



A model hierarchy to investigate heatwave persistence: From climate models to storm-resolving simulations

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Abstract.

Heatwave persistence is shaped by processes ranging from large-scale circulation to convection and land–atmosphere interactions. In conventional global climate models, deep convection remains parameterized, whereas storm-resolving simulations explicitly represent more of this variability. How grid spacing and convection treatment affect simulated heatwave persistence, however, remains unclear.

We investigate these sensitivities using a hierarchy of atmosphere-only ICON simulations comprising a storm-resolving 2.5 km configuration, two intermediate-resolution 10 km configurations that differ in the treatment of deep convection, and a coarser 40 km configuration with parameterized convection. Heatwave occurrence and persistence, land–atmosphere relationships, post-heatwave precipitation conditions, and blocking–heatwave associations are evaluated against ERA5. All ICON configurations reproduce the broad spatial structure of heatwave occurrence, but agreement with ERA5 does not improve systematically with finer grid spacing and remains strongly region-dependent. Differences are clearer for persistence: ICON-2.5 km overestimates very persistent heatwaves in several regions, with upper-tail exceedance probabilities reaching approximately 40% above ERA5 in the tropics. The tropical Americas show the strongest sensitivity to convection treatment. There, the 2.5 km and 10 km configurations without parameterized deep convection exhibit positive persistence biases and substantially drier conditions following heatwave termination, whereas configurations with parameterized deep convection are wetter and closer to ERA5. The contrast between the two 10 km simulations shows that convection treatment can strongly affect heatwave persistence even at fixed grid spacing. In the extratropics, where large-scale circulation plays a stronger role, regional heatwave underestimation is more consistently associated with underestimated blocking frequency or a weaker blocking–heatwave relationship.

These results show that there is no single mechanism through which finer resolution or more explicit convection modifies heatwaves. Greater process explicitness does not necessarily reduce heatwave biases; instead, changes in convection, precipitation, land–atmosphere coupling, and persistent large-scale atmospheric circulation can reinforce or compensate each other in a regionally dependent manner. Storm-resolving simulations therefore provide important process insights, but improved process representation should not be equated with systematically improved climatological agreement.



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1 Introduction

Heatwaves have become more frequent, longer-lasting, and more intense in most regions of the globe as the climate warms (Perkins-Kirkpatrick and Lewis, 2020). They have major consequences for human health (Vicedo-Cabrera et al., 2021), agricultural production (Heino et al., 2023), energy systems (van Vliet et al., 2016), and terrestrial ecosystems and their carbon uptake (Ciais et al., 2005). Prolonged events are often associated with the largest impacts (Zuo et al., 2015), and therefore the duration of the heatwave is a characteristic of particular relevance. Despite advances in understanding heatwave dynamics, the processes controlling their persistence remain an important research topic (Domeisen et al., 2023). Predicting such long-lasting events and projecting how their occurrence and duration may change under future warming pose a challenge because their persistence arises from a complex interplay of atmospheric and land-surface processes (Pappert et al., 2025; Pappert and Martius, 2026).

In mid-latitudes and polar regions, temperature extremes are frequently associated with quasi-stationary anticyclones, commonly referred to as atmospheric blocking (Pfahl and Wernli, 2012; Brunner et al., 2017; Jiménez-Esteve and Domeisen, 2022; Dolores-Tesillos et al., 2025; de Vries et al., 2026). The impacts of blocking on surface-temperature extremes vary spatially around the blocked circulation and depend strongly on season: During summer, subsidence and reduced cloud cover within and beneath the blocked anticyclone can favour persistent hot and dry conditions through enhanced shortwave radiation and suppressed precipitation, while convective activity can preferentially develop along the block flanks (e.g., Mohr et al., 2019; Kautz et al., 2022). In winter, blocking can instead favour cold extremes through changes in atmospheric advection, particularly downstream of the blocked circulation (e.g., Kautz et al., 2022). Moist processes upstream of the blocked region can also influence blocking itself: latent heating associated with ascending airstreams, including warm conveyor belts, can amplify upper-level ridges and contribute to the formation and maintenance of blocking (Pfahl et al., 2015; Steinfeld and Pfahl, 2019). In tropical regions, heat extremes can instead be modulated by large-scale tropical circulation variability, including monsoon active-break cycles and intraseasonal modes such as the Madden-Julian Oscillation, which influence large-scale subsidence and precipitation (e.g., Raymond et al., 2021). For the large-scale circulation component of our analysis, we therefore focus on the association between summer heatwaves and blocking, which is most directly applicable to the extratropics. Tropical heatwaves are considered in relation to the local and mesoscale processes discussed below. Although the statistical relationship between blocking and heatwaves is well established (e.g., Kautz et al., 2022), important questions remain regarding the mechanisms linking the two phenomena. In particular, how the evolution and decay of blocking are related to heatwave persistence and termination is still not fully understood (Wang et al., 2026).

Beyond the large-scale circulation, local and mesoscale processes also play an important role in shaping heatwave evolution. The relative contribution of atmospheric advection, subsidence, land-surface fluxes, boundary-layer processes, and convection can vary substantially among regions of heatwave occurrence, heatwave events and throughout the heatwave life-cycle (Hirsch and King, 2020; Hotz et al., 2024). Soil moisture provides an important link between surface and atmospheric



processes: through its control on the partitioning of surface energy into latent and sensible heat, soil moisture can amplify near-surface temperature anomalies while also modifying boundary-layer development and the conditions for convective initiation (Seneviratne et al., 2006; Fischer et al., 2007; Seneviratne et al., 2010; Dolores et al., 2019; Martius et al., 2021). These land–atmosphere interactions can be particularly important for heat extremes over land in the tropics, where hot conditions are closely associated with surface dryness and soil-moisture anomalies can strongly influence the development and persistence of hot and dry conditions (Byrne, 2021; Jiang and Wang, 2024). Convection can interact with heatwaves and their large-scale circulation across different spatial scales, including through convective activity upstream of the heatwave region (Feldmann et al., 2025) and through more remote upscale effects, whereby mesoscale convective systems can modify Rossby-wave evolution and its downstream propagation (Lojko et al., 2022). During persistent hot conditions, large-scale subsidence and boundary-layer stratification can suppress deep moist convection, although dry or shallow convection may continue (e.g., Richter and Bosart, 2002). Recent work suggests that a low-level temperature inversion can strengthen during a heatwave and inhibit the development of deep moist convection (Li and Tamarin-Brodsky, 2026). As instability accumulates, this inhibition may eventually be overcome, favoring deep convection and precipitation that can contribute to heatwave termination. Consistent with such a transition, observational and modeling studies have documented an increased likelihood of extreme precipitation after heatwaves (Chen et al., 2022; Sauter et al., 2023a, b).

Accurately representing the above described processes remains a major challenge for current climate models. Most global climate models operate at grid spacings that require deep convection to be parameterized and exhibit biases in heatwave characteristics and atmospheric blocking (Davini and D’Andrea, 2020; Hirsch et al., 2021; Zhao et al., 2025). These biases cannot be attributed to convection parameterization alone, because grid spacing also determines which atmospheric and surface heterogeneities and mesoscale circulation can be explicitly represented. Both grid-spacing and convection treatment can therefore affect precipitation, land-atmosphere coupling, and moist diabatic influences on the large-scale circulation, including processes relevant for atmospheric blocking (Dolores-Tesillos et al., 2025). For example, explicitly representing convection can modify the strength and sign of soil-moisture–precipitation coupling (Hohenegger et al., 2009; Lee and Hohenegger, 2024), while resolving mesoscale soil-moisture heterogeneity can reveal localized circulations associated with humid-heat extremes (Chagnaud et al., 2025, 2026).

Global storm-resolving models (SRMs), including the ICOSahedral Nonhydrostatic model (ICON) (Hohenegger et al., 2023), the Integrated Forecasting System coupled to the Finite-volume Sea ice-Ocean Model (IFS-FESOM) (Rackow et al., 2025), the Nonhydrostatic Icosahedral Atmospheric Model (NICAM) (Takasuka et al., 2024) or the Energy Exascale Earth System Model (E3SM) (Donahue et al., 2024), offer new opportunities to explicitly simulate convection and thereby reduce long-standing biases in Earth system modeling (Davini et al., 2017; Schiemann et al., 2017; Woollings et al., 2018; Schiemann et al., 2020; Takasuka et al., 2024; Dolores-Tesillos et al., 2025; Dipankar et al., 2026; Prein et al., 2026; Pothapakula et al., 2026). Operating at horizontal grid spacings of a few kilometers, SRMs begin to resolve deep convective systems triggered by local forcing and surface heterogeneity (Lee and Hohenegger, 2024). The first generation of global SRMs, developed within projects such as nextGEMS (Segura et al., 2025) and Destination Earth (Doblas-Reyes et al., 2026), has generated considerable interest because these models provide a more realistic representation of both convection and land-surface heterogeneity



than conventional coarse-resolution climate models (Wille et al., 2025; Brunner et al., 2025; Poujol et al., 2025; Brunner et al., 2026), while retaining the global domain needed to capture interactions with the synoptic- and planetary-scale circulation (McKinnon-Gray et al., 2026; Rixen et al., 2026). This capability provides a unique opportunity to investigate how local convective processes interact with the planetary- and synoptic-scale circulation patterns that are associated with heatwaves. Understanding these process sensitivities is also important for interpreting kilometre-scale climate projections as moist processes and their circulation feedbacks change under a warming climate (e.g., Dolores-Tesillos et al., 2022; Dolores-Tesillos and Pfahl, 2024; Steinfeld et al., 2022; Raymond et al., 2020; Russo et al., 2017).

Attributing heatwave biases to individual atmospheric processes remains difficult in coupled simulations, biases in sea-surface temperatures can contribute to a misrepresentation of the large-scale circulation and atmospheric blocking by modifying the background state in which these phenomena develop (Dolores-Tesillos et al., 2026). Accordingly, we use atmosphere-only ICON simulations with prescribed sea-surface temperatures, which reduce uncertainties associated with interactive ocean–atmosphere coupling and provide a more controlled framework for assessing the sensitivity of heatwaves to atmospheric model formulation, in particular grid spacing and the representation of convection.

Research questions

Based on this framework, we hypothesize that grid spacing and the treatment of convection can affect heatwave characteristics through both local land–atmosphere processes and changes in the large-scale circulation, with the relative importance and sign of these mechanisms varying among regions. We therefore address the following research questions:

1. How do heatwave occurrence, persistence, and spatial distribution differ among ICON configurations with different grid spacings and treatments of convection, and what can the comparison at fixed grid spacing reveal about the sensitivity to the treatment of deep convection?
2. How are regional differences in heatwave characteristics associated with differences in the land–atmosphere coupling, and are these changes consistent with local processes affecting heatwave persistence or termination?
3. How are regional differences in heatwave characteristics associated with the representation of the blocking–heatwave relationship, and are these large-scale circulation differences consistent with changes in heatwave persistence?

This manuscript is structured as follows. Section 2 describes the ICON simulations, datasets, and methodology. Section 3 presents the results. Section 4 summarizes and discusses the main findings, and the final section presents the conclusions.

2 Data and Methods

2.1 ICON simulations and ERA5

We analyze global simulations performed with the Icosahedral Nonhydrostatic (ICON) model within the EXCLAIM (EXtreme-scale Computing and data platform for cLoud-resolving weAther and cIimate Modeling) project (Kroll et al., 2025; Dipankar



et al., 2026; Prein et al., 2026; Pothapakula et al., 2026). A detailed description of the model configuration is provided by Dipankar et al. (2026). Briefly, EXCLAIM employs a GT4Py-based dynamical core designed to leverage advances in modern high-performance computing architectures. Simulations are performed in an atmosphere-only configuration and are forced with identical observed daily updated sea surface temperatures and the sea-ice fraction from the ESA Climate Change Initiative (ESA-CCI) product (Merchant et al., 2019). In addition, all simulations employ the same TERRA land-surface model (Schrodin and Heise, 2001; Grasselt et al., 2008; Schulz and Vogel, 2020). More details on the configuration of the model are provided in Supplementary material (Fig. S1). This experimental design allows us to isolate the effects of grid spacing and convection representation on heatwave characteristics.

We analyze four simulations that differ in grid spacing and in the treatment of deep convection (Table 1). The 2.5 km simulation and one of the two 10 km configurations are run without a deep-convection parameterization, allowing deep convective processes to be represented explicitly, although they are only partially resolved at 10 km grid spacing (Prein et al., 2015; Vergara-Temprado et al., 2020; Hohenegger et al., 2023). The second 10 km configuration employs a parameterization for both shallow and deep convection. Including the 10 km configuration twice, with and without parameterized deep convection, is an intentional part of the experimental design and allows for the influence of deep-convection treatment to be examined at fixed grid spacing. The 40 km configuration also uses parameterized shallow and deep convection and is representative of the grid spacing commonly employed in high-resolution CMIP6 experiments (Haarsma et al., 2016).

