

Physical Regimes and Lifecycle Evolution of Global Heatwaves

Ce Bian

cebian@ideo.columbia.edu

Columbia University

Zijie Zhao

University of California

Alex Sen Gupta

University of New South Wales

Andréa S. Taschetto

University of New South Wales

Lixin Wu

Ocean University of China

Article

Keywords:

Posted Date: October 5th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-11089952/v1>

License: © ⓘ This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Additional Declarations: No competing interests reported.

Physical Regimes and Lifecycle Evolution of Global Heatwaves

Ce Bian^{1,2}, Zijie Zhao^{3,4}, Alex Sen Gupta^{5,6}, Andréa S. Taschetto^{5,6,7}, Lixin Wu^{8,9}

¹Lamont Doherty Earth Observatory Laboratory, Columbia University, New York City, NY,
USA

²Columbia Climate School, Columbia University, New York City, NY, USA

³Department of Earth System Science, University of California, Irvine, CA, USA

⁴Institute for Marine and Antarctic Studies, University of Tasmania, Hobart, TAS, Australia

⁵Climate Change Research Centre, University of New South Wales, Sydney, New South
Wales, Australia

⁶Centre for Marine Science and Innovation, University of New South Wales, Sydney, New
South Wales, Australia

⁷Australian Research Council Centre of Excellence for the 21st Century Weather, Australia

⁸Frontiers Science Center for Deep Ocean Multispheres and Earth System and Key
Laboratory of Physical Oceanography, Ocean University of China, Qingdao, China.

⁹Laoshan Laboratory, Qingdao, China

Corresponding author: Ce Bian (cebian@ldeo.columbia.edu)

Abstract

Heatwaves rank among the most damaging climate extremes, with rising impacts on human health, ecosystems, and infrastructure. Despite substantial advances, heatwave research is still largely fragmented across regions, event types, and individual case studies, lacking a unified framework for characterizing heatwave evolution across different climatic regimes and spatial scales. Here, we present a framework, termed CELL, that tracks heatwaves as connected structures through space and time, enabling analysis of co-evolving thermodynamic and dynamical conditions throughout their lifecycles. Heatwaves globally exhibit pronounced propagation, expansion, and intensity changes throughout their lifecycle. Based on dominant thermodynamic and dynamical conditions during the mature stage, we classify global heatwaves into eight types that further consolidate into three principal environmental regimes: an extratropical circulation regime, a tropical oceanic subsidence regime, and a tropical continental surface-heating regime. Despite their diversity, global heatwaves exhibit coherent geographical distributions and preferred evolutionary pathways, revealing an physically interpretable organization underlying global heatwave diversity. These results highlight the value of representing climate extremes as evolving event–environment systems rather than isolated threshold exceedances.

Heatwaves (HWs) rank among the most dangerous weather hazards, characterized by prolonged extreme heat that threaten both ecosystems and human societies^{1,2}. Their impacts include elevated morbidity and mortality, agricultural losses, infrastructure strain, and economic disruption^{3–7}. When coinciding with droughts, wildfires, or severe air pollution, HWs form compound extremes that further amplify health risks and ecological stress^{8–10}. As global temperatures rise, such events are becoming more frequent, intense, and persistent^{11–13}. Now a recurring feature of the summer season, HWs have become a defining signal of climate change—shaping not only atmospheric conditions but also human behavior and societal tension^{14,15}. From urban unrest triggered by unbearable heat to disruptions in daily life and productivity, the social consequences of extreme temperatures are intensifying. Yet despite their rising prevalence and social consequences, the underlying physical diversity and spatial organization of HWs along their trajectory remain insufficiently understood at the global scale.

Previous studies have shown that atmospheric HWs can arise from different combinations of horizontal temperature advection, adiabatic warming, diabatic heating, and land–atmosphere feedbacks, with their relative importance varying substantially across regions and events^{3,16,17}. These studies provide important process-level understanding of why HWs occur. Subsequent work further demonstrated that many HWs are coherent and evolving phenomena, with Rossby-wave packets, blocking highs, and associated horizontal temperature transport playing important roles in their propagation and persistence^{18–22}. Together, these studies established that HWs should be viewed not only as local temperature extremes but also as coherent spatiotemporal structures embedded within larger-scale circulation systems.

Lagrangian approaches have attempted to bridge these perspectives by combining air-parcel tracking with process attribution. For example, Röthlisberger and Papritz²³ quantified the relative

contributions of horizontal advection, adiabatic warming, and diabatic heating to atmospheric hot extremes at the global scale. However, such approaches remain fundamentally parcel-centred, focusing on the thermal histories of air masses contributing to hot extremes rather than providing a common representation of HW events themselves. Consequently, while they provide powerful process attribution, they are less suited to comparing the lifecycle evolution, morphology, and environmental context of large HW populations.

Object-based approaches were subsequently developed to explicitly represent HWs as coherent spatiotemporal entities^{24–27}. These frameworks successfully quantify event characteristics such as duration, propagation, persistence, area, intensity, and trajectories, and have substantially improved our understanding of individual HW events. Some recent studies have further connected HW propagation to large-scale dynamical mechanisms, particularly Rossby-wave activity and associated temperature transport (e.g., Jiménez-Esteve and Domeisen²⁰; Wang et al.²¹). However, existing approaches remain focused on specific events, processes, or regional populations and do not provide a standardized framework through which HWs can be systematically compared across climatic regimes, spatial scales, and lifecycle stages.

The CELL framework builds upon the object-based perspective by representing HWs as coherent spatiotemporal entities while explicitly preserving their complete lifecycle evolution. Unlike conventional tracking approaches that primarily focus on the HW object itself, CELL simultaneously characterizes both the HW core and its surrounding environment, enabling the evolution of event–environment interactions to be examined within a unified framework. The environmental variables considered here are motivated by previous heat-budget and process-attribution studies, which consistently identify horizontal temperature advection, adiabatic warming, and diabatic heating as first-order contributors to atmospheric hot extremes (e.g.,

Zschenderlein et al.¹⁶; Schumacher et al.¹⁶; Röthlisberger and Papritz²³). Accordingly, the variables selected in CELL are not intended to constitute a closed heat budget, but rather to provide physically interpretable indicators of the thermodynamic and dynamical environments associated with HW evolution.

Most importantly, CELL standardizes the representation of HWs. By mapping events with different durations, spatial scales, morphologies, propagation pathways, and climatic backgrounds onto a common lifecycle coordinate system, the framework transforms diverse HW events into comparable objects regardless of their duration, size, trajectory, or geographical location, while preserving their associated environmental context. This enables large ensembles of HWs from different regions of the globe to be aggregated, compared, and analysed within a unified event-centred framework. As a result, recurring thermodynamic and dynamical structures, together with their associated environmental conditions, can be identified across the global HW population, enabling commonalities and regional differences to be examined within a single framework. Such synthesis is difficult to achieve using either process-attribution studies or conventional event-tracking approaches alone.

Here we apply CELL to 41 years of ERA5 reanalysis data²⁸ (1982–2022) to examine the lifecycle evolution of global HWs as coherent event–environment systems. By mapping individual HWs into a common lifecycle coordinate system, we compare their evolving thermodynamic and dynamical environments across regions, seasons, and spatial scales. We show that most global HWs can be organized into three physically interpretable regimes: extratropical HWs associated with circulation-driven warm-air transport, tropical oceanic HWs linked to subsidence and suppressed convection, and tropical continental HWs characterized by surface sensible heating and land–atmosphere coupling. Within these regimes, eight recurring lifecycle types and preferred

transition pathways describe how HWs form, intensify, propagate, and decay across different climatic settings. To focus on large-scale and persistent events, we retain only HWs with a spatial extent exceeding $5^\circ \times 5^\circ$ and a duration longer than five days (Fig. S1). Although developed here for HWs, CELL is formulated in general terms and could be adapted to other evolving climate extremes.

