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Vertical structure and dynamical regimes of Mediterranean extreme warm events from surface to high troposphere

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Abstract. Climate change is rapidly accelerating the frequency of Extreme Warm Events (EWEs) across the Mediterranean, yet their vertical thermodynamic structure and dynamical evolution remain poorly understood. This study investigates the three-dimensional patterns of EWEs over Rome during the 1991-2025 period using ERA5 temperature data at 1000 hPa (near-surface), 500 hPa (middle troposphere), and 300 hPa (high troposphere).

EWEs were identified through percentile- and persistence-based criteria and classified using a K-means clustering approach. Their evolution was further investigated through precursor analysis, synoptic composites, and HYSPLIT backward trajectories. Five Extreme Warm Regimes (EWRs) were identified, spanning from shallow boundary-layer warming to vertically coherent deep-column structures. These regimes naturally separate into two broader classes: vertically coupled events, characterized by warming throughout the tropospheric column, and vertically decoupled events, in which thermal anomalies remain confined to specific atmospheric layers.

Trend analysis reveals a marked increase in the frequency of vertically coupled regimes after 2015, particularly during summer and autumn. While the average duration and mean thermal intensity of episodes have remained remarkably stable over the 35-year period, the higher recurrence of deep-column anomalies is effectively extending summer-like atmospheric conditions into autumn months. Representative case studies show that the coupled regimes develop through different pathways, involving persistent blocking, subsidence, and/or subtropical warm-air advection, while the remaining regimes maintain persistent vertical decoupling throughout their evolution.

Overall, these findings indicate a progressive climatic transition toward more vertically organized and synoptically controlled EWEs, providing key information on the physical nature of Mediterranean heat extremes that cannot be inferred from near-surface temperatures alone. This three-dimensional framework offers a physically based approach for interpreting, classifying, and improving the prediction of EWEs in Mediterranean environments.

1 Introduction

The Mediterranean basin is widely recognized as a climate change hotspot (Giorgi, 2006), with surface air temperature having already reached approximately 1.5 °C above pre-industrial levels, outpacing the global average by roughly 0.4 °C (Cramer et al., 2018; Seneviratne et al., 2021). Sea surface temperatures (SST) follow a similar trend, with the Mediterranean Sea warming substantially faster than the global ocean. Mean Mediterranean SST increased by about 0.35 °C decade^{-1} during 1982-2019,

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corresponding to more than twice the global mean SST warming rate (Pastor et al., 2020; Seneviratne et al., 2021). Under high-emission scenarios (SSP5-8.5), climate projections consistently identify annual warming for the Mediterranean projected to exceed the global mean by about 20%, while summer warming may reach 40-50% above global rates, especially across the northern Mediterranean basin (Cos et al., 2022; Hassoun et al., 2025). In addition, the European State of the Climate report (ESOTC, 2025) indicated that the European continent has become increasingly susceptible to more frequent and more intense extreme warm events (EWEs) due to alterations in large-scale atmospheric circulation (C3S/ECMWF and WMO, 2026). Furthermore, multi-model projections suggest a progressive intensification in the frequency, intensity, and duration of heatwaves (HWs) throughout the 21st century (Zittis et al., 2021; Cos et al., 2022).

The primary drivers of the development of EWEs include coupled large-scale atmospheric and oceanic circulation patterns, land-atmosphere feedback, and interannual thermal variability (Seneviratne et al., 2010; Stéfanon et al., 2014; C3S/ECMWF and WMO, 2026). Extensive literature has highlighted how the marked warming in the Arctic region (Arctic amplification), driven by global warming, modulates the jet stream's behaviour, leading to an increased frequency of summer EWE dsacross Europe (Coumou et al., 2018; C3S/ECMWF and WMO, 2026). This process induces regional and global temperature anomalies that favour the establishment of persistent atmospheric blocking over Europe. European HWs are intrinsically linked to these persistent high-pressure systems, which obstruct or divert mid-to-high latitude westerly winds for extended periods, thereby facilitating the intensification of thermal extremes (Woollings et al., 2018; Sousa et al., 2018). Beyond atmospheric dynamics, SST anomalies in the Atlantic Ocean and Mediterranean basin play a critical role in modulating the duration and intensity of HW, suggesting a significant teleconnection between oceanic SST variations and extreme continental heat (Duchez et al., 2016; Capozzi et al., 2025).

