proportion
 67 of global HWs represented by that type. Each map shows the relative spatial distribution of HWs
 68 during their mature phase, normalized to 100% across all events of that type. White regions
 69 indicate areas where no events of that given type. The color scale reflects the relative spatial
 70 preference: **red regions** (higher relative ratios) indicate areas where the HWs are most likely to
 71 occur, whereas **blue regions** (lower relative ratios) indicate less frequent occurrence.



Supplementary Figure 9 | Seasonal dependence of dominant heatwave regimes. Spatial distributions of the dominant heatwave types identified by the CELL framework for (a) March–April–May (MAM), (b) June–July–August (JJA), (c) September–October–November (SON), and (d) December–January–February (DJF). (e) Seasonal distribution of heatwave types. Values indicate the percentage contribution of each type to the total number of heatwave events within a given season (rows sum to 100%). Red numbers denote the most frequent heatwave type in each season. There are 20023 events in total, including 5019 in MAM, 5412 in JJA, 4798 in SON, 4794 in DJF.

82 **Supplementary Table 1 | Definition of heatwave (HW) related metrics.**

Metric	Description
Centroid	Geometric center of a HW object at a certain time (used in Fig. 1c).
Duration (days)	Temporal length (“Lifetime”) of a tracked HW event (used in Fig. 1d).
Area (km ²)	Spatial extent of a HW object at a certain time (used in Fig. 1b).
Maximum Area (km ²)	Maximum area reached by a HW during its lifetime (used in Fig. 1e).
Maximum Displacement (km)	The greatest distance between the HW centroid and its point of origin over the course of the event’s lifespan (used in Fig. 1f).
Intensity (°C)	Temperature anomaly within a HW object at a given time.
Maximum Intensity (°C)	Highest intensity reached during HW lifecycle (used in Fig. 1g).
Cumulative Intensity (°C·10 ⁶ km ²)	Area-integrated HW intensity at each time point (used in Fig. 1b).
Peak Time	Time step when the event reaches its maximum cumulative intensity (used in Fig. 1b).
Object	The snapshot of the tracked HW event at a point of time (used in Fig. 2a).
Evolution pathway	The snapshot of HW area at each time point and print along the whole HW lifecycle. These connected HW objects path are referred to as HW evolution pathway (used in calculation of Fig. 1h-m).
Pathway Densities	Number of HW objects appeared at each local grid (used in Fig. 1a).
Originate Phase	Phase of HW at its onset/ start time ($t = 0$).
Mature phase	Mean spatial pattern during the mature stage ($t = 0.25\text{--}0.75$, defined in Fig. 1b, used in HW classification).
Collapse phase	Phase of HW at its termination/ end time ($t = 1$).

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Supplementary Table 2 | Parameters used in the tracking algorithm and their rationale. The tracking framework involves only a limited number of user-defined parameters. To clarify the parameter choices used in this study, we summarize the key parameters and their rationale. In addition, we conducted a sensitivity test using alternative temperature products, including daytime maximum, nighttime maximum, daytime mean, nighttime mean, and daily mean temperature.

Parameter	Value (used in this study)	Rationale
Overlap ratio	50%	A commonly used criterion for tracking moving objects; see our response above.
Minimum duration	3 days	Consistent with the minimum duration commonly used to define grid-cell heatwaves ³⁹ , and here extended to moving-object heatwaves.
Smoothing scale	5 degrees	A commonly used spatial smoothing scale that retains large-scale temperature extremes while balancing computational cost and physical interpretability. Similar smoothing scales have been used in Scannell et al. (2024) ⁴¹ and Sun et al. (2023) ⁴² .
Smoothing method	K-nearest neighbors (KNN)	A commonly used method for regularizing moving objectss ^{40,42} . Previous evaluations suggest that KNN performs better than the opening-closing image-processing method used by Scannell et al. (2024) ⁴¹ , which may introduce unrealistic information when the smoothing scale becomes large ⁴⁰ .
Temperature product	Daily maximum temperature	Daily maximum temperature is a commonly used metric for defining temperature extremes ^{27,39} . We also tested alternative temperature products, including daytime maximum, nighttime maximum, daytime mean, nighttime mean, and daily mean temperature. These alternatives produced similar numbers of tracks compared with daily maximum temperature.

92 **Supplementary Table 3 | Sensitivity test using alternative temperature products.**

Temperature product	Number of tracks	Splitting/merging ratio
Daily maximum temperature, used in this study	20,023	19.6%
Daytime maximum temperature	20,129	21.5%
Nighttime maximum temperature	19,989	19.1%
Daytime mean temperature	19,945	18.7%
Nighttime mean temperature	20,110	19.2%
Daily mean temperature	20,133	20.5%

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