Characteristics of Global HW Lifecycles

By applying spatial and temporal filters, the semi-Lagrangian framework removes a large proportion of short-lived and spatially limited events. As a result, the number of detected HWs is substantially lower than under the Eulerian perspective, particularly in the tropics and mid-latitudes where Eulerian HWs occur frequently but are much less common after filtering (Fig. 1a and Fig. S2). This contrast reflects the exclusion of small-scale and short-duration anomalies from the semi-Lagrangian catalogue (Fig. S1c). To compare HW temporal evolution, each HW lifetime is normalized to a 0–1 scale, where $t = 0$ marks initiation and $t = 1$ marks termination (Fig. 1b). Compositing all HW events we find that area and cumulative intensity follow a similar evolution, on average increasing monotonically to a maximum at $t = 0.5$ and then decreasing monotonically thereafter. In contrast, the maximum intensity saturates by $t \approx 0.25$, remains stable until $t \approx 0.75$, and then declines (Fig. 1b). We therefore define this interval ($t \approx 0.25 - 0.75$) as the HW “mature phase,” during which heat sources and sinks modulate cumulative intensity primarily through expansion or contraction of the HW, while the maximum intensity remains relatively stable.

To examine differences between land and ocean HWs, we classify events by their centroid location at onset, designating them as land- or ocean-originated (Fig. 1c). Of all HWs, 33.7% are land-originated and 66.3% are ocean-originated, a ratio close to the relative area of land and ocean. For both types, HW occur more frequently near the coast, with events frequency decreasing

progressively with offshore distances (Fig. 1c). This is a statistical artefact: because the surface area contained within each distance bin diminishes away from the coast, uniformly distributed points produce a peak at the coastline that reflects the geometry of available area, not any real change in event density. The proportion of HWs decreases with increasing lifetime, a pattern that holds for both land- and ocean-originated events (Fig. 1d). Nearly half (46%) of tracked HWs persist for more than one week, whereas 81% terminate within two weeks (Fig. 1d). The primary distinction between these HWs lies in their intensity: land-originated HWs generally reach stronger maximum values than ocean-originated HWs (Fig. 1e). The interquartile range of maximum intensity for land-originated HWs is 7.8–14.5 °C, compared with 2.8–9.2 °C for ocean-originated HWs (Fig. 1e). By contrast, both types display similarly skewed distributions toward longer and larger displacements, with largely overlapping interquartile ranges (Fig. 1f–g).

Examining HW centroid displacement across their lifecycles, we find that 40% of events occur in the tropics (0–30°N/S), evenly split between hemispheres, and propagating primarily in the east–west direction (Fig. 1h–i). Given that the tropics cover ~50% of Earth’s surface, this indicates a lower-than-expected event density compared to a random distribution. Another 35% originate in the midlatitudes (15% in 30°–60°N; 20% in 30°–60°S), where they propagate mainly eastward, consistent with prevailing westerlies (Fig. 1j–k). The remaining 25% of events are distributed across the polar regions (12% in 60–90°N and 13% in 60–90°S, Fig. 1l–m). In contrast to the tropics, the polar regions occupy only ~13% of Earth’s surface, suggesting a higher than would be expected from a random distribution. The regional density of HWs exhibits a pronounced latitude dependence²⁹ (Fig. S3a). Events within 0–30°N/S are characterized by low density and predominantly weaker intensities. By contrast, HWs originate in latitudes above 60°N/S contribute

disproportionately to the highest-intensity events, although their maximum area and displacement remain smaller than those in other regions (Fig. S3b-d).

HW Classification via the CELL Method

Beyond their geographic displacement, HWs undergo substantial changes in shape, area, and environmental context throughout their lifecycles. To compare these evolving structures, we use the CELL framework (see “Event-centered CELL representation” for details) to represent each HW within a common event-centered domain (Fig. 2a). In this representation, the inner CELL captures the HW core, while the outer CELL captures the surrounding environment. This two-zone structure allows thermodynamic and dynamical conditions inside the HW and in its environmental background to be compared consistently across events with different sizes, durations, and trajectories.

Composites of all tracked HWs show pronounced warming within the inner CELL and weaker anomalies in the surrounding environment, confirming that the CELL representation captures the contrast between the HW core and its environmental background (Fig. 2b). The associated thermodynamic and dynamical anomalies exhibit broadly similar spatial structures across lifecycle stages, with the clearest and most stable organization during the mature phase (Fig. S4). We therefore use the mature phase to classify HWs into recurring process states based on three diagnostic dimensions³: surface sensible heat flux anomalies (SHA), 850-hPa vertical velocity anomalies (W850), and surface pressure anomalies (SPA). These indicators were selected because they represent complementary thermodynamic and dynamical aspects of HW evolution. SHA characterizes the contribution of surface–atmosphere heat exchange, W850 represents vertical motion and its associated adiabatic effects, and SPA provides information on large-scale circulation patterns and preferential warm-air transport. Together, these diagnostics provide a

physically interpretable description of HW states while remaining compatible with the event-centered CELL representation. They are used here as process-state indicators rather than as a complete decomposition of temperature tendencies.

We therefore use the mature phase as a reference window to classify global HWs into eight recurring process states (Fig. 2c–e). Types 1–4 are characterized by negative SHA, whereas Types 5–8 exhibit positive SHA (Fig. 2c). Within each group, vertical motion further separates states associated with subsidence (Types 1–2 and 5–6) from those associated with ascent (Types 3–4 and 7–8) (Fig. 2d). In addition, odd-numbered types (1, 3, 5, and 7) exhibit coherent SPA dipole structures associated with poleward-directed circulation, whereas even-numbered types generally lack a pronounced circulation signature (Fig. 2e). Together, these three diagnostic dimensions organize global HWs into eight physically interpretable process states. Similar classifications obtained during the growing and decaying phases show broadly consistent spatial distributions of dominant HW types (Figs. S5–6), indicating that the identified process states are robust throughout the HW lifecycle. Anomalies of additional HW-related variables, including cloud cover, precipitation and humidity, are shown in Fig. S7.

These dynamic/thermodynamic types exhibit clear geographical preferences (Fig. 3a–c). Positive SHA states are most common across tropical and subtropical land regions, including southern Africa, the Indian subcontinent, northern South America, and northern Australia, whereas negative SHA states are more prevalent over tropical oceans and high-latitude regions (Fig. 3a). States characterized by anomalous subsidence occur widely across tropical oceans, tropical rainforest regions, and parts of the subtropics, whereas ascent-associated states are more common in the extratropics (Fig. 3b). Poleward-directed geostrophic flow dominates HWs across much the

globe, except for parts of the tropical Pacific and the region encompassing Indian subcontinent and the surrounding seas (Fig. 3c).

The combination of these three diagnostic dimensions produces distinct geographical distributions of the eight HW process states (Fig. 3d; Fig. S8). Rather than being randomly distributed, individual HW types occupy coherent spatial domains, indicating that the occurrence of different process states is strongly influenced by regional climate and circulation backgrounds. Similar geographical patterns emerge when the classification is applied during the growing and decaying phases (Figs. S5–6), suggesting that the identified states are robust throughout the HW lifecycle. This geographical organization provides the basis for the broader HW regimes discussed below.