Simulation	Resolution (km)	Deep convection	Shallow convection
ICON-2.5 km	2.5	Explicit	Explicit
ICON-10 km	10	Explicit	Parameterized
ICON-10 km-ON	10	Parameterized	Parameterized
ICON-40 km-ON	40	Parameterized	Parameterized

Table 1. Overview of the EXCLAIM ICON simulations used in this study. The Tiedtke-Bechtold convection scheme is used in the parameterized simulations (Tiedtke, 1989; Bechtold et al., 2008).

As a reference dataset, we use the ERA5 reanalysis (Hersbach et al., 2020), which provides a dynamically consistent and observation-constrained estimate of the atmospheric state. A recent evaluation of the 2.5 km EXCLAIM simulation showed that it reproduces the broad global patterns of near-surface temperature and precipitation, while exhibiting warm and dry biases over mid-latitude continents during summer (Prein et al., 2026). These biases were associated with excessive incoming shortwave radiation, reduced latent heat fluxes, and enhanced sensible heat fluxes. These documented mean-state biases provide important context for our analysis of simulated heatwave characteristics and land–atmosphere interactions. Daily maximum 2 m temperature is calculated from hourly ERA5 data for the period 1994–2024. ERA5 therefore provides an observational benchmark for evaluating the resulting heatwave occurrence, duration, and spatial characteristics. A complete list of all ERA5/ICON variables used in this study is provided in the Supplementary material (Section S2).



For consistency across datasets, all fields are remapped to a common regular latitude–longitude grid of $0.5^\circ \times 0.5^\circ$. This common grid facilitates the comparison of heatwave statistics, atmospheric blocking, and associated environmental fields across model configurations.

To focus the analysis on the warm season while retaining a consistent global framework, we define local summer as June–August (JJA) in the Northern Hemisphere and December–February (DJF) in the Southern Hemisphere, following previous global heatwave studies (e.g., Wu et al., 2024). The analysis includes tropical land regions, with the seasonal assignment determined by hemisphere. This definition facilitates a consistent comparison of heatwaves across the globe and between model configurations, but it does not necessarily correspond to the locally warmest or climatologically most relevant season in all tropical regions, where temperature and precipitation seasonality can vary geographically. Hence, this transition from JJA to DJF introduces a discontinuity at the Equator. Results close to this boundary are therefore interpreted with caution.

The primary objective of this study is not to provide a comprehensive evaluation of the ICON simulations against ERA5. The broader climatological performance and principal mean-state biases of the 2.5 km EXCLAIM simulation have already been examined against reanalysis and observational datasets (Prein et al., 2026). Instead, we focus on understanding how heatwave characteristics and their relationship with local and large-scale processes vary across model configurations with different grid spacings and treatments of convection. ERA5 is used as a reference reanalysis for interpreting the simulated heatwave characteristics and associated processes, while recognizing that reanalysis fields are influenced by both assimilated observations and the underlying forecast model.

The ICON simulations cover the period from January 2020 to March 2024, which defines the temporal extent of the analysis. The resulting approximately four-year sample is a limitation, particularly for evaluating interannual variability and rare persistent heatwaves.

2.2 Standardized temperature and circulation fields

Using the hemispheric local-summer definition introduced above, heatwave and blocking events are identified within extended seasonal windows to avoid truncating events that begin shortly before or end shortly after the target season. Northern Hemisphere events are detected using data from May–September and Southern Hemisphere events using data from November–March, while only events overlapping JJA and DJF, respectively, contribute to the reported summer statistics.

The seasonal assignment changes abruptly at the Equator, where the analysis switches from JJA to DJF. This may introduce an artificial spatial discontinuity in tropical diagnostics and does not necessarily represent the locally warmest season in all tropical regions. Results near the Equator are therefore interpreted with caution.

Prior to heatwave and blocking identification, daily maximum 2 m temperature ($T_{\max}$) and 500 hPa geopotential height (Z_{500}) are transformed relative to climatological conditions calculated separately for each dataset and model configuration. For $T_{\max}$, the climatology varies through the seasonal cycle; that is, daily temperatures are not standardized using a single mean and standard deviation calculated over all JJA or DJF days. Instead, each daily $T_{\max}$ value is expressed relative to the climatological mean and variability representative of that time of year. Standardized temperature anomalies are calculated as



$$T'_{\text{std}} = \frac{T_{\text{max}} - \mu_T}{\sigma_T},$$

where μ_T and σ_T denote the climatological mean and standard deviation, respectively. Standardization expresses temperature anomalies relative to the local temperature variability and facilitates the identification and comparison of heat extremes across regions and datasets with different mean climates and temperature variances.

185 For ERA5, climatological means and standard deviations are estimated using a 30-day moving window and an 8-year rolling climatology, following Pappert et al. (2025). This procedure removes the mean seasonal cycle and accounts for the long-term warming trend while providing a smooth estimate of the local temperature distribution. Removing the seasonal cycle before calculating percentile-based thresholds also reduces biases in estimated heatwave days (Brunner and Voigt, 2024).

Because the ICON simulations cover only approximately four years, the full simulation period is used to estimate a separate
 190 climatology for each model configuration. The resulting heatwave thresholds are therefore dataset-specific and are intended to identify events relative to the climatological distribution of each simulation, rather than to measure absolute mean-state temperature biases.

For Z_{500} , anomalies are calculated by subtracting the climatological mean,

$$Z'_{500} = Z_{500} - \mu_{Z_{500}},$$

195 but are not divided by the climatological standard deviation. This is because the blocking diagnostic is formulated in terms of the physical magnitude and spatial coherence of geopotential-height anomalies. Standardizing Z_{500} would instead express each anomaly relative to the local variability, potentially amplifying weak anomalies in regions with low variability and reducing the relative magnitude of strong anomalies in regions with high variability. Retaining Z'_{500} in physical units therefore preserves the dynamical interpretation of the anomaly-based blocking criterion (e.g., Dolores-Tesillos et al., 2026).

200 2.3 Heatwave and blocking diagnostics

Heatwave events are identified as periods of at least three consecutive days during which the standardized daily maximum temperature exceeds the grid-point-specific 90th-percentile threshold. The percentile threshold is calculated independently at each grid cell and separately for ERA5 and each ICON simulation using the climatology of the respective dataset. This dataset-specific, grid-point-based definition reduces the influence of systematic differences in mean climate and temperature variability,
 205 allowing heatwave-day occurrence and persistence to be compared across regions and model configurations. At each grid point and for each local-summer season, we identify the maximum duration among all heatwave events occurring during that season. The seasonal maximum-duration fields are subsequently averaged across the available seasons to obtain the mean seasonal maximum heatwave duration. This metric emphasizes the persistence of the longest event in a typical summer and is distinct from both the total number of heatwave days and the duration summed across all events.

210 Atmospheric blocking is diagnosed from daily 500 hPa geopotential-height anomalies using an object-based method based on Steinfeld et al. (2022). Atmospheric blocking anomalies are identified separately for the two hemispheres using the latitude



bands 50–80°N and 50–80°S. At each grid point within these reference bands, blocked conditions are identified when the daily Z_{500} anomaly exceeds its dataset-specific climatological 90th-percentile threshold. Spatially contiguous anomaly objects are then tracked between consecutive daily time steps, requiring at least 50% spatial overlap and a minimum lifetime of five days.

215 The 50–80° latitude bands define the reference regions used for identifying mid- and high-latitude blocking events; they do not necessarily restrict the complete spatial extent of the resulting blocking objects. Blocking anomalies can extend equatorward of 50° and may therefore contribute to blocking frequencies and blocking–heatwave co-occurrence at lower latitudes.

The detection and tracking criteria are similar to those of Dolores-Tesillos et al. (2026), but the treatment of the background climatology differs. Here, ERA5 anomalies and percentile thresholds are calculated using a 30-day moving window and an 8-
220 year rolling climatology, whereas Dolores-Tesillos et al. (2026) calculated anomalies relative to separate decadal climatologies. For each ICON configuration, the corresponding climatology is calculated independently using the full available simulation period.

All analyses are restricted to local summer to compare heatwave characteristics and their associated processes within a broadly consistent warm-season context. In the extratropics, this seasonal restriction is particularly important for interpret-
225 ing blocking–heatwave relationships, because the surface-temperature response to persistent anticyclonic circulation depends strongly on season as described in the Sec. 1. In tropical regions, where the annual temperature cycle is weaker and the timing of the warm season is more regionally variable, the JJA/DJF definition should be regarded as an approximate hemispheric local-summer framework. Tropical results are therefore interpreted primarily in terms of heatwave persistence and local to mesoscale processes, including land–atmosphere coupling and precipitation.

230 We additionally tested the sensitivity of heatwave occurrence to the length of the rolling climatological window by repeating the ERA5 analysis using a 4-year rather than an 8-year window. The resulting climatological patterns were highly consistent, with a global spatial correlation of 0.97 and a mean absolute difference of 0.37 heatwave days per local summer. The 4-year window produced slightly fewer heatwave days overall, particularly in the USA, but the principal spatial patterns were preserved. We therefore retain the 8-year rolling climatology, which provides a balance between following changes in the
235 background climate and maintaining a sufficiently large sample for estimating climatological temperature variability.

2.4 Significance testing

The ICON simulations provide only four complete local-summer seasons in each hemisphere, which limits the sampling of interannual variability and rare events. To assess whether differences between ICON and ERA5 exceed the sampling variability expected from a four-season record, we construct an empirical reference distribution from ERA5.

240 For each diagnostic, one seasonal field is first calculated at every grid point for each available ERA5 local summer. In the Northern Hemisphere, the ERA5 sample comprises thirty JJA seasons from 1994 to 2023. In the Southern Hemisphere, it comprises thirty DJF seasons from 1994/1995 to 2023/2024, with each DJF season treated as one seasonal realization. Thus, a “seasonal field” represents the value of a given diagnostic during one local-summer season, such as the seasonal heatwave-day occurrence, mean event duration, or blocking frequency at each grid point.



245 For each hemisphere and diagnostic, 500 bootstrap samples are generated by drawing four ERA5 seasonal fields with replacement from the corresponding 30-season record and calculating their four-season mean. The resulting distribution represents the sampling variability of an ERA5 mean estimated from the same number of local-summer seasons as available in the ICON simulations. These bootstrap realizations are therefore referred to as four-season mean fields rather than independent ERA5 climatologies.

250 The four-season mean from each ICON simulation is compared with the corresponding ERA5 bootstrap distribution at each grid point. Two-sided empirical p values are calculated from the smaller of the fractions of bootstrap values below and above the ICON value,

$$p = 2 \min \left[P \left(\bar{X}_{\text{ERA5}}^* \leq \bar{X}_{\text{ICON}} \right), P \left(\bar{X}_{\text{ERA5}}^* \geq \bar{X}_{\text{ICON}} \right) \right],$$

with p limited to a maximum value of one. An ICON value is considered significantly different from the ERA5 sampling 255 distribution at the 5% level when it lies below the 2.5th percentile or above the 97.5th percentile of the bootstrap distribution. By contrast, a value at the 95th percentile corresponds to $p \approx 0.10$ in a two-sided test, while values between the 95th and 97.5th percentiles correspond to $0.05 < p < 0.10$ and are therefore not significant at the 5% level.

This procedure does not determine whether a simulation is correct, nor does it account for uncertainty arising from the single ICON realization. Instead, it identifies locations where the simulated four-season mean is unlikely to arise solely from 260 the interannual sampling variability represented by ERA5. Unless an additional correction for multiple testing is applied, the resulting significance is interpreted pointwise rather than as field significance.

3 Results

3.1 Representation of summer heatwave occurrence

We begin by assessing how the ICON simulations represent the spatial distribution of summer heatwave days relative to ERA5. 265 Figure 1 shows the mean number of heatwave days per local summer season. A discontinuity is visible near the Equator over northern South America, which is related to the hemispheric switch between JJA and DJF discussed in Section 2.1. Results in this region are therefore interpreted with caution. For comparison we provide the year-round heatwave-day occurrence in the Appendix (Fig. A1). The corresponding mean temperature and total precipitation fields and their differences relative to ERA5 are also provided in the Supplementary material (Figs. S2 and S3).

270 At first glance, all ICON configurations reproduce the large-scale spatial patterns of heatwave occurrence observed in ERA5. Most regions exhibit differences that remain within the range of four-year variability estimated from the ERA5 bootstrap distribution, indicating that the simulated heatwave days are broadly consistent with the observational benchmark.

Despite this overall agreement, systematic regional biases emerge. Positive biases occur in parts of the tropical latitudes (23.5°S–23.5°N) and over East Asia. A particularly pronounced positive bias ($\approx +4$ days) occurs over northern tropical 275 South America and adjacent Central America, including parts of Colombia, Venezuela, Ecuador, and northern Brazil. The



bias is largest in ICON deep convection off, although the magnitude does not vary uniformly with grid spacing across all configurations. East Asia also exhibits a positive bias ($\approx +4$ days for ICON-2.5 km) and, together with tropical America, is examined in more detail using regional land–atmosphere and precipitation diagnostics in Section 3.3.