Traditionally, research has focused on HWs occurring during the boreal summer, as this coincides with the annual peaks in air and sea surface temperatures. However, it is now evident that global warming is triggering an increase in warm anomalies across all seasons, with profound implications for ecosystems, biodiversity, and phenology (Perkins-Kirkpatrick and Lewis, 2020; Rousi et al., 2022; Mahecha et al., 2024). Furthermore, most studies have approached HWs primarily as surface-level phenomena, largely to assess their impacts on human health and socio-economic sectors (Margolis, 2020; Lin and Li, 2026). While valuable, this two-dimensional approach overlooks the complex atmospheric processes governing the intensity and persistence of Mediterranean heat extremes, highlighting the need for a three-dimensional perspective (Lhotka and Kyselý, 2024). In fact, although HWs are traditionally defined using near-surface temperature anomalies, recent evidence suggests that persistent warm anomalies may also develop as vertically decoupled atmospheric structures, where significant warming remains confined to the middle or high troposphere without exhibiting a direct surface signature (Lhotka and Kyselý, 2024; Hassoun et al., 2025). These configurations reflect distinct dynamical and thermodynamic processes that are not fully captured by surface-centric analytical frameworks alone.

In this study, it is worth noticing that a clear distinction is provided among three related but conceptually distinct phenomena. The term "*Heatwave*" (HW) refers to persistent periods of anomalously high near-surface air temperature exceeding a high, location-specific percentile threshold for a minimum multi-day period, consistent with standard surface climatological

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definitions (World Meteorological Organization and World Health Organization, 2015). The broader term "*Extreme Warm Event*" (EWE) is here used to describe any episode of anomalously high temperature within the tropospheric column (spanning from the surface to the high troposphere, approximated by the 300 hPa level), including both surface-based HW and vertically limited warm anomalies that do not necessarily manifest at the surface. Finally, the term "*Extreme Warm Regime*" (EWR) is introduced to denote the distinct three-dimensional atmospheric configurations, representing vertical profiles of temperature anomalies across different pressure levels, regardless of whether the warming encompasses the entire column or remains isolated at specific altitudes.

Building upon this framework, the present study defines the degree of thermodynamic coupling among atmospheric layers during an EWE, ranging from anomalies confined to specific atmospheric layers to fully coupled tropospheric structures. A critical yet under-explored aspect is the lead-lag relationship between these layers: distinguishing between "top-down" intensification, driven by synoptic-scale subsidence, and "bottom-up" thermodynamics, where surface processes may precede or amplify tropospheric warming. The approach proposed here intentionally includes vertically confined warm regimes to investigate the full spectrum of atmospheric thermal structures associated with Mediterranean warm extremes and their dynamical coupling.

This study addresses this knowledge gap by leveraging ERA5 pressure-level reanalysis data for the city of Rome (Italy), covering the period 1991-2025. Rome represents a compelling case study, where large-scale atmospheric forcing interacts with Mediterranean coastal processes and urban microclimate. The main objectives of this paper are to: (i) identify the three-dimensional regimes of Mediterranean EWEs using a multi-level clustering framework; (ii) investigate their long-term temporal evolution, seasonal expansion, and changes in vertical coupling over the last 35 years; and (iii) interpret the physical mechanisms governing each regime by combining precursor analysis, synoptic diagnostics, and backward air-mass trajectories. The paper is structured as follows: Sect. 2 outlines the datasets and the multi-level diagnostic framework; Sect. 3 presents and discusses the long-term trends, the EWR classification, and the physical mechanisms driving the selected case studies. Finally, Sect. 4 summarizes the main conclusions of the study.

2 Materials and methods

This Section describes the datasets, diagnostic framework, and analytical procedures adopted to investigate the three-dimensional structure and evolution of EWEs over Rome. A schematic overview of the complete methodological workflow is presented in Fig. 1, illustrating the sequence of steps from data processing and event detection to clustering, synoptic characterization, and precursor analysis.

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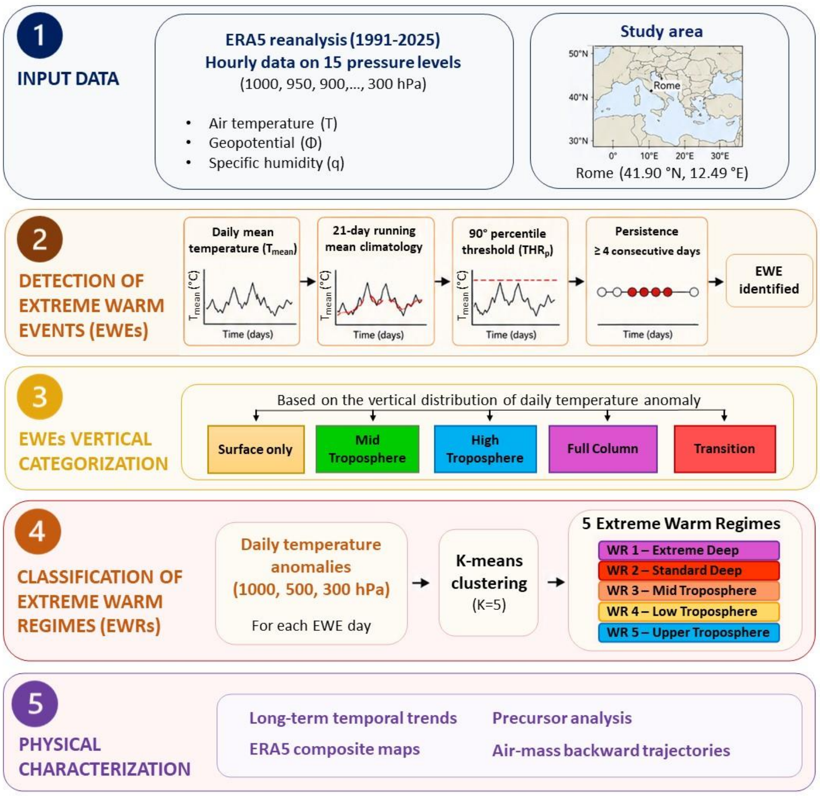