Statistical Traits of the Eight HW Types

Type 3, which is associated with strong poleward advection, is the most prevalent category, making up the dominant HW type for 51% of global events (Fig. 3d; Fig. S8c). In addition to its frequent occurrence and broad spatial coverage, Type 3 HWs tend to be the largest (Fig. 3e). These events are characterized by poleward-directed geostrophic flow, as indicated by the wind direction, which would contribute to warming in non tropical regions where climatological temperatures consistently decrease towards the poles. Interestingly, Type 3 HWs are also associated with upward motion and negative SHA, both of which would have a cooling influence on the surface air.

Types 1 and 2 collectively comprise 26% of global events and dominate tropical oceanic regions, except in the eastern Pacific (Fig. 3d; Fig. S8a-b). Despite their prevalence, other factors including their intensity, duration, and spatial extent are not notably distinct from other HW types

(Fig. 3e). Both are linked to subsidence-driven warming yet exhibit negative SHA, with Type 1 additionally showing a poleward wind-stress dipole (SPA), a feature absent in Type 2 (Fig. 2d).

Types 4–6 are less frequent, accounting for 11% of global events (Fig. 3d). Type 4 (4%) HWs are primarily confined to the Arabian Sea and Ross Sea (Fig. S8d). Surprisingly this type exhibits cooling signatures across all three indicators. Despite this unfavorable configuration, it is associated with the highest peak intensity and second highest cumulative intensity (Fig. 3e). In contrast, Type 5 HWs (4%) exhibit favorable heating signatures across all three indicators. These events are most prevalent over parts of the Amazon Basin (Fig. 3d; Fig. S8e). Notably, Type 5 HWs have the longest mean duration among all HW types (Fig. 3e). Type 6 HWs account for 3% of global events and occur predominantly over the Indian subcontinent and the Indochina Peninsula (Fig. 3d; Fig. S8f). They are characterized by positive SHA, weak or near-neutral vertical motion, and represent a positive SPA gradient across the entire CELL, although the anomalies are more pronounced within the core CELL (Fig. 2b-e). Both Type 5 and 6 are associated with strong reductions in cloud cover, which would heat the land potentially amplifying sensible heat flux (Fig. S7).

Types 7 and 8 together account for 12% of global events and are largely associated with tropical continental interiors (Fig. 3d; Fig. S8g-h). Type 7 (9%) HWs are widespread over tropical landmasses, occurring across southern Africa, inland Australia, northeastern South America, and the Tibetan Plateau (Fig. S8g). This Type combines positive SHA and poleward geostrophic flow to promote surface warming, while exhibiting ascending motion that would have a new cooling effect aloft. Type 7 ranks second among all types in both composite average intensity and duration (Fig. 3e). By contrast, Type 8 accounts for only 3% of global events and does not dominate any particular region (Fig. S8h), but ranks highest in cumulative intensity (Fig. 3e).

Organization of global heatwave regimes

Based on the above analysis, global HWs organize into three dominant regimes characterized by distinct combinations of thermodynamic and dynamical conditions: (i) extratropical HWs, (ii) tropical oceanic HWs, and (iii) tropical continental HWs (Fig. 4). These regimes are not defined a priori, but emerge from the geographical organization of the eight HW types shown in Fig. 3d. The dominant-type distribution indicates that different process states occupy coherent spatial domains, suggesting that the diversity of global HWs is strongly constrained by regional climate and circulation backgrounds.

Extratropical HWs are predominantly represented by Type 3, which represent the most frequent process state in the global population (Fig. 3d, Fig. 4a). These events occur widely across the midlatitudes and high latitudes and are characterized by poleward-directed geostrophic flow and surface-pressure dipoles that favor warm-air transport toward the HW center. The widespread occurrence of this regime is consistent with previous studies highlighting the importance of warm-air advection, Rossby-wave activity, blocking, and baroclinic circulation anomalies in shaping extratropical heat extremes^{30,31}. The apparent dominance of Type 3 does not necessarily imply a larger number of independent events, but likely reflects the persistence, propagation, and spatial expansion of these HWs, which increase their contribution to the global HW population (Fig. S2).

Tropical HWs occurring within 15°S to 15°N are most commonly associated with large-scale subsidence in the free troposphere (Fig. 3b). These conditions reduce cloud cover and enhance incoming shortwave radiation, creating an environment favorable for surface warming and HW development (Fig. S7). Such circulation environments are broadly consistent with previous studies linking tropical heat extremes to large-scale modes of atmospheric variability, including variations in MJO activity, Walker circulation, and Indian Ocean circulation patterns^{17,32–34}.

Despite sharing a common subsidence-dominated background, tropical oceanic and continental HWs exhibit contrasting thermodynamic characteristics due to fundamental differences in surface properties. Tropical oceanic HWs (Types 1–2) occur primarily over the tropical Pacific, Atlantic, and Indian Oceans and are characterized by negative SHA despite enhanced incoming shortwave radiation (Fig. 3d). This pattern suggests a reduction in upward sensible heat flux as the lower atmosphere warms relative to the ocean surface (Fig. 4b). In contrast, tropical continental HWs (Types 5–8) dominate tropical and subtropical land regions and exhibit positive SHA, reflecting enhanced surface sensible heating and stronger land–atmosphere coupling (Fig. 4c). The stronger thermal response of land surfaces to radiative forcing promotes the development of near-surface thermal anomalies and contributes to sustained HW conditions.

Within tropical continental regions, Types 5–6 occur preferentially in climatologically convective environments, whereas Types 7–8 are more common over drier continental interiors. Although these subtypes differ in their local environmental conditions, both are characterized by positive SHA and enhanced land–atmosphere coupling, indicating that surface heating remains the dominant organizing feature of tropical continental HWs. This interpretation is consistent with previous studies emphasizing the importance of land-surface feedbacks and boundary-layer processes in amplifying continental heat extremes³⁵.

Large seasonal changes in background climate conditions are expected to influence the environments in which HWs occur. We therefore repeated the classification separately for each season (Fig. S9). While the broad geographical organization of HW types remains similar across seasons, several notable regional shifts emerge. During boreal summer (JJA), Type 5 expands substantially and becomes the dominant HW state across large parts of East Asia and North America. At the same time, Type 8 becomes increasingly prominent across Europe, while Type 1

extends westward into the western North Atlantic. Despite these seasonal variations, Type 3 remains the dominant HW type globally in every season, accounting for 43–55% of all events and retaining its widespread distribution across the extratropics. This indicates that the global prevalence of Type 3 is not simply an artifact of seasonal aggregation.

Taken together, the spatial organization shown in Fig. 3d and the seasonal analysis in Fig. S9 demonstrate that the eight HW types are not randomly distributed but cluster into coherent geographical and seasonal regimes. Rather than forming a continuous spectrum of independent behaviors, global HWs organize into a limited number of recurring process states and broader dynamical regimes. These results provide an event-centered view of how extreme heat is structured across regions, seasons, and climates.

Discussion.

Traditional HW analyses have primarily relied on Eulerian frameworks that diagnose events using time series at fixed locations, whereas more recent object-based approaches have enabled coherent tracking of individual events^{25–27}. However, comparing the physical evolution of HWs across different climatic environments remains challenging because events differ substantially in their duration, morphology, propagation, and surrounding environmental conditions. Here we address this challenge using an event-centered representation that characterizes both HW evolution and its co-evolving environment within a common framework. Using this approach, we show that most global HWs can be organized into three recurring physical regimes: extratropical HWs dominated by circulation-driven warm-air transport, tropical oceanic HWs associated with large-scale subsidence, and tropical continental HWs characterized by enhanced surface sensible heating and land–atmosphere coupling. Within these regimes, eight recurring lifecycle types and preferred evolutionary pathways describe how HWs form, intensify, propagate, and decay across diverse

climatic settings (Fig. 3 and Fig. 4). Together, these findings show that the apparent diversity of global HWs can be understood within a limited number of recurring physical regimes despite their wide geographical distribution and environmental variability.