The larger number of heatwave days at higher resolution and explicit convection should not be interpreted as a direct measure of how frequently heatwaves terminate. Changes in termination can modify event duration while also splitting otherwise continuous hot periods into multiple shorter events; consequently, heatwave duration, event counts, and the total number of heatwave days need not vary in parallel. The spatial differences identified here therefore motivate the subsequent analysis of heatwave duration and of the circulation, precipitation, and land–atmosphere processes associated with regional heatwave biases.

As a complementary view of broad meridional differences, the Appendix Fig. A2 shows heatwave days aggregated over three latitude bands: the tropics (23.5°S – 23.5°N), the extratropics regions (23.5° – 65° in both hemispheres), and the polar regions (poleward of 65° in both hemispheres). These boundaries follow the geographical classification used in previous heatwave studies (e.g., Bekris et al., 2026). Previous work has also shown that the thermodynamic structure of hot extremes differs systematically among tropical, mid-latitude, and polar climate regimes (e.g., Hotz et al., 2026). For each latitude band, we calculate the area-weighted mean number of heatwave days per local-summer season for each available year. Because zonal aggregation can obscure geographically localized biases, this analysis is used only to assess whether differences among the simulations are coherent across broad latitude bands rather than as the basis for regional process attribution.

The latitude-band analysis does not reveal a uniform dependence of heatwave days on either grid spacing or convection treatment across all regions. Most ICON configurations simulate slightly more heatwave days than ERA5, but the magnitude and ordering of the biases vary among latitude bands. The positive bias in the 2.5 km simulation is most evident in the tropical and extratropics bands, where it also exhibits the largest RMSE relative to ERA5, whereas the differences among configurations are less systematic in the polar regions. Thus, the higher heatwave-day occurrence in ICON-2.5 km is a regionally dependent feature rather than a response that is consistent across all latitude bands.

In summary, the ICON simulations reproduce the broad spatial characteristics of global heatwave days, although notable regional biases remain. We next examine whether the configurations differ more clearly in their representation of heatwave duration.

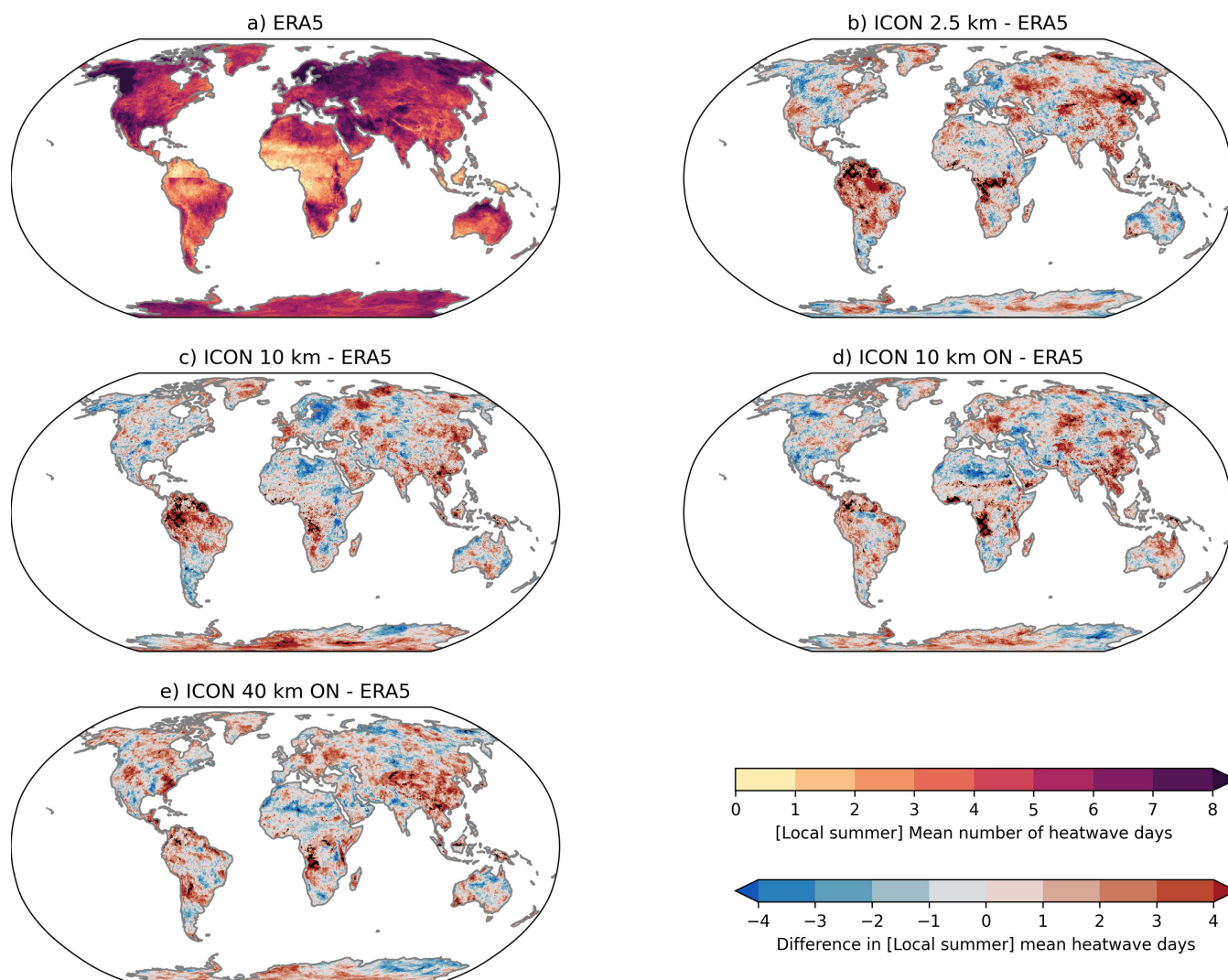


Figure 1. Global distribution of heatwave occurrence during local summer (days season⁻¹). Local summer is defined as JJA north of the Equator and DJF south of the Equator, following the hemispheric definition described in Section 2.1. Panel (a) shows the ERA5 reference climatology, while panels (b–e) show biases relative to ERA5 for ICON-2.5 km, ICON-10 km, ICON-10 km-ON, and ICON-40 km-ON, respectively. Crosses indicate grid points where the ICON four-season mean lies outside the central 95% of the corresponding ERA5 four-season bootstrap distribution ($p < 0.05$, two-sided test). A discontinuity near the Equator may arise from the hemispheric seasonal definition, which switches from JJA in the Northern Hemisphere to DJF in the Southern Hemisphere; see Sect. 2.1.



3.2 Heatwave persistence

Although the simulations produce a broadly comparable number of heatwave days at the global scale, they may differ more clearly in their representation of persistent events. Here, heatwave persistence is characterized by event duration. Figure A3 shows the mean seasonal maximum heatwave duration at each grid point. For each local-summer season, the longest heatwave event is first identified at each grid point, and the resulting seasonal maxima are then averaged over all available seasons. The diagnostic therefore represents the typical duration of the longest event in a summer.

Visual comparison with the heatwave-day biases in Fig. A3 shows that several regions with positive biases in seasonal maximum duration also exhibit an overestimation of the number of heatwave days. Where both quantities are overestimated, the bias is therefore more consistent with an excess of persistent hot conditions than with a simple fragmentation of long heatwaves into a larger number of shorter events. To determine whether these spatial differences are accompanied by systematic changes in the complete event-duration distribution, we analyse all detected heatwaves, including the minimum-duration events of three days, within three broad latitude bands: tropical regions (23.5°S – 23.5°N), extratropical regions (24° – 65.5° in both hemispheres), and polar regions (poleward of 66° in both hemispheres).

Rather than separating events into predefined short- and long-duration categories, we quantify the probability that a heatwave exceeds a set of duration thresholds derived from the ERA5 distribution. The thresholds correspond to the discrete durations at which the ERA5 cumulative duration distribution reaches the 50th, 75th, 90th, 95th, and 97.5th percentiles. This approach retains information from the complete duration distribution while progressively emphasizing its upper tail, allowing differences in both typical and particularly persistent heatwaves to be evaluated without imposing arbitrary duration classes. Figure 2 shows the relative difference between each ICON configuration and ERA5 in the probability of exceeding these thresholds.

Although differences in overall heatwave occurrence are relatively modest, the event-duration analysis reveals clearer configuration-dependent changes towards the upper tail of the distribution (Fig. 2). ICON-2.5 km shows the most consistent shift towards longer heatwave persistence. In the tropics, the probability of a heatwave exceeding the ERA5 95th- and 97.5th-percentile duration thresholds (8 and 9 days, respectively) is approximately 38% and 40% higher than in ERA5. A similar response occurs in the extratropics, where exceedance probabilities increase by approximately 28% and 35% at the same thresholds. The increase is weaker in the polar regions, reaching approximately 7% and 16% for events lasting at least 8 and 9 days, respectively.

The other ICON configurations exhibit less consistent changes. In the extratropics and polar regions, their upper-tail exceedance probabilities are generally close to or below ERA5, whereas positive differences occur more commonly in the tropics. Thus, the response does not follow a simple monotonic dependence on grid spacing or convection treatment. Moreover, despite the pronounced upper-tail differences in ICON-2.5 km, the Cramér-von Mises test does not indicate a significant difference in its complete duration distribution relative to the variability expected from four-year ERA5 samples, suggesting that the strongest changes are concentrated in the relatively rare, persistent events.

The enhanced persistence of heatwaves in ICON-2.5 km was not the expected response. Finer grid spacing and a more explicit representation of convection might be expected to provide a more faithful representation of the processes controlling



heatwave duration and, consequently, closer agreement with ERA5. Instead, ICON-2.5 km produces more persistent heatwaves in several regions, indicating that a more explicit representation of these processes does not necessarily translate into reduced heatwave-duration biases.

Several processes introduced above could contribute to these differences in heatwave duration. Locally, less frequent precipitation or longer dry intervals could reduce soil-moisture replenishment and evaporative cooling, thereby favouring the persistence of hot surface conditions; conversely, precipitation and associated cooling can interrupt persistent heat. Differences in convection and diabatic heating may also influence the large-scale circulation, while stronger or more persistent blocking could favour longer-lasting heatwaves. The following sections therefore examine whether regional differences in heatwave persistence are associated with the representation of atmospheric blocking, precipitation characteristics, soil moisture, and land-atmosphere coupling across the ICON configurations.

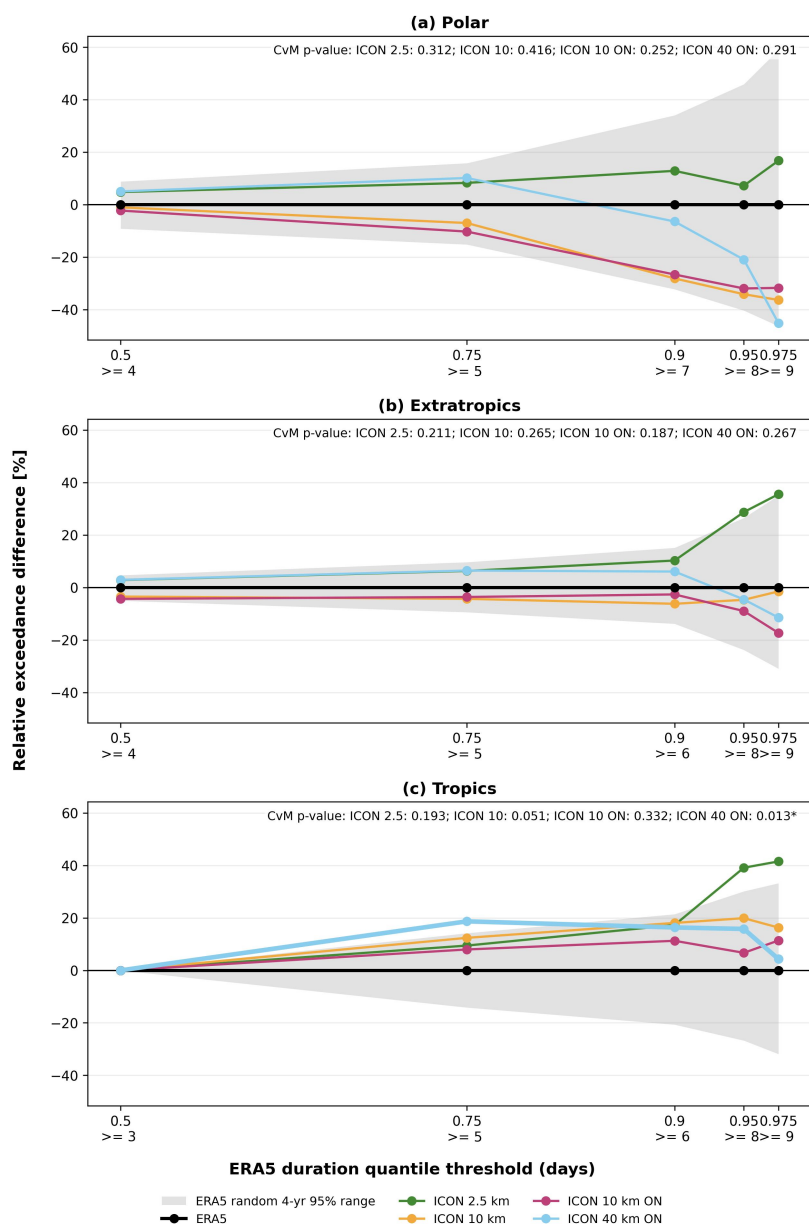


Figure 2. Relative difference between the ICON simulations and ERA5 in the conditional probability of heatwave events exceeding ERA5-derived duration thresholds during local summer over (a) polar regions (poleward of 66° in both hemispheres), (b) extratropical regions (24° – 65.5° in both hemispheres), and (c) tropical regions (23.5°S – 23.5°N). All detected heatwaves with durations of at least three days are included. Thresholds correspond to the discrete durations at which the ERA5 cumulative duration distribution reaches the 50th, 75th, 90th, 95th, and 97.5th percentiles; the corresponding durations (days) are shown on the x-axis. Positive values indicate that a larger fraction of ICON heatwaves exceed the ERA5-derived threshold for a particular simulation, as indicated in the legend. Events are aggregated over land using cosine-of-latitude weighting. Grey shading denotes the 95% range obtained from 10,000 ERA5 resamples containing the same number of seasons as the ICON simulations. Asterisks denote ICON configurations whose complete duration distribution differs significantly from ERA5 according to the resampling-based Cramér–von Mises test ($p \leq 0.05$).



3.3 Land–atmosphere coupling controls on heatwave persistence

To explore processes that may contribute to the regional differences in heatwave persistence, we next examine land–atmosphere coupling and precipitation conditions during heatwave evolution. In particular, soil-moisture–temperature coupling and precipitation provide potential mechanisms through which differences among model configurations may influence the maintenance or termination of heatwaves. Given the short simulation period and the regional nature of these relationships, these diagnostics are used to identify relationships consistent with the proposed processes rather than to establish causal attribution.

We first examine the background warm-season relationship between soil moisture and near-surface air temperature as a measure of land–atmosphere coupling (Fig. 3). The correlations are calculated using all days within the local summer season rather than heatwave days only, providing a more robust estimate of the climatological coupling regime in which heatwaves develop. ERA5 exhibits predominantly negative correlations in many land regions, consistent with the established relationship between reduced soil moisture, lower evaporative cooling, and enhanced near-surface temperatures discussed in Section 1. The ICON simulations show a generalized misrepresentation of spatial structure of this relationship, although the sign of the soil–moisture–temperature relationship remain similar to ERA5. In particular, the two 10 km configurations exhibit distinct departures from ERA5 over large parts of South America and southern Africa, indicating sensitivity of the simulated land–atmosphere coupling to the treatment of deep convection even at fixed grid spacing.

Previous studies have shown that biases in soil-moisture–atmosphere coupling can contribute to regional errors in simulated summer temperatures and that the strength of this coupling varies substantially across geographical regions (e.g., Day et al., 2025). In our simulations, the spatial correspondence between heatwave biases and soil-moisture–temperature coupling differences is likewise heterogeneous rather than globally uniform. The relationship is most evident in the tropical Americas and East Asia, motivating a regional examination of whether differences in precipitation and soil-moisture conditions accompany the simulated heatwave biases. We therefore focus next on the hydroclimatic conditions associated with heatwaves in these two regions rather than interpreting a global relationship between coupling strength and heatwave occurrence.

In the tropical Americas, the positive heatwave-day occurrence and persistence biases in ICON-2.5 km coincide with negative precipitation biases relative to ERA5 during the local summer (see the Supplementary material Fig. S3) and pronounced soil-moisture–temperature coupling. This spatial correspondence is consistent with a possible hydroclimatic mechanism linking reduced precipitation, soil-moisture depletion, and enhanced surface warming, but does not by itself establish causality. East Asia exhibits a different combination of heatwave, hydroclimatic, and circulation biases, and therefore provides an important contrasting case for assessing the relative contribution of local and large-scale processes.

Mean seasonal soil-moisture differences relative to ERA5 are shown in the Supplementary material (Fig. S4). These absolute differences should be interpreted with caution because ERA5 and ICON do not provide strictly equivalent soil-moisture variables or layer depths. For this reason, the coupling analysis emphasizes correlations rather than absolute soil-moisture biases. The following analyses examine whether the regional coupling differences are accompanied by systematic changes in soil-moisture–precipitation relationships and in the occurrence of dry and wet conditions during heatwave termination.

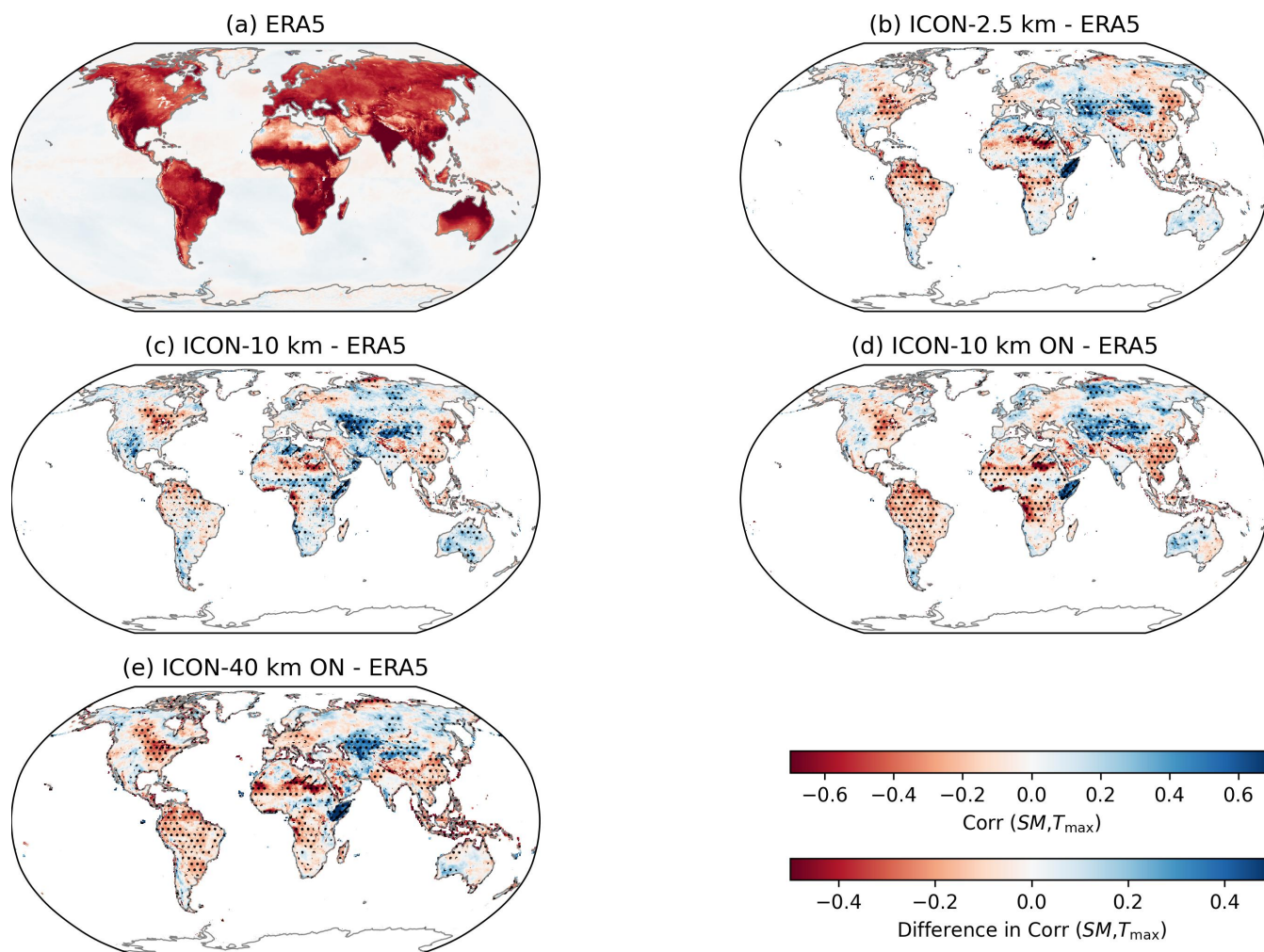


Figure 3. Spatial correlation between daily soil moisture and daily 2 m air temperature during local summer. Panel (a) shows the ERA5 correlation field, while panels (b–e) show differences relative to ERA5 for the ICON simulations. Stippling denotes regions where the simulated values lie outside the range of four-year variability estimated from ERA5 using a bootstrap significance test ($p < 0.05$). Diagonal hatching indicates regions where the simulated soil-moisture–temperature correlation has the opposite sign to ERA5. A discontinuity near the Equator may arise from the hemispheric seasonal definition, which switches from JJA in the Northern Hemisphere to DJF in the Southern Hemisphere; see Sect. 2.1.

We additionally examine the relationship between daily soil moisture and precipitation (Fig. A4). This diagnostic is included to assess whether the configuration dependence identified in soil-moisture–temperature coupling is accompanied by systematic differences in the hydroclimatic relationship between soil moisture and precipitation. The configurations without parameterized deep convection (ICON-2.5 km and ICON-10 km) generally exhibit weaker or more negative correlations than those with parameterized deep convection, with particularly clear contrasts between the two 10 km configurations over parts



of the tropical Americas. This behaviour is qualitatively consistent with previous studies showing that the simulated soil-
moisture–precipitation relationship is sensitive to the representation of convection (e.g., Lee and Hohenegger, 2024). However,
because the correlations are contemporaneous, they do not establish the direction of the interaction: positive correlations may
partly reflect the wetting of soils by precipitation rather than an influence of antecedent soil moisture on subsequent rainfall.
We therefore treat this diagnostic as a supporting measure of the soil-moisture–precipitation relationship rather than as direct
evidence of a soil-moisture–precipitation feedback.

To examine whether regional heatwave-persistence biases are accompanied by differences in local precipitation conditions
around heatwave termination, we quantify the occurrence of wet and dry conditions at the grid points where heatwaves are
identified. Precipitation is evaluated one day after the final heatwave day, corresponding to the first post-heatwave day. This
measure characterizes the local precipitation conditions immediately following heatwave termination rather than convection
occurring upstream or in the surrounding region. Dry conditions are defined as daily precipitation below 1 mm day^{-1} and wet
conditions as precipitation of at least 1 mm day^{-1} .

We focus on the tropical Americas and East Asia, where the preceding analyses identify contrasting heatwave and land–
atmosphere coupling biases (Fig. 4). In the tropical Americas, ERA5 classifies approximately 83.6% of first post-heatwave days
as wet and 16.4% as dry. Relative to these ERA5 frequencies, ICON-2.5 km and ICON-10 km have wet-day frequencies that
are lower by approximately 5.4% and 21.5%, respectively, while their dry-day frequencies are higher by approximately 27.9%
and 112.1%. By contrast, ICON-10 km-ON and ICON-40 km-ON have wet-day frequencies approximately 8.4% and 7.6%
higher than ERA5 and dry-day frequencies approximately 43.6% and 39.6% lower than ERA5. Thus, the ICON configurations
without parameterized deep convection exhibit relatively drier local conditions immediately following heatwave termination in
this region, whereas the configurations with parameterized deep convection exhibit relatively wetter conditions. At fixed 10 km
grid spacing, the reversal in the sign of the wet- and -dry differences between ICON-10 km and ICON-10 km-ON indicates a
strong sensitivity of the simulated post-heatwave precipitation conditions to the treatment of deep convection.

East Asia exhibits a less systematic dependence on convection treatment. ERA5 classifies approximately 58.1% of first
post-heatwave days as wet and 41.9% as dry. Relative to ERA5, wet-day frequencies are lower by approximately 17.2%,
24.6%, and 17.0% in ICON-2.5 km, ICON-10 km, and ICON-40 km-ON, respectively, while dry-day frequencies are higher by
approximately 23.9%, 34.0%, and 23.5%. ICON-10 km-ON instead remains close to ERA5, with differences of only +0.5%
for wet-day frequency and -0.7% for dry-day frequency. The contrast between the two 10 km configurations again indicates
sensitivity of the simulated post-heatwave precipitation conditions to the treatment of deep convection at fixed grid spacing.
However, the similar departures from ERA5 in ICON-2.5 km and ICON-40 km-ON show that this relationship is not systematic
across the full set of ICON configurations. Local post-heatwave precipitation differences alone therefore do not provide a
consistent explanation for contrasting heatwave behaviour among the East Asian simulations, motivating consideration of
large-scale circulation and blocking in the following section.