The three identified regimes reflect fundamental contrasts in the thermodynamic and dynamical environments that support heatwave development across the globe. Extratropical HWs are predominantly associated with circulation-driven warm-air transport, consistent with the importance of Rossby-wave activity, blocking, and meridional temperature gradients documented in previous studies^{3,20,23,36}. In contrast, tropical oceanic HWs develop preferentially under large-scale subsidence, where suppressed convection and enhanced incoming shortwave radiation favour atmospheric warming. Tropical continental HWs, by comparison, are characterized by enhanced surface sensible heating and strong land–atmosphere coupling, reflecting the rapid thermal response of land surfaces to radiative forcing. These results suggest that, despite the remarkable diversity of individual heatwaves, their physical evolution is governed by a limited number of recurring environmental regimes.

The CELL framework is not intended to replace process-attribution studies based on temperature-budget analyses, air-parcel tracking^{36–38}, or existing object-based tracking approaches^{25–27}. Instead, it complements these methods by providing a standardized event-centered representation through which heatwaves with different sizes, durations, trajectories, and morphologies can be compared systematically throughout their lifecycle. This complementary perspective facilitates global synthesis while remaining fully compatible with detailed process-based analyses.

More broadly, our results suggest that representing heatwaves as evolving event–environment systems enables systematic comparison of their physical evolution across regions and climates.

Rather than viewing heatwaves solely as isolated temperature anomalies, this perspective reveals recurring physical regimes and common evolutionary pathways across diverse climatic settings. Such an event-centered framework provides a useful foundation for future studies of heatwave predictability, climate-change responses, and impacts, and can be readily extended to other coherent climate extremes, including marine heatwaves, heavy precipitation, atmospheric blocking, and compound events.

Methods

Data. This study utilizes the ERA5²⁸ global reanalysis dataset for HW tracking and analysis of their synoptic characteristics. Produced by the European Centre for Medium-Range Weather Forecasts (ECMWF), ERA5 is a fifth-generation global reanalysis product, replacing ERA-Interim and offering improved accuracy in temperature, precipitation, and wind speed. ERA5 provides atmospheric data at a 0.25° horizontal resolution, with six-hourly output frequency. The dataset used for HW tracking spans 1982–2022, with HW identification based on daily maximum temperature (T_{max}) at 2-meter above the surface, derived from the highest T_{max} recorded each day. Beyond temperature, additional atmospheric and oceanic variables—including total and decomposed heat fluxes, horizontal and vertical near-surface winds, total cloud cover, and precipitation during HW events—are also extracted from ERA5 to characterize the environmental conditions associated with HWs.

Heatwave identification and object tracking. HWs are first identified at each grid cell using daily T_{max} from ERA5. A HW is defined as a period during which T_{max} exceeds its day-of-year varying 90th percentile climatological threshold, calculated over the 1982–2022 baseline period, for at least three consecutive days³⁹. This produces a binary global HW field at each time step, with HW-affected grid cells assigned a value of 1 and all other grid cells assigned a value of 0. At

each time step, we apply a K-nearest-neighbour spatial smoothing filter, defining a HW occurrence in a grid cell when more than half of the surrounding $5^\circ \times 5^\circ$ neighbourhood also experiences HW conditions. Contiguous regions of HW conditions are then delineated as HW objects, and only objects exceeding an area of $5^\circ \times 5^\circ$ are retained.

Because the smoothing and size thresholds are defined on a latitude–longitude grid, the method does not fully account for the decrease in grid-cell area toward the poles. This may introduce a latitude-dependent sampling bias. To evaluate its potential influence, we compared the observed latitudinal distribution of HW centroids with an area-based null expectation generated from 1,000 random redistributions of the same number of centroids. The bootstrap experiment yields 50.2% of events within 30°N/S , compared with 40% in the observed HW catalogue, indicating that the primary latitudinal patterns reported here cannot be explained solely by the geometry of the underlying grid. Similar grid-based smoothing approaches have been adopted in previous object-based studies of marine heatwave^{40–42} and atmospheric heatwaves²⁶.

To capture the evolution of spatially coherent HW structures, we apply an object-based semi-Lagrangian tracking framework⁴². We use the term semi-Lagrangian to indicate that the framework follows the evolving HW object rather than fixed grid points, while not tracking individual air parcels. The continuity of HW objects is determined using an overlap-based tracking criterion: objects at consecutive time steps are considered part of the same HW event when their areal overlap exceeds 50%. This criterion balances temporal continuity against the risk of linking unrelated anomalies; higher thresholds tend to fragment evolving events, whereas lower thresholds increase the likelihood of false connections between nearby structures. These connected HW objects are referred to as HW trajectories (Table S1).

Only HW events that persist for at least five consecutive days are retained. The rationale for the principal tracking parameters, including the smoothing procedure, connectivity definition, minimum event size, minimum event duration, and overlap criterion, is summarized in Table S2. As with all object-based tracking methods, rapidly evolving events may undergo growth, decay, deformation, splitting, or merging. The treatment of these cases follows the same object-continuity logic and is described in Table S2. Sensitivity analyses using alternative tracking choices and temperature products are summarized in Table S3 and indicate that the principal characteristics of the tracked HW population remain broadly consistent across reasonable parameter variations.

Event-centered CELL representation. To facilitate comparisons among HW trajectories with different sizes, shapes, durations, and geographical locations, we introduce an event-centered representation referred to as a CELL. The objective is not simply to track HW objects, but to express diverse events within a common coordinate system that enables systematic comparison of their structure, environmental context, and lifecycle evolution.

For each time step in a HW evolution pathway, we compute the object centroid and the maximum distance from the centroid to the HW boundary (HW extent). We define R as the maximum extent attained during the full HW evolution pathway. At each time step, the HW object is translated such that its centroid is located at the center of the coordinate system and scaled by R . This normalization removes differences in absolute location and event size while preserving the relative spatial structure of the HW. To examine variables associated with HW evolution, we define a circular CELL domain with radius $2R$, consisting of an inner HW core and an outer annulus representing the surrounding environment (Fig. 2a). The R - $2R$ annulus is not intended to represent a unique or physically optimal environmental boundary. Rather, it provides a standardized environmental reference against which the HW core can be evaluated throughout its

lifecycle. This event–environment configuration enables direct comparison between conditions inside and outside the HW, allowing event–environment contrasts and the co-evolution of the HW with its surrounding atmosphere to be characterized consistently across events.

The resulting framework occupies an intermediate position between traditional Eulerian analyses and parcel-based Lagrangian approaches. While the evolving HW object is followed through space and time, the framework does not track individual air parcels. Instead, it provides a standardized event-centered representation that preserves both event identity and environmental context, enabling HWs with different morphologies, sizes, and trajectories to be analyzed within a common physical framework.

Lifecycle normalization. HW duration is defined as the number of consecutive days during which the tracked object exists. To facilitate comparisons among events with different lifetimes, each HW evolution period is normalized to a dimensionless timescale ranging from 0 to 1, where ($t = 0$) and ($t = 1$) denote event initiation and termination, respectively, and ($t = 0.5$) represents the midpoint of the event (Fig. 1b). Combined with the spatial normalization described above, this temporal normalization allows HWs with different sizes, durations, and trajectories to be represented within a common event-centered framework. Consequently, lifecycle evolution can be compared systematically across a global population of HWs, enabling the identification of recurring growth, mature, and decay characteristics that would otherwise be difficult to detect using conventional Eulerian analyses. The complete procedure—from HW identification and object tracking to spatial and temporal normalization—is referred to as the CELL method.