As sensitivity test of the selected timing, we repeat the analysis using precipitation on the final heatwave day (Fig. A5). The
main regional contrast are similar, although generally less pronounced. We therefore retain the first post-heatwave day as the
primary diagnostic because the end of a heatwave is expected to coincide with a transition toward a more convectively active



environment, as surface heating, boundary layer instability and moisture convergence can promote precipitation after the event
420 has terminated as described in the Section 1.

In general, the local land-atmosphere and precipitation diagnostics reveal regionally coherent associations with simulated
heatwave persistence, but do not provide a uniform explanation across all regions and model configurations. The clearest
relationship occurs in the tropical Americas, where the configurations without parameterized deep convection exhibit both
stronger heatwave persistence and substantially drier conditions around heatwave termination, together with pronounced soil-
425 moisture–temperature coupling. This combination is consistent with a reduced precipitation and soil-moisture replenishment
contributing to the maintenance of hot and dry conditions. In East Asia, however, several ICON configurations exhibit drier
conditions relative to ERA5 despite differing heatwave biases, indicating that local processes alone cannot account for the
simulated differences and motivating consideration of the large-scale circulation.

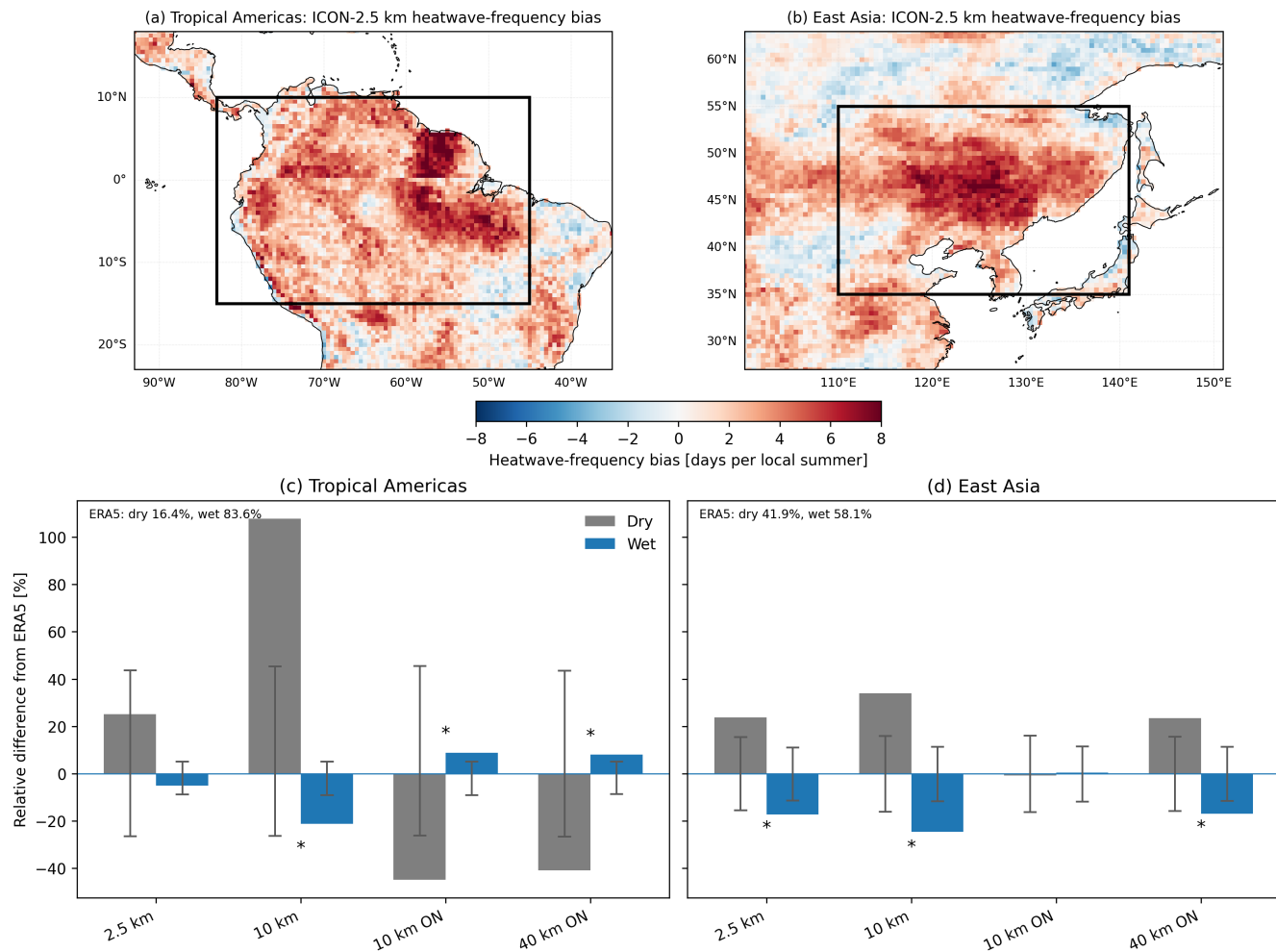


Figure 4. Heatwave-frequency biases and local wet and dry conditions following heatwave termination over the Tropical Americas and East Asia. (a,b) Spatial bias in local-summer heatwave frequency in ICON-2.5 km relative to ERA5, expressed in days per local summer. Black boxes indicate the regions used for the corresponding regional wet/dry analysis. (c,d) Relative differences between each ICON simulation and ERA5 in the frequency of local wet and dry conditions one day after heatwave termination in the tropical Americas and East Asia, respectively. Wet conditions are defined as daily precipitation $\geq 1 \text{ mm day}^{-1}$ and dry conditions as precipitation $< 1 \text{ mm day}^{-1}$. Precipitation is evaluated at the grid point where the heatwave is identified. Differences are expressed relative to the ERA5 climatological frequency as $100(F_{\text{ICON}} - F_{\text{ERA5}})/F_{\text{ERA5}}$, where F denotes the corresponding wet- or dry-condition frequency. Positive values indicate a higher occurrence frequency than ERA5 and negative values a lower frequency. Grey error bars denote the 95% range obtained from 10,000 four-season ERA5 bootstrap samples, matching the length of the ICON simulations. Asterisks indicate ICON values lying outside this ERA5 short-record variability range ($p < 0.05$). Wet and dry classifications are mutually exclusive and exhaustive, thus their absolute frequencies sum to 100%; their relative differences from ERA5 do not necessarily sum to zero. The discontinuity near the Equator in a) results from the hemispheric seasonal definition, which switches from JJA in the Northern Hemisphere to DJF in the Southern Hemisphere; see Sect. 2.1.



3.4 Role of atmospheric blocking

430 We next assess whether regional differences in heatwave characteristics are associated with biases in the representation of blocking and in the co-occurrence of blocking and heatwave days. Because the blocking identification method is designed primarily to detect persistent extratropical anticyclonic anomalies, results in the tropics are not used here for detailed dynamical attribution.

To quantify the relationship between heatwaves and blocking, we compute, at each grid point, the probability that a heatwave
 435 day coincides with a blocking event (Fig. 5). In ERA5, the strongest co-occurrence occurs over extratropical and high-latitude land regions, but with substantial longitudinal variability. A pronounced hotspot extends across northern Europe and north-western Russia, where up to approximately 60% of heatwave days coincide with atmospheric blocking, whereas substantially weaker associations occur at similar latitudes elsewhere. This spatial structure is consistent with the established role of blocking in maintaining persistent warm and dry conditions over midlatitude land regions, while also highlighting the strong regional
 440 dependence of the blocking–heatwave relationship.

The ICON simulations reproduce the broad spatial structure of the blocking–heatwave relationship, although regional differences are evident. Among the model configurations, ICON-2.5 km generally shows the closest spatial agreement with ERA5 in the Northern Hemisphere. Statistically significant differences according to the four-season ERA5 bootstrap test are confined to relatively limited land areas, indicating that much of the simulated blocking–heatwave co-occurrence lies within the variability
 445 expected from a four-year ERA5 sample. Nevertheless, regional deviations remain, and their magnitude and spatial structure differ among the model configurations. Given the short simulation period, the limited extent of significant differences should therefore not be interpreted as evidence that the blocking–heatwave relationship is equally well represented in all simulations.

A comparison of the heatwave days, blocking frequency, and blocking–heatwave diagnostics (Figs. 1, A6, and 5) reveals that their regional biases are not related uniformly across the globe. In several extratropical regions, negative heatwave-occurrence
 450 biases occur together with underestimated blocking frequency or a weaker blocking–heatwave association, consistent with large-scale circulation biases contributing to the underestimation of heatwave occurrence. Conversely, the relationship is not systematic where heatwaves are overestimated. Over East Asia, for example, ICON-2.5 km exhibits positive heatwave biases despite underestimated heatwave–blocking co-occurrence to the north, indicating that the heatwave bias there cannot be explained by a simple local correspondence with excessive blocking. This lack of one-to-one correspondence is consistent with
 455 the additional influence of land–atmosphere and precipitation differences discussed in the previous section.

This contrast indicates that local and large-scale processes contribute differently to the simulated heatwave biases. Local precipitation and land–atmosphere coupling provide a coherent process for some of the positive persistence biases, particularly over the tropical Americas, whereas deficiencies in blocking and in the blocking–heatwave relationship are more closely associated with regions where heatwave occurrence is underestimated. Atmospheric blocking therefore provides an additional
 460 large-scale dynamical factor associated with the regional heatwave differences across the model hierarchy.

The model hierarchy further shows that neither finer grid spacing nor a more explicit treatment of convection systematically leads to closer agreement with ERA5 in large-scale circulation or heatwave statistics. Although ICON-2.5 km reproduces some



aspects of the spatial blocking–heatwave relationship more closely than the coarser configurations (e.g. in western Canada), it also exhibits substantial regional heatwave biases. Conversely, some coarser configurations agree more closely with ERA5
465 for individual diagnostics. Such agreement in a given diagnostic does not by itself establish that the underlying processes are represented more accurately. Thus, the results indicate that grid spacing and convection treatment can affect local land–atmosphere processes and large-scale circulation differently across the model configurations.

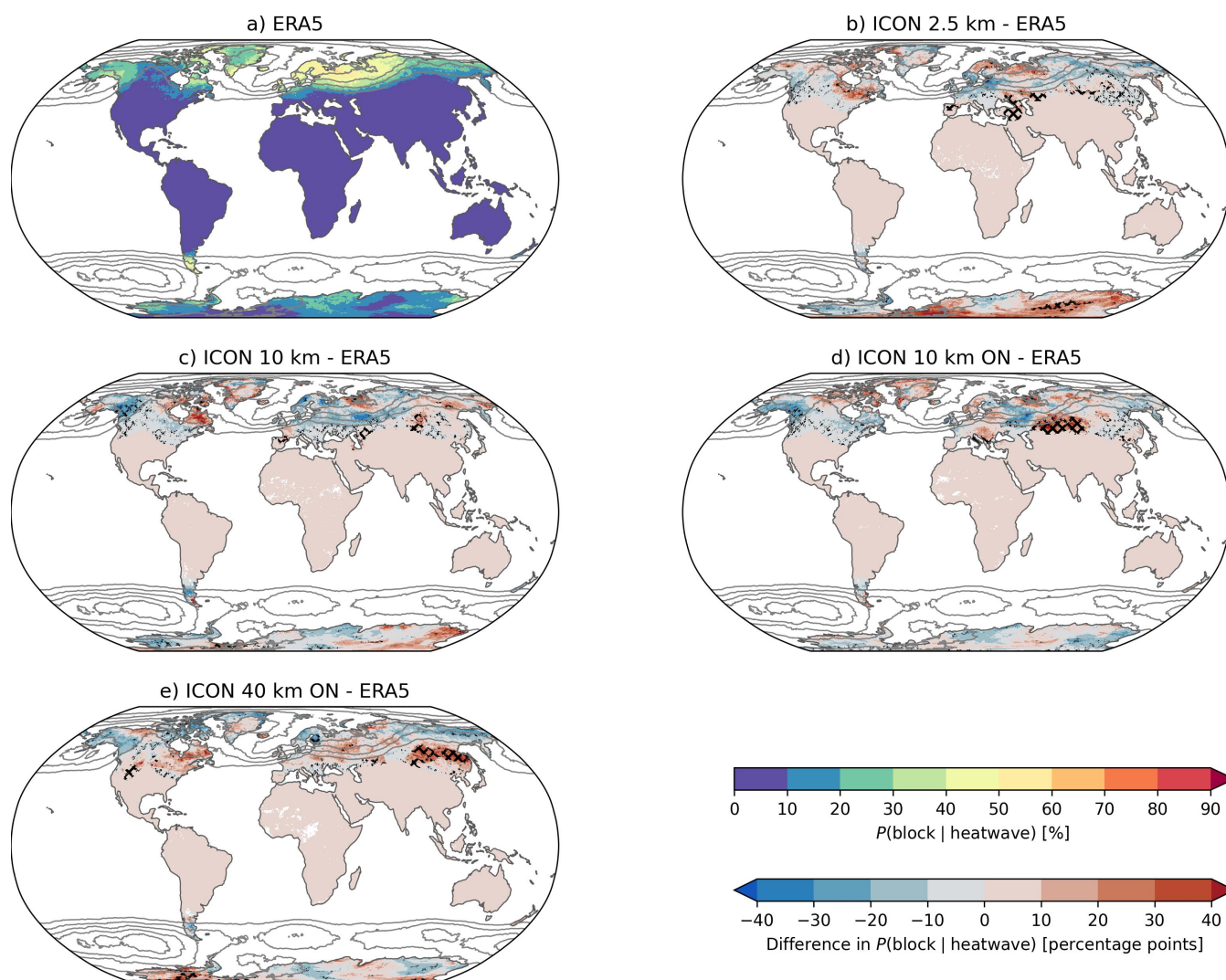


Figure 5. Conditional probability of atmospheric blocking given a heatwave day, $P(\text{Blocking} | \text{Heatwave})$, during local summer. Panel (a) shows the ERA5 climatology, while panels (b–e) show differences relative to ERA5 for the ICON simulations. Grey contours indicate the ERA5 blocking-frequency climatology. Crosses denote grid points where the simulated blocking–heatwave co-occurrence differs significantly from the ERA5 four-season bootstrap distribution ($p < 0.05$).



4 Summary and discussion

Our results show that increasing model resolution and representing a larger fraction of convective processes explicitly does not lead to a systematic reduction of heatwave biases. ICON-2.5 km frequently produces more persistent heatwaves than ERA5, while the response varies substantially among regions and diagnostics. This behaviour is consistent with the influence of competing local and large-scale processes, whose relative contribution to heatwaves differs among model configurations.

The clearest local land-atmosphere mechanism emerges over the tropical Americas. Here, ICON-2.5 km exhibits positive heatwave-day occurrence and persistence biases together with reduced precipitation, stronger soil-moisture–temperature coupling, and substantially drier conditions around heatwave termination. The 10 km simulation without parameterized deep convection shows a similar, and in some diagnostics even stronger, response. The contrast between the two 10 km configurations further indicates that these regional differences are in part shaped by the different treatment of deep convection even at fixed grid spacing. In the 10 km simulation without parameterized deep convection, the dry-condition frequencies on the first post-heatwave day lie well outside the range expected from ERA5 variability over the full annual cycle, whereas the configurations with parameterized deep convection remain considerably closer to ERA5. These relationships are consistent with reduced precipitation and soil-moisture replenishment favoring stronger sensible heating and persistent hot and dry conditions.

Known characteristics of the ICON-2.5 km simulation provide a plausible physical context for this tropical response. Prein et al. (2026) identify continental warm and dry warm-season biases and show that, although mesoscale convective systems (MCS) occur frequently over tropical land, long-lived systems are too infrequent and too small. Deficiencies in the persistence and spatial organization of precipitation-producing systems could therefore reduce effective soil-moisture replenishment even when convective activity itself is not deficient, potentially favoring the dry land-surface state found here. This interpretation is also qualitatively consistent with previous work demonstrating that the sign and strength of soil-moisture–precipitation interactions can depend strongly on whether convection is explicitly represented or parameterized (Lee and Hohenegger, 2024). However, our simulations do not track MCS evolution during individual heatwaves, and the direction of soil-moisture–precipitation coupling cannot be determined from the contemporaneous correlation analysis performed here. Direct attribution of the tropical heatwave bias to the deficiencies in convective organization therefore requires dedicated event-based analysis and a larger sample of heatwave cases.

The tropical Americas heatwave bias also illustrates that moving into the storm-resolving regime does not necessarily eliminate biases present in conventional climate models. Previous CMIP5 and CMIP6 evaluations identified substantial regional biases in tropical heatwave occurrence and duration, including positive biases over tropical South America (Hirsch et al., 2021). Substantial biases remain in the much finer ICON simulations examined here, although this similarity does not imply a common mechanism. This comparison reinforces the need for processes-oriented evaluation of precipitation organization and land–atmosphere interactions across model generations.

Large-scale circulation provides a complementary rather than competing explanation for the regional heatwave biases. ERA5 shows a strong but geographically heterogeneous relationship between atmospheric blocking and heatwaves, with particularly high co-occurrence over northern Europe and Russia. Regional heatwave underestimation more frequently coincides with



underestimated blocking or a weaker blocking–heatwave association, suggesting that persistent large-scale circulation biases contribute particularly to negative heatwave biases. Positive heatwave biases do not show an equally systematic relationship with excessive blocking and may instead reflect local land-atmosphere processes or combined local and large-scale influences.

505 East Asia illustrates this distinction: several ICON configurations exhibit relatively dry post-heatwave conditions, yet their heatwave biases differ, indicating that local dryness alone is insufficient and that circulation differences must also be considered.

These results also clarify how the added value of storm-resolving simulations should be evaluated. Greater process explicitness does not necessarily imply smaller biases in heatwave-day occurrence, duration, or regional precipitation, just as closer climatological agreement in a parameterized configuration does not establish that the underlying processes are more realistic. Evaluation of kilometre-scale climate simulations should therefore consider both process relationships and conventional mean-state and extreme-event biases.

Several limitations constrain the interpretation of our results. Most importantly, the ICON simulations span only approximately four years. This short period strongly limits sampling of interannual variability and rare persistent heatwaves, and prevents a robust analysis of event-to-event variability in convective organization. We account for this limitation where possible by comparing ICON statistics with ERA5 samples of equivalent length, but resampling cannot fully replace longer simulations. The atmosphere-only configuration excludes interactive ocean feedbacks but reduces uncertainty arising from coupled ocean biases, allowing for atmosphere-model sensitivities to be assessed more directly. Furthermore, the standardized, dataset-specific heatwave definition used here is designed to compare relative extremes and dynamical relationships while minimizing the influence of mean-state temperature biases; it therefore differs from impact-oriented definitions based on absolute temperature or humidity thresholds. Finally, several diagnostics characterize associations rather than causal feedbacks. The soil-moisture correlations use complete local-summer seasons, and precipitation around termination is evaluated locally at the heatwave grid point rather than through Lagrangian tracking of surrounding convection. Longer storm-resolving simulations would permit event-centred analyses of precipitation organization, upstream diabatic processes, and land-surface changes before, during, and after heatwaves.

525 The model hierarchy therefore reveals a regionally dependent heatwave response arising from interactions among convection, precipitation, land-atmosphere processes, and persistent large-scale circulation. Understanding when greater process explicitness improves simulated heatwave characteristics, and when regional biases persist or become amplified, will be important for interpreting future kilometre-scale climate simulations.

5 Conclusions

530 In this study, we investigated how grid spacing and the treatment of convection are associated with differences in heatwave characteristics and their relationships with local land–atmosphere processes and large-scale circulation using a hierarchy of atmosphere-only ICON simulations from the EXCLAIM project. The hierarchy comprises a 2.5 km storm-resolving configuration, two 10 km simulations that differ in the treatment of deep convection, and a 40 km configuration with parameterized



convection, allowing for a comparison of heatwave occurrence and persistence, land–atmosphere relationships, and the associ-
535 ation between heatwaves and atmospheric blocking with ERA5.

Our main findings are as follows:

1. All ICON configurations reproduce the first-order spatial structure of global heatwave occurrence, but substantial re-
gional biases remain. Differences in heatwave-day occurrence do not exhibit a simple monotonic dependence on grid
spacing or convection treatment, and many regional differences lie within the variability expected from ERA5 based on
540 the full seasonal cycle. Thus, increasing horizontal resolution alone does not systematically improve the representation
of heatwave days.
2. Heatwave persistence shows clearer configuration-dependent differences than heatwave-day occurrence, particularly to-
ward the upper tail of the duration distribution. ICON-2.5 km exhibits an enhanced probability of long-duration heat-
waves in several regions, including the tropics and extratropics, while the response of the coarser configurations is less
545 systematic. Greater process explicitness therefore does not necessarily lead to more realistic heatwave durations, indi-
cating that the processes controlling heatwave occurrence, maintenance, and termination can respond in competing ways
to changes in model configuration.
3. The tropical Americas exhibit the clearest evidence for a local hydroclimatic mechanism associated with positive heatwave-
persistence biases. ICON-2.5 km and the 10 km simulation without parameterized deep convection show substantially
550 fewer wet and more frequent dry conditions around heatwave termination, together with differences in soil-moisture–
temperature coupling. The 10 km dry-condition anomalies lie outside the range expected from ERA5 variability, whereas
the two configurations with parameterized deep convection remain considerably closer to ERA5. These differences are
consistent with reduced precipitation and soil-moisture replenishment favouring the maintenance of hot and dry condi-
tions, although the diagnostics used here do not establish a causal sequence.
- 555 4. Atmospheric blocking provides a complementary large-scale mechanism rather than a uniform explanation for heatwave
biases. ERA5 exhibits a strong but geographically heterogeneous blocking–heatwave relationship, with pronounced co-
occurrence over regions such as northern Europe and Russia. Across the ICON simulations, regions with underestimated
heatwave occurrence frequently coincide with underestimated blocking or a weaker blocking–heatwave association. In
contrast, regions with positive heatwave biases do not show an equally systematic correspondence with overestimated
560 blocking. This indicates that deficiencies in persistent large-scale circulation are particularly relevant for some regional
heatwave underestimations, whereas positive persistence biases can arise through local hydroclimatic processes or inter-
actions between local and large-scale mechanisms.
5. The comparison between the two 10 km simulations demonstrates that convection treatment can produce substan-
tial differences even at fixed grid spacing. Across several diagnostics, particularly over the tropical Americas, ICON-
565 10 km without parameterized deep convection resembles ICON-2.5 km, whereas ICON-10 km-ON more closely re-
sembles ICON-40 km-ON in heatwave characteristics, precipitation conditions around heatwave termination, and land–



atmosphere relationships. Differences across the model hierarchy therefore cannot be interpreted as effects of grid spacing alone. However, this classification is not consistent across all regions and diagnostics, showing that the influence of convection treatment depends on the regional setting and on other aspects of the model configuration.

570 Our results show that there is no single mechanism through which finer grid spacing or a more explicit representation of convection modifies heatwaves. Positive heatwave-persistence biases are most clearly associated with dry hydroclimatic conditions and land–atmosphere coupling in some regions, whereas deficiencies in blocking and in the blocking–heatwave relationship are more closely associated with regional heatwave underestimation. Heatwave biases therefore emerge from the interaction of local and large-scale processes rather than from either mechanism acting independently.

575 More broadly, our results highlight that greater process explicitness in storm-resolving simulations should not be equated with systematically improved climatological agreement with ERA5. A model can represent convection and related processes more explicitly while amplifying biases in heatwave statistics, whereas a coarser configuration can reproduce bulk climate metrics more closely through compensating parameterized processes. The added value of storm-resolving global models therefore lies not only in potentially reducing biases, but mostly in providing a framework for diagnosing how convection, precipitation, 580 land–atmosphere coupling, and large-scale circulation interact to shape climate extremes.

Longer simulations will be essential to better constrain interannual variability, rare persistent events, and regional process understanding. Complementary to longer kilometre-scale climate integrations, targeted simulations initialized shortly before selected heatwave events could provide a controlled framework for testing the mechanisms identified here. Applying the same ICON model hierarchy from comparable pre-heatwave atmospheric states would help isolate how convection treatment and 585 resolution influence heatwave development, persistence, and termination, while also assessing the associated consequences for heatwave predictability. Future work should additionally examine the organization and lifetime of convection around heatwaves across the globe, the evolution of soil moisture before and during persistent events, and the role of upstream diabatic processes in modifying large-scale circulation in model resolution and process hierarchies. Extending this model hierarchy to future climate conditions will help determine whether the competing local and dynamical mechanisms identified here change as the 590 climate warms and whether storm-resolving simulations alter projections of persistent heatwave risk.

Code and data availability. The ICON model version used in this study corresponds to ICON-EXCLAIM v0.2.0. The complete model source code, including the EXCLAIM extensions, is publicly archived at Zenodo (Dipankar, 2025). <https://doi.org/10.5281/zenodo.17255275>. The code of blocking identification is available from <https://github.com/steidani/ConTrack> (Steinfeld, 2020). A repository of the python code to reproduce the main figures of this study is available at <https://github.com/edgardotes/exclaim-heatwave-figures>.