Process-state classification. To characterize the thermodynamic and dynamical conditions associated with HW evolution, we extract three diagnostic indicators from each CELL: (i) surface sensible heat flux anomalies (SHA), representing anomalous surface heating; (ii) 850-hPa vertical

velocity anomalies (W850), representing vertical motion and associated adiabatic effects; and (iii) surface pressure anomalies (SPA), representing large-scale circulation configurations associated with preferential warm-air transport. These indicators are not interpreted as closed temperature-budget terms, nor are they intended to provide a complete decomposition of temperature tendencies. Instead, they serve as physically interpretable diagnostics that capture recurring thermodynamic and dynamical states associated with HW evolution. The selection of these indicators is motivated by their ability to represent three complementary dimensions of HW development: surface heating, vertical motion, and large-scale circulation.

HWs are classified according to the sign combinations of these three diagnostic dimensions. Positive and negative anomalies of SHA and W850 define four thermodynamic–dynamical states, while the presence or absence of poleward-directed large-scale flow inferred from the circulation pattern further separates these states, yielding a total of eight HW types (Fig. 2 and Fig. 3). The resulting classification therefore corresponds to the 2^3 combinations of three physically interpretable process dimensions. Importantly, the eight HW types are not obtained from an unconstrained clustering algorithm. Rather than seeking statistically optimal separation, the classification is designed to preserve physical interpretability and facilitate comparisons of lifecycle evolution across regions, climates, and event types. In this framework, each HW type should be interpreted as a recurring process state rather than a unique physical mechanism. To further characterize the environmental conditions associated with each process state, we additionally examine humidity, precipitation, cloud cover, and other auxiliary variables (Fig. S7). These variables are not used in the classification itself but provide additional physical context for interpreting the thermodynamic and dynamical characteristics of each HW type.

Data availability.

The ERA5 reanalysis data used in this study are publicly available from the Copernicus Climate Data Store (<https://cds.climate.copernicus.eu/>). Additional intermediate outputs are available from the corresponding author upon reasonable request.

Code availability.

The code implementing the CELL framework, including heatwave tracking, structural diagnostics, and classification algorithms, will be uploaded to the Code Ocean platform upon request from the editor. For peer review, an anonymized version of the scripts is temporarily available at:

https://github.com/ZijieZhaoMHW/MHW_tracking. A patent application covering this method is currently under preparation, and the full public release of the repository will follow once the review and protection process are completed.

References

1. Barriopedro, D., García-Herrera, R., Ordóñez, C., Miralles, D. G. & Salcedo-Sanz, S. Heat Waves: Physical Understanding and Scientific Challenges. *Reviews of Geophysics* **61**, e2022RG000780 (2023).
2. Perkins, S. E. A review on the scientific understanding of heatwaves—Their measurement, driving mechanisms, and changes at the global scale. *Atmospheric Research* **164–165**, 242–267 (2015).
3. Horton, R. M., Mankin, J. S., Lesk, C., Coffel, E. & Raymond, C. A Review of Recent Advances in Research on Extreme Heat Events. *CURRENT CLIMATE CHANGE REPORTS* **2**, 242–259 (2016).
4. Mora, C. *et al.* Global risk of deadly heat. *NATURE CLIMATE CHANGE* **7**, 501+ (2017).
5. Lesk, C., Rowhani, P. & Ramankutty, N. Influence of extreme weather disasters on global crop production. *NATURE* **529**, 84+ (2016).

- 470 6. Dunne, J. P., Stouffer, R. J. & John, J. G. Reductions in labour capacity from heat stress
471 under climate warming. *NATURE CLIMATE CHANGE* **3**, 563–566 (2013).
- 472 7. Anderegg, W. R. L., Kane, J. M. & Anderegg, L. D. L. Consequences of widespread tree
473 Mortality triggered by drought and temperature stress. *NATURE CLIMATE CHANGE* **3**, 30–36
474 (2013).
- 475 8. De Luca, P., Messori, G., Faranda, D., Ward, P. J. & Coumou, D. Compound warm–dry
476 and cold–wet events over the Mediterranean. *Earth Syst. Dynam.* **11**, 793–805 (2020).
- 477 9. Zscheischler, J. & Seneviratne, S. I. Dependence of drivers affects risks associated with
478 compound events. *Sci. Adv.* **3**, e1700263 (2017).
- 479 10. Zuo, J. *et al.* Impacts of heat waves and corresponding measures: a review. *JOURNAL*
480 *OF CLEANER PRODUCTION* **92**, 1–12 (2015).
- 481 11. Wang, C. *et al.* Changes in Global Heatwave Risk and Its Drivers Over One Century.
482 *Earth's Future* **12**, e2024EF004430 (2024).
- 483 12. Perkins-Kirkpatrick, S. E. & Lewis, S. C. Increasing trends in regional heatwaves.
484 *NATURE COMMUNICATIONS* **11**, (2020).
- 485 13. Gao, Y. *et al.* More Frequent and Persistent Heatwaves Due To Increased Temperature
486 Skewness Projected by a High-Resolution Earth System Model. *Geophysical Research Letters*
487 **50**, e2023GL105840 (2023).
- 488 14. Coumou, D., Petoukhov, V., Rahmstorf, S., Petri, S. & Schellnhuber, H. J. Quasi-
489 resonant circulation regimes and hemispheric synchronization of extreme weather in boreal
490 summer. *Proc. Natl. Acad. Sci. U.S.A.* **111**, 12331–12336 (2014).
- 491 15. Domeisen, D. I. V. *et al.* Prediction and projection of heatwaves. *Nat Rev Earth Environ*
492 **4**, 36–50 (2022).

- 493 16. Zschenderlein, P., Fink, A. H., Pfahl, S. & Wernli, H. Processes determining heat waves
494 across different European climates. *Quart J Royal Meteor Soc* **145**, 2973–2989 (2019).
- 495 17. Schumacher, D. L., Hauser, M. & Seneviratne, S., I. Drivers and Mechanisms of the 2021
496 Pacific Northwest Heatwave. *EARTHS FUTURE* **10**, (2022).
- 497 18. Fragkoulidis, G., Wirth, V., Bossmann, P. & Fink, A. H. Linking Northern Hemisphere
498 temperature extremes to Rossby wave packets. *QUARTERLY JOURNAL OF THE ROYAL*
499 *METEOROLOGICAL SOCIETY* **144**, 553–566 (2018).
- 500 19. Kornhuber, K. *et al.* Amplified Rossby waves enhance risk of concurrent heatwaves in
501 major breadbasket regions. *Nat. Clim. Chang.* **10**, 48–53 (2020).
- 502 20. Jiménez-Esteve, B. & Domeisen, D. I. V. The role of atmospheric dynamics and large-
503 scale topography in driving heatwaves. *Quart J Royal Meteor Soc* **148**, 2344–2367 (2022).
- 504 21. Wang, M. *et al.* Evidence for preferred propagating terrestrial heatwave pathways due to
505 Rossby wave activity. *Nat Commun* **16**, 4742 (2025).
- 506 22. Chapman, C. C. *et al.* The Typicality of Regimes Associated with Northern Hemisphere
507 Heatwaves. *Journal of Climate* **38**, 3729–3750 (2025).
- 508 23. Röthlisberger, M. & Papritz, L. Quantifying the physical processes leading to
509 atmospheric hot extremes at a global scale. *Nat. Geosci.* **16**, 210–216 (2023).
- 510 24. Sánchez-Benítez, A., Barriopedro, D. & García-Herrera, R. Tracking Iberian heatwaves
511 from a new perspective. *Weather and Climate Extremes* **28**, 100238 (2020).
- 512 25. Lo, S.-H., Chen, C.-T., Russo, S., Huang, W.-R. & Shih, M.-F. Tracking heatwave
513 extremes from an event perspective. *Weather and Climate Extremes* **34**, 100371 (2021).
- 514 26. King, M. J. & Reeder, M. J. Extreme heat events from an object viewpoint with
515 application to south-east Australia. *Intl Journal of Climatology* **41**, 2693–2709 (2021).