595 **Appendix A: Additional material**

A1 Heatwave days – annual sensitivity and stratified by latitude bands



Heatwave-day frequency sensitivity: Annual

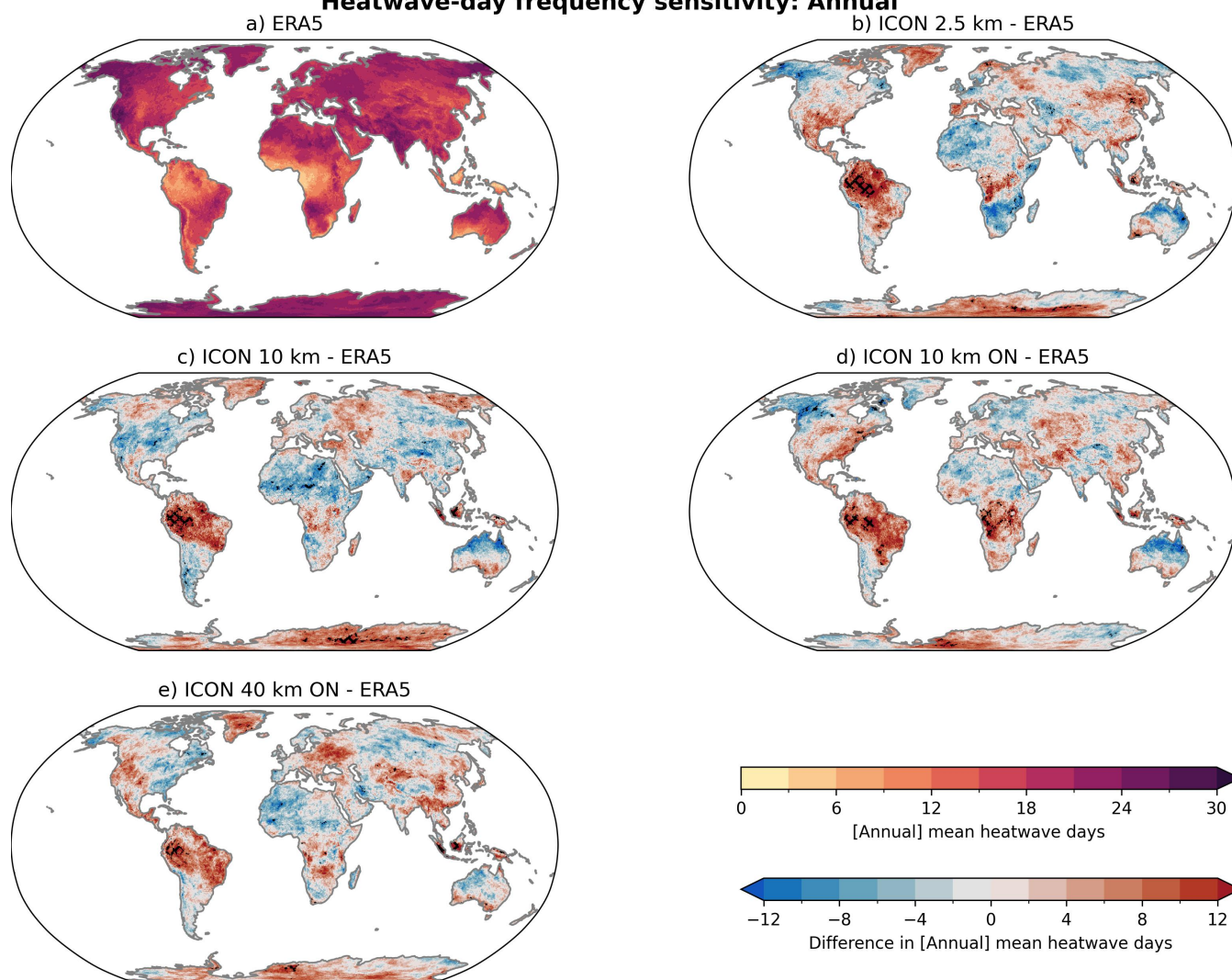


Figure A1. Global distribution of heatwave days for the year-round (days season⁻¹). Panel (a) shows the ERA5 reference climatology, while panels (b–e) show biases relative to ERA5 for ICON-2.5 km, ICON-10 km, ICON-10 km-ON, and ICON-40 km-ON, respectively. Stippling indicates grid points where the ICON four-season mean lies outside the central 95% of the corresponding ERA5 four-season bootstrap distribution ($p < 0.05$, two-sided test).

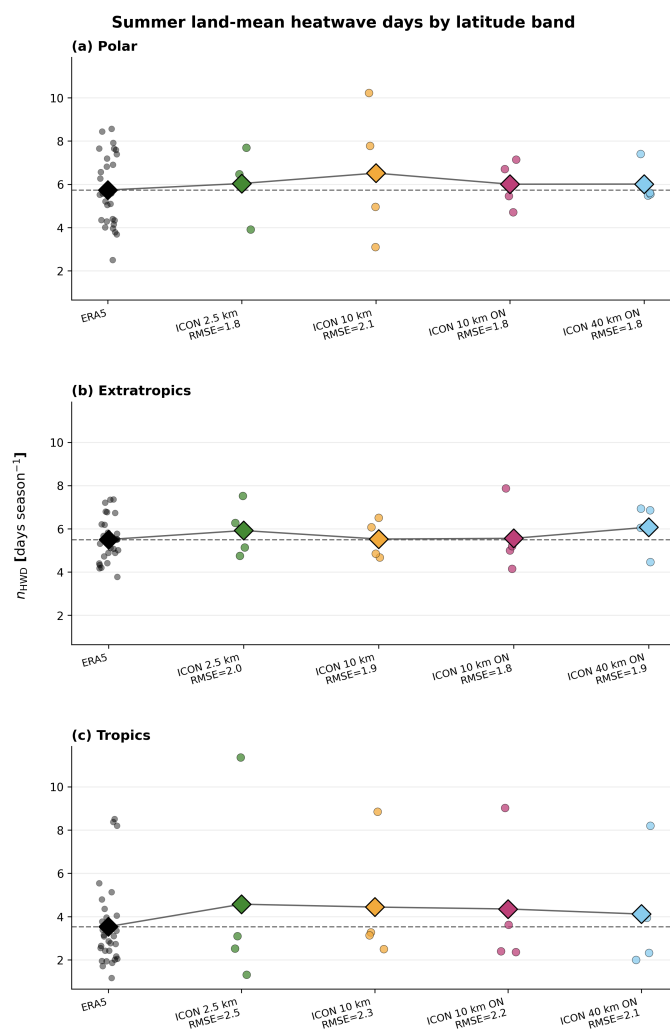


Figure A2. Number of heatwave days per summer season for ERA5 and the ICON simulations. Results are aggregated within three latitude bands: tropics (23.5°S–23.5°N), extratropics (23.5°–65° in both hemispheres), and polar regions (poleward of 65° in both hemispheres).



A2 Seasonal maximum heatwave duration in the local summer

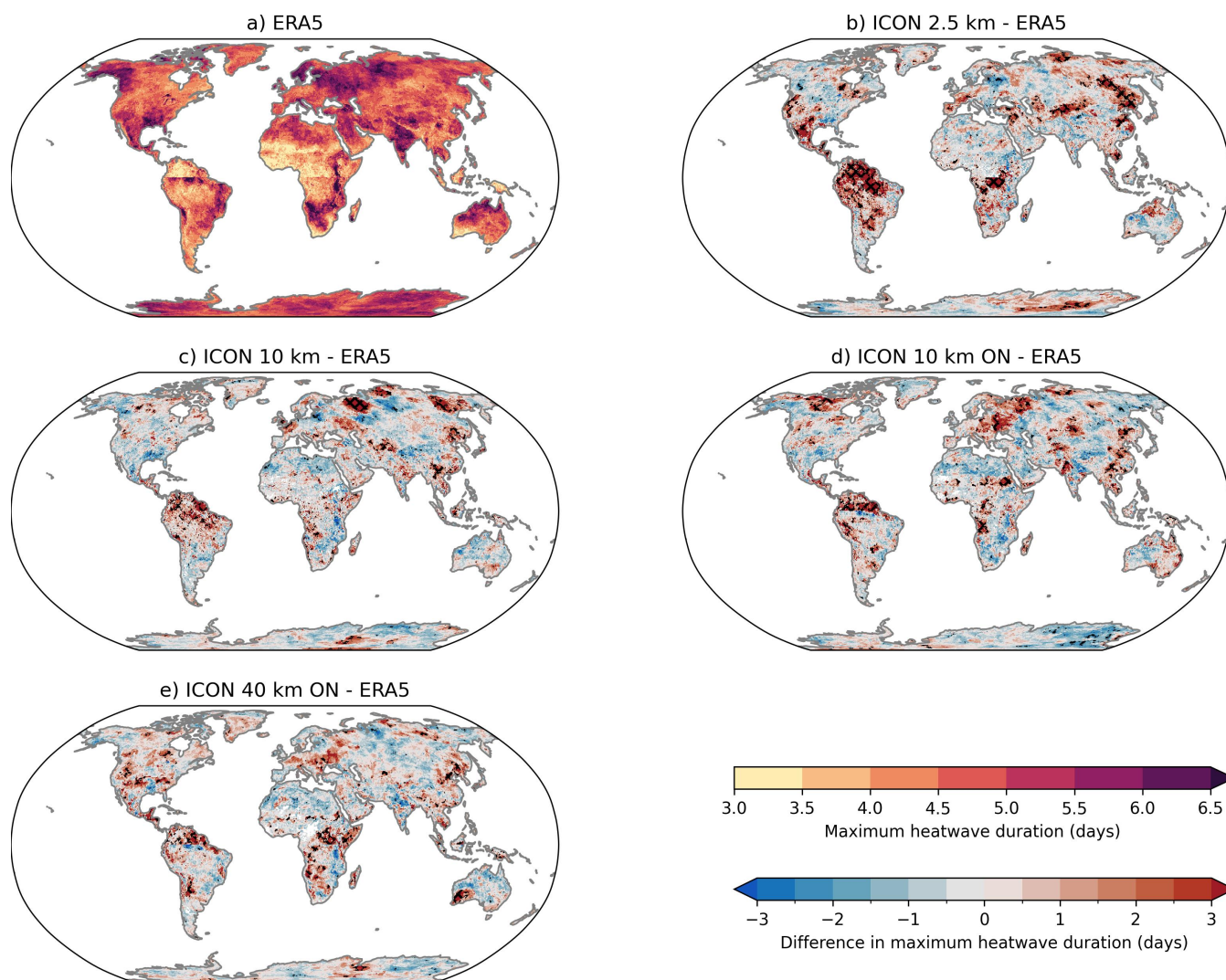


Figure A3. Global distribution of mean seasonal maximum heatwave duration (days) during local summer. Panel (a) shows the ERA5 climatology, while panels (b–e) show biases relative to ERA5 for ICON-2.5 km, ICON-10 km, ICON-10 km-ON, and ICON-40 km-ON, respectively. Crosses denote regions where the simulated values lie outside the range of four-year variability estimated from ERA5 using a bootstrap significance test conditional on heatwave occurrence ($p < 0.05$). A discontinuity near the Equator may arise from the hemispheric seasonal definition, which switches from JJA in the Northern Hemisphere to DJF in the Southern Hemisphere; see Sect. 2.1.

A3 Land–atmosphere coupling

We next examine how land–atmosphere coupling and the convective environment during heatwaves differ between convection-
 600 permitting and convection-parameterized simulations, in order to provide mechanistic context for the model-dependent differ-
 ences in heatwave persistence and blocking attribution identified above.