- 516 27. Luo, M. *et al.* Anthropogenic forcing has increased the risk of longer-traveling and
517 slower-moving large contiguous heatwaves. *Sci. Adv.* **10**, ead11598 (2024).
- 518 28. Hersbach, H. *et al.* The ERA5 global reanalysis. *Quart J Royal Meteor Soc* **146**, 1999–
519 2049 (2020).
- 520 29. Jimenez-Esteve, B., Kornhuber, K. & Domeisen, D. I., V. Heat Extremes Driven by
521 Amplification of Phase-Locked Circumglobal Waves Forced by Topography in an Idealized
522 Atmospheric Model. *GEOPHYSICAL RESEARCH LETTERS* **49**, (2022).
- 523 30. Byers, H. R. *General Meteorology*. (McGraw-Hill, 1959).
- 524 31. Charney, J. G. The Dynamics of Long Waves in a Baroclinic Westerly Current. *J.*
525 *Meteor.* **4**, 136–162 (1947).
- 526 32. Rajeev, A., Mahto, S. S. & Mishra, V. Climate warming and summer monsoon breaks
527 drive compound dry and hot extremes in India. *iScience* **25**, 105377 (2022).
- 528 33. Devi, R., Gouda, K. C. & Lenka, S. Intensity duration and frequency of Heat wave in
529 different phases of MJO over India. *Atmospheric Research* **300**, 107250 (2024).
- 530 34. Eggeling, J. *et al.* Spatiotemporal link between El Niño Southern Oscillation (ENSO),
531 extreme heat, and thermal stress in the Asia–Pacific region. *Sci Rep* **14**, 7448 (2024).
- 532 35. Liu, J. & Li, M. Characteristics and Driving Mechanisms of Heatwaves in China During
533 July and August. *Atmosphere* **16**, 434 (2025).
- 534 36. Noyelle, R., Faranda, D., Robin, Y., Vrac, M. & Yiou, P. Attributing the occurrence and
535 intensity of extreme events with the flow analogue method. *Weather Clim. Dynam.* **6**, 817–839
536 (2025).
- 537 37. Mayer, A. & Wirth, V. Two different perspectives on heatwaves within the Lagrangian
538 framework. *Weather Clim. Dynam.* **6**, 131–150 (2025).

38. Mayer, A. & Wirth, V. Lagrangian description of the atmospheric flow from Eulerian tracer advection with relaxation. *Quart J Royal Meteorol Soc* **149**, 1271–1292 (2023).
39. Perkins, S. E. & Alexander, L. V. On the Measurement of Heat Waves. *Journal of Climate* **26**, 4500–4517 (2013).
40. Zhao, Z. *et al.* Toward a mechanistic characterisation of marine heatwaves. *Sci Rep* **16**, 11092 (2026).
41. Scannell, H. A. *et al.* Spatiotemporal Evolution of Marine Heatwaves Globally. *Journal of Atmospheric and Oceanic Technology* **41**, 1247–1263 (2024).
42. Sun, D., Jing, Z., Li, F. & Wu, L. Characterizing global marine heatwaves under a spatio-temporal framework. *Progress in Oceanography* **211**, 102947 (2023).
43. Luo, M. *et al.* Two different propagation patterns of spatiotemporally contiguous heatwaves in China. *npj Clim Atmos Sci* **5**, 89 (2022).

553 **Acknowledgments.**

554 Computing resources were provided by the National Computational Infrastructure (NCI),
555 supported by the Australian Government. ERA5 reanalysis data used in this study were provided
556 by the European Centre for Medium-Range Weather Forecasts (ECMWF).

557 **Funding**

558 The authors received no specific funding for this work.

559 **Author Contributions.**

560 C.B. conceived the study, designed the analytical framework, developed the CELL-based
561 diagnostic system, elucidated the physical mechanisms, and led the manuscript writing. Z.Z. wrote
562 the main codes, conduct the computational analysis, and process the main figure generations.
563 A.S.G. provided invaluable scientific input throughout the study, offering key suggestions that
564 helped sharpen the methodological structure, improve the diagnostic clarity, and strengthen the
565 physical interpretation. A.S.G, A.T. and L. W. contributed to manuscript review and provided
566 insightful feedback during the final revision stages. All authors contributed to the interpretation of
567 findings and reviewed the manuscript.

568 **Competing Interests**

569 The authors declare no competing interests.

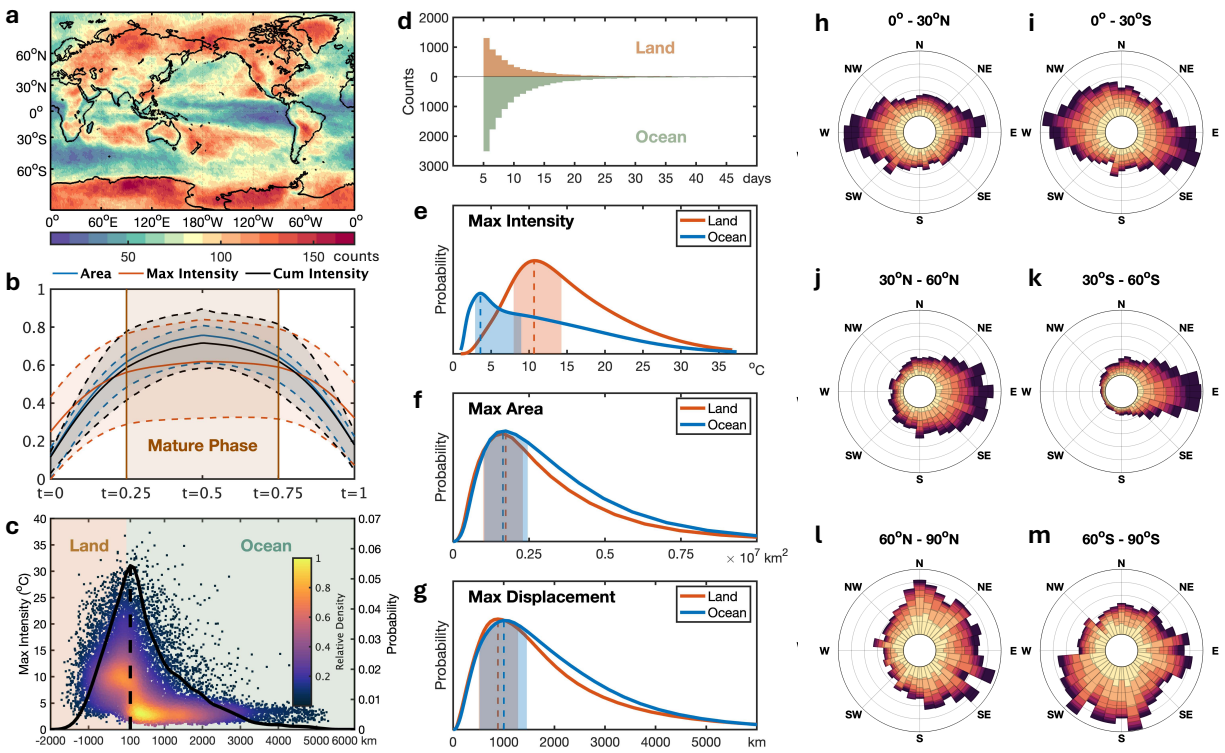


Figure 1 | Global Heatwave (HW) trajectories and properties. (a) HW evolution pathway densities, representing the number of tracked HWs passing through each grid cell during 1982–2022. (b) Average relative cumulative intensity (black), relative intensity (red), and relative spatial area (blue) of HWs, shown on a normalized 0–1 timescale ($t = 0$ and $t = 1$ denote initiation and termination). Apart from the unified timescale, each factor is normalized by dividing its maximum value during the HW lifecycle, referred to as “relative.” Definitions of these factors are provided in Table S1. Shading between dashed lines indicates the standard deviation across all HW events. The shaded region between $t = 0.25$ and $t = 0.75$ defines the “mature phase”. (c) Probability distribution of tracked HWs as a function of their centroid distance from the coastline at start time. Red and light blue shading indicate the land and ocean sides, respectively. Colored spots represent the relative density of HW events. The black line shows the probability distribution of HWs with respect to their distance from the coastline, and the dashed line marks the location with the highest

583 probability ratio. **(d)** Frequency distribution of land- and ocean-originated HW lifetimes, shown
584 as orange and green bars, respectively. **(e)** Probability distributions of the maximum intensity of
585 land-originating HWs (red) and ocean-originating HWs (blue). Shaded bands denote the
586 interquartile range (25th–75th percentiles), and the dashed line marks the location of the highest
587 probability density. Similarly, **(f)** and **(g)** show the probability distributions of the maximum area
588 and maximum displacement of land- and ocean- originate HWs, respectively. **(h–m)** Distribution
589 of HW centroid displacements? for different latitude ranges, shown as wind rose charts: **(h)** 0°–
590 30°N, **(i)** 0°–30°S, **(j)** 30°N–60°N, **(k)** 30°S–60°S, **(l)** 60°N–90°N, and **(m)** 60°S–90°S. Movement
591 direction is defined as the vector from the centroid during the first half of the lifecycle to that in
592 the second half, following Luo et al. in 2022⁴³. The latitude band is assigned based on the centroid
593 location of the HW event at its origin time. Colours denote HW densities, and radial displacement
594 from the plot centre is scaled to the maximum centroid displacement observed.
595

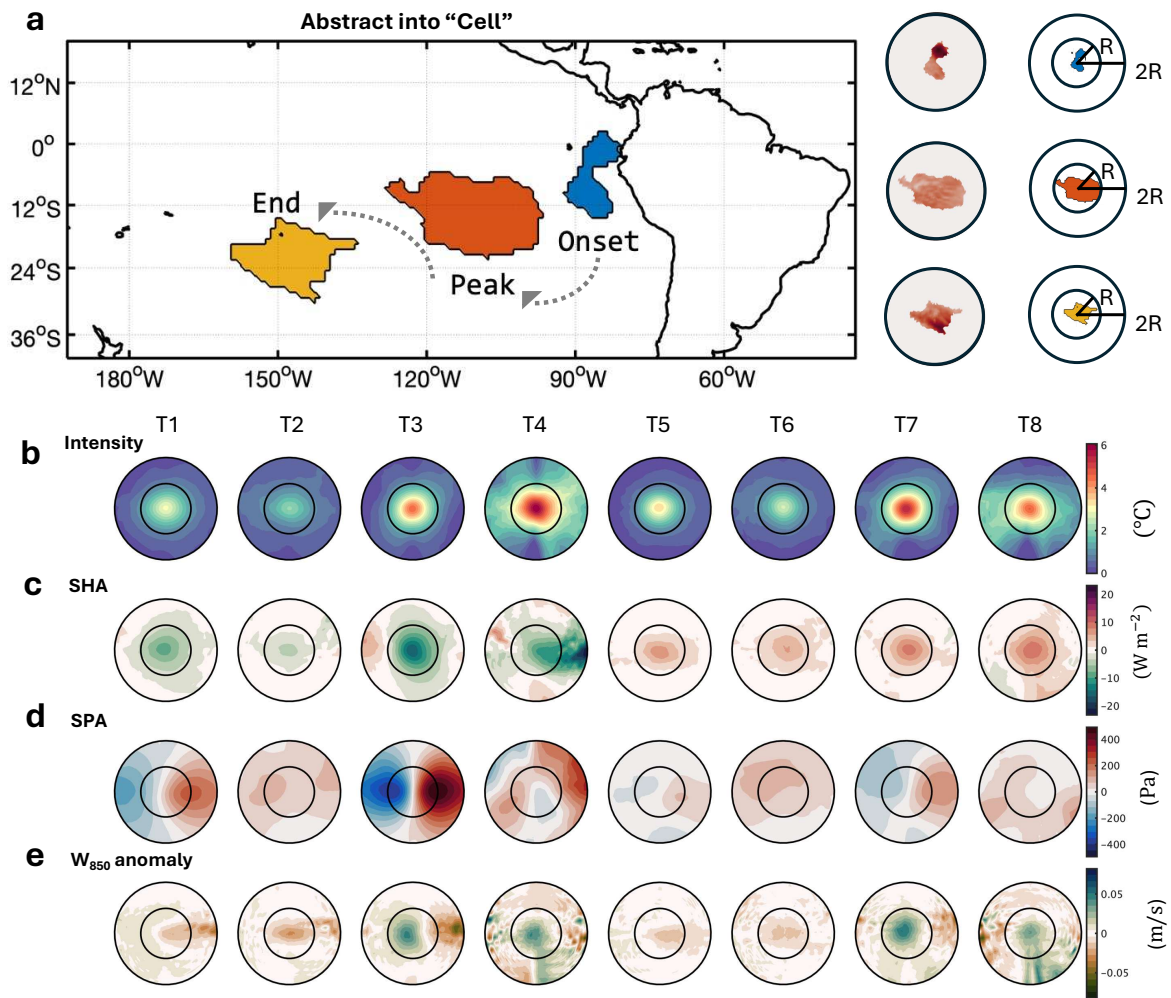


Figure 2 | Event-centered CELL representation and process-state classification of global heatwaves. (a) The evolution of a HWs is illustrated from its onset (blue) to peak (red) and end (yellow), highlighting its location and smoothed shape. The first right column is the spatial distribution of HW intensity shaped by their outline, from top to bottom are during the onset, peak, and end time point. The peak pattern play a key role in defining the radius of the CELL model, which is depicted in the second right column. (b–e) Mean CELL patterns for eight identified HW types (Type 1 to Type 8, marked as T1 to T8) based on the mature phase, where (b) represents HW intensity, (c) illustrates the associated sensible heat flux anomaly (SHA), (d) shows the

605 surface pressure anomaly (SPA), and (e) depicts the vertical velocity anomaly at 850 hPa (W850).
606 The other factors, including anomaly of humidity, precipitation, and cloud coverage are in [Fig. S7](#).