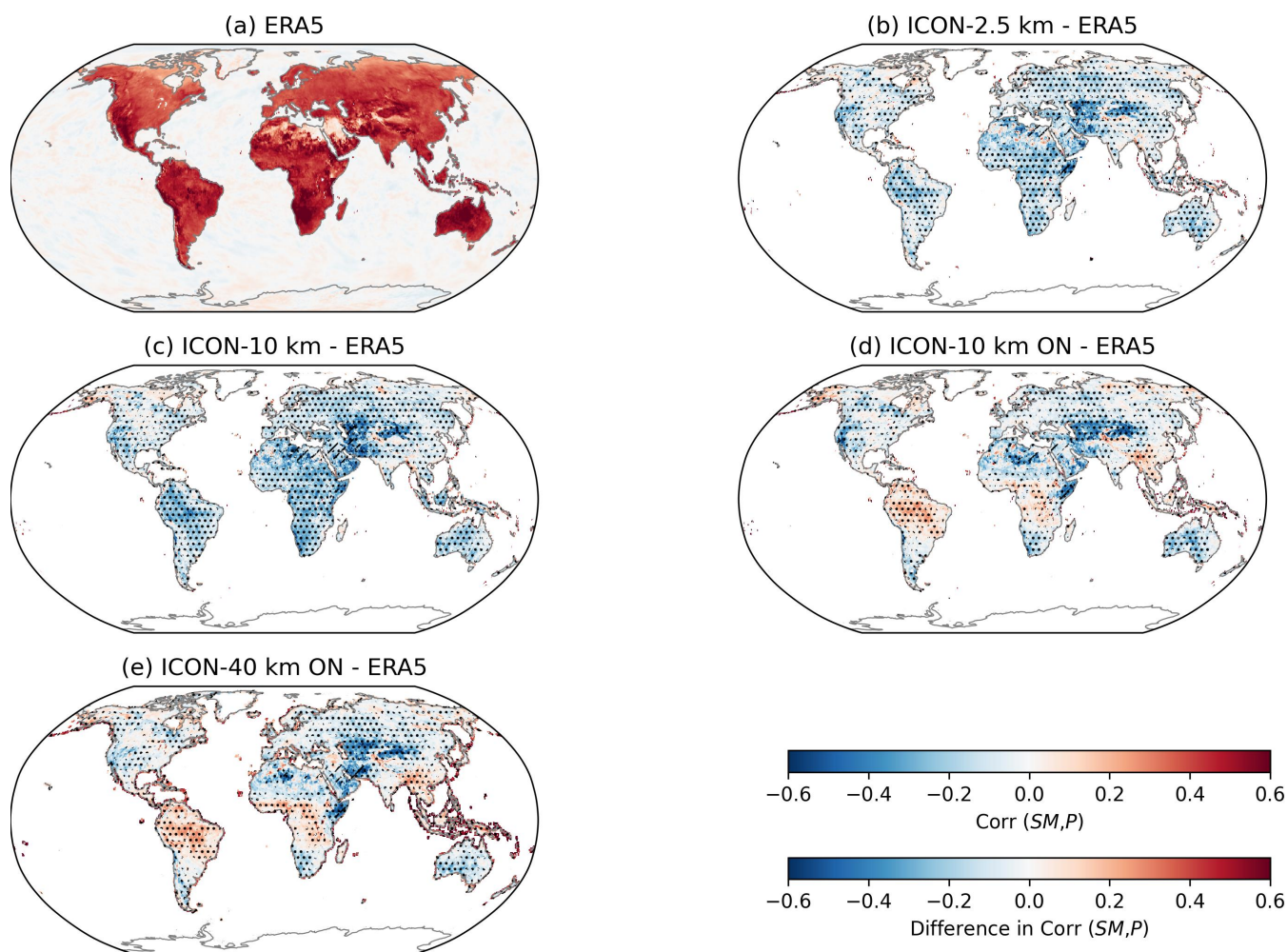


Figure A4. Spatial correlation between daily soil moisture and daily precipitation during local summer (JJA in the Northern Hemisphere and DJF in the Southern Hemisphere). Panel (a) shows the ERA5 correlation field, while panels (b–e) show differences relative to ERA5 for the ICON simulations. Stippling denotes regions where the simulated values lie outside the range of four-year variability estimated from ERA5 using a bootstrap significance test ($p < 0.05$). Diagonal hatching indicates regions where the simulated soil-moisture–precipitation correlation has the opposite sign to ERA5. A discontinuity near the Equator may arise from the hemispheric seasonal definition, which switches from JJA in the Northern Hemisphere to DJF in the Southern Hemisphere; see Sect. 2.1.

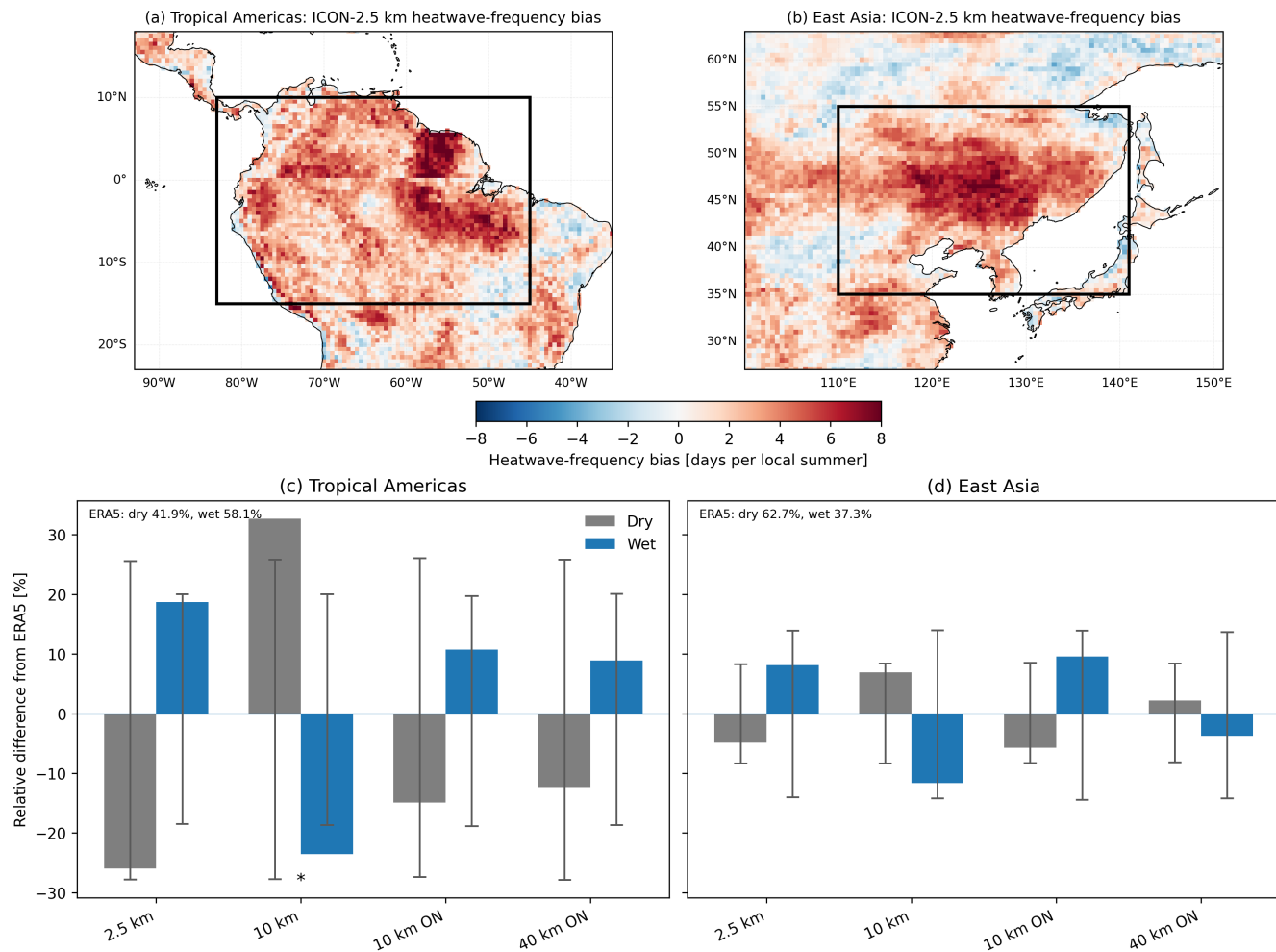


Figure A5. Heatwave-frequency biases and local wet and dry conditions on the heatwave termination over the Tropical Americas and East Asia (last day). (a,b) Spatial bias in local-summer heatwave frequency in ICON-2.5 km relative to ERA5, expressed in days per local summer. Black boxes indicate the regions used for the corresponding regional wet/dry analysis. (c,d) Relative differences in the frequency of local wet and dry conditions one day after heatwave termination within the Tropical Americas and East Asia, respectively. Wet conditions are defined as daily precipitation $\geq 1 \text{ mm day}^{-1}$ and dry conditions as precipitation $< 1 \text{ mm day}^{-1}$. Precipitation is evaluated at the grid point where the heatwave is identified, with no spatial averaging or search for surrounding or upstream convective activity. Differences are expressed relative to the ERA5 climatological frequency as $100(F_{\text{ICON}} - F_{\text{ERA5}})/F_{\text{ERA5}}$, where F denotes the corresponding wet- or dry-condition frequency. Positive values indicate a higher occurrence frequency than ERA5 and negative values a lower frequency. Grey error bars denote the 95% range obtained from 10,000 four-season ERA5 bootstrap samples, matching the length of the ICON simulations. Asterisks indicate ICON values lying outside this ERA5 short-record variability range ($p < 0.05$). Wet- and dry-condition frequencies are complementary and therefore do not constitute independent significance tests. The discontinuity near the Equator in a) results from the hemispheric seasonal definition, which switches from JJA in the Northern Hemisphere to DJF in the Southern Hemisphere; see Sect. 2.1.



A4 Blocking representation

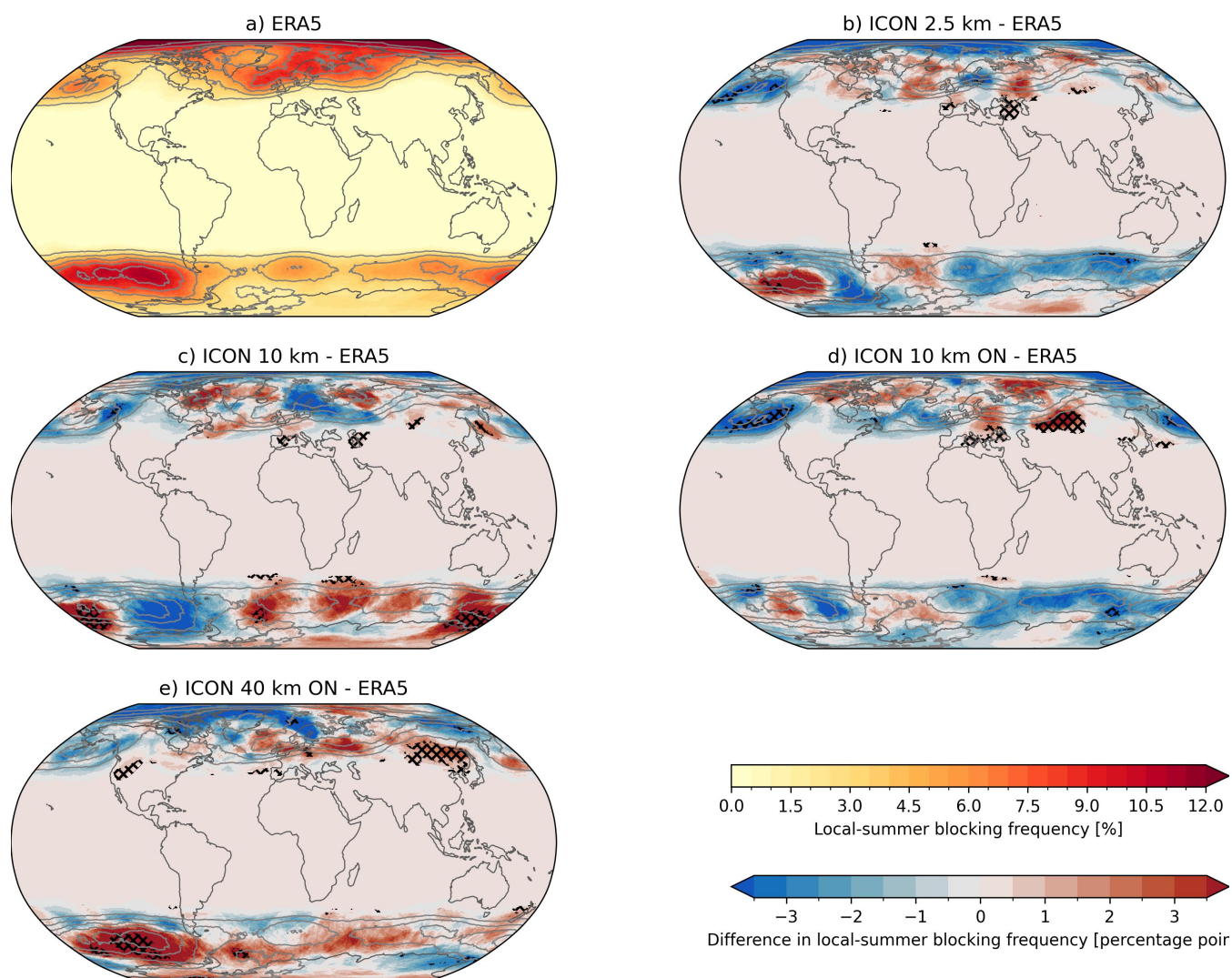


Figure A6. Atmospheric blocking frequency (% of blocked days) diagnosed using the anomaly-based blocking index described in Section 2.3 during local summer. Panel (a) shows the ERA5 climatology, while panels (b–e) show differences relative to ERA5 for ICON-2.5 km, ICON-10 km, ICON-10 km-ON, and ICON-40 km-ON, respectively. Positive values indicate an overestimation of blocking frequency relative to ERA5. Crosses denote regions where the simulated values differ significantly from the ERA5 bootstrap distribution ($p < 0.05$).



Author contributions. EDT and DD designed the study. EDT performed the analysis, produced the figures, and drafted the manuscript. PKP designed and conducted the 2.5 km simulation, and CZ performed the remainder of the ICON runs. All authors discussed the results and edited the manuscript.

Competing interests. The authors have the following competing interests: At least one of the (co-)authors is a member of the editorial board of Weather and Climate Dynamics.

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