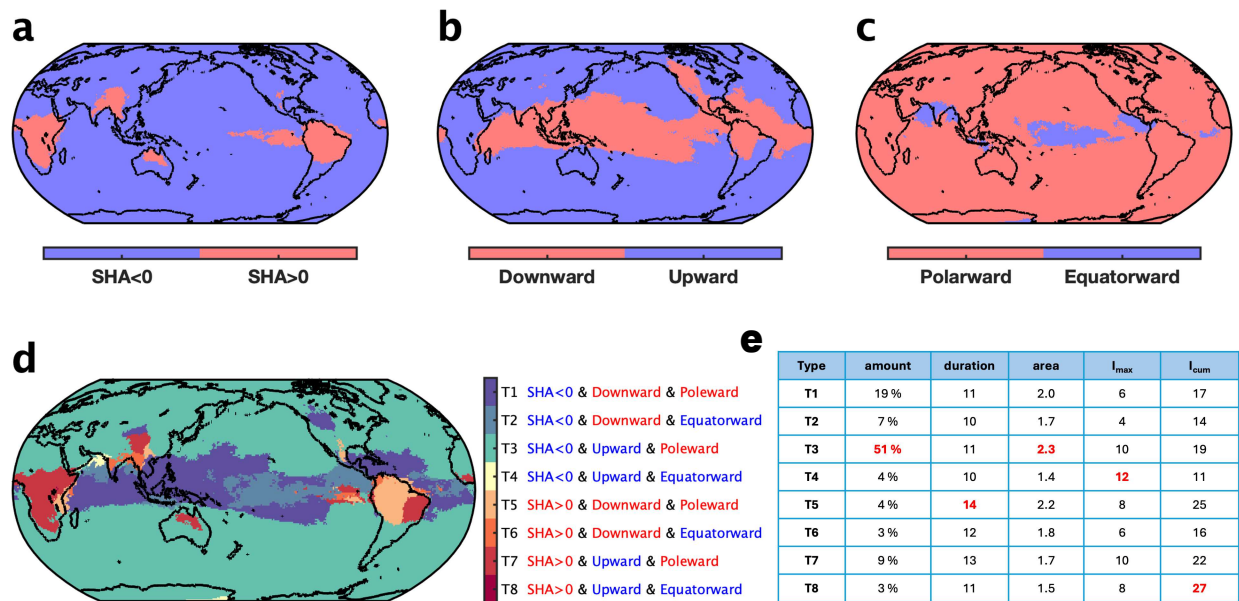
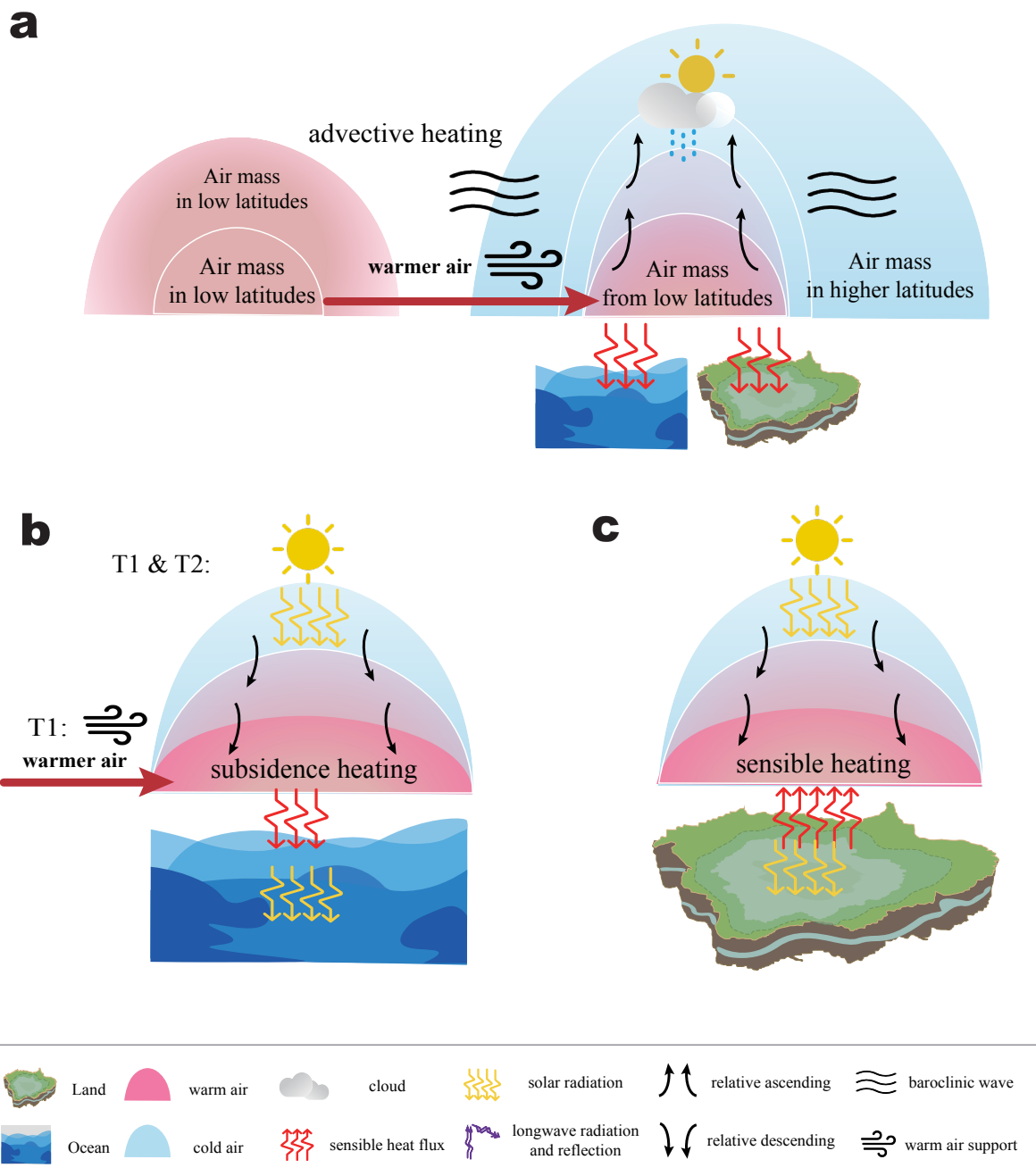


Figure 3 | Global distribution of dominant HW types. (a) The predominant direction of composite sensible heat flux anomaly (SHA) during the mature phase, determined by comparing the number of HWs associated with positive versus negative SHA anomalies. The red indicating an excess heating effect and blue representing a cooling effect. (b) The predominant direction of composite vertical motion anomaly associated with HWs, where red signifies downward motion linked to subsidence-induced heating, while blue indicates upward motion dominance. (c) The predominant direction of composite prevailing wind stress direction which represent the moving direction of air mass, with red indicating poleward transport (heating) and blue equatorward transport (cooling). (d) Regional distribution of dominant HW types worldwide, defined as the most frequent HW type among all events occurring locally. The color bar indicates the combination of three diagnostic indicators associated with each type, with font color denoting their thermal effect—red for warming and blue for cooling. (e) The table summarizes the eight HW types (first column) along with the type-averaged values of five key metrics: global proportion of events (second column), mean duration (days), mean maximum area ($area$, 10^6 km²), mean peak intensity (I_{max} , °C), and mean cumulative intensity (I_{cum} , °C· 10^6 km²·day). Values highlighted in

623 red indicate the highest among all types for each metric. The specific explanation of these factors
624 are in [Table S1](#).

625



626

627 **Figure 4 | Conceptual synthesis of recurrent HW process states. (a)** Schematic representation
 628 of the dominant extratropical heatwave regime, represented primarily by Type 3 events. These
 629 heatwaves are characterized by poleward warm-air transport associated with large-scale
 630 circulation anomalies and frequently occur in environments influenced by baroclinic development

631 and frontal ascent. Positive temperature anomalies can therefore coexist with ascent and relatively
632 weak surface sensible heating. **(b)** Schematic representation of the dominant tropical oceanic
633 heatwave regime, represented primarily by Types 1–2. These events are associated with large-
634 scale subsidence, suppressed convection, and reduced upward surface heat flux, creating favorable
635 conditions for near-surface warming. Type 1 events additionally exhibit circulation patterns
636 associated with poleward warm-air transport. **(c)** Schematic representation of the dominant tropical
637 and subtropical continental heatwave regime, represented primarily by Types 5–8. These events
638 are characterized by enhanced surface sensible heating and land–atmosphere coupling, with
639 variations associated with humidity conditions, cloud cover, and large-scale circulation patterns.
640

Supplementary Files

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

- [SupplementaryInformation.pdf](#)