Figure 1: Schematic overview of the methodological framework adopted to investigate EWEs over Rome during the 1991-2025 period. ERA5 reanalysis data were used to identify EWEs using both percentile-based and persistence-based detection criteria. Events were first grouped according to their vertical thermal structure and subsequently classified into EWRs using K-means clustering.

2.1 Study area description

Rome (41.90° N, 12.49° E) is located in the central-western part of the Italian Peninsula, approximately 27 km inland from the coast of the Tyrrhenian Sea (Fig. 1). The city's geographical setting is characterized by a complex topography, settled along the Tiber River valley and flanked by the Apennine Mountains to the east and the volcanic Alban Hills to the southeast. This positioning makes Rome a strategic location for investigating the interplay between synoptic-scale and mesoscale coastal dynamics.

According to the Köppen-Geiger classification, Rome experiences a typical Mediterranean climate class (Csa, temperate climate), with hot, dry summers and mild, wet winters (Beck et al., 2018). In addition, the urban structure of Rome contributes to the development of a pronounced Urban Heat Island (UHI) (Di Bernardino et al., 2025). During near-surface HWs, urban warming may interact with large-scale subsidence and weak ventilation conditions, favouring elevated nocturnal temperatures and limiting the cooling typically associated with the sea breeze circulation (Cecilia et al., 2023; Di Bernardino et al., 2023).

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From a dynamic perspective, the city is frequently influenced by the northward extension of the North African High, which brings warm, dry air masses aloft that progressively gain moisture in the lower troposphere as they cross the marine path across the Mediterranean (Gobbi et al., 2019). The vertical structure of the atmosphere over Rome is further modulated by the penetration of the sea breeze during the afternoon hours, which can induce a stable thermal stratification that temporarily decouples the near-surface layer from the free troposphere (Di Bernardino et al., 2021; Di Bernardino et al., 2023). Such local thermodynamic modifications are critical for understanding the three-dimensional evolution and vertical structure of EWEs. By focusing on this site, the study captures the co-existence and mutual feedback among large-scale subsidence, synoptic warm-air advection, and urban-coastal microclimates, providing a comprehensive view of the EWE development in a vulnerable Mediterranean metropolitan area.

2.2 ERA5 Reanalysis dataset

Atmospheric data used in this study were obtained from the ERA5 reanalysis, the fifth-generation global atmospheric reanalysis produced by the European Centre for Medium-Range Weather Forecasts (ECMWF). ERA5 integrates a wide range of observations with numerical weather prediction models through data assimilation, providing a temporally and spatially consistent reconstruction of the Earth's atmospheric state from the surface to the upper atmosphere (Hersbach et al., 2020).
To investigate the three-dimensional thermodynamic structure of the troposphere over Rome, hourly ERA5 fields covering 1 January 1991-31 December 2025 were retrieved. The vertical domain was characterized using 15 pressure levels, from 1000 hPa to 300 hPa, with a constant vertical decrement of 50 hPa. These levels were dynamically subsetted according to the specific analytical requirements of the study: (i) three core pressure levels (1000, 500, and 300 hPa) were used for the identification and vertical classification of EWEs; (ii) four key reference levels (1000, 850, 500, and 300 hPa) were selected to analyse long-term climatological and temporal trends; and (iii) the complete 15-level vertical profile was exploited to resolve high-resolution time-height cross-sections during the precursory phases and individual case studies.
Specifically, the 1000 hPa level captures near-surface thermodynamic conditions and planetary boundary layer (PBL) processes directly influenced by surface heat sources/sinks. The 850 hPa level serves as a standard diagnostic for air-mass characterization. Being located above the PBL, it is largely decoupled from local surface influences, including UHI effects, and can therefore be used to assess whether warm extremes are associated with regional warm-air advection or with the thermal properties of advancing subtropical air masses. The 500 hPa level represents the mid troposphere and provides information on whether heat extremes are accompanied by large-scale subsidence, ridge amplification, or warm-core anticyclonic structures. Finally, the 300 hPa level characterizes upper-tropospheric circulation and allows the identification of jet-stream variability, Rossby-wave activity, and high troposphere dynamical perturbations that may contribute to persistent atmospheric blocking and warm episodes over the Mediterranean basin (Sousa et al., 2018; Rousi et al., 2022).
The following variables were selected at each level: air temperature (T, °C) to quantify the intensity and vertical extension of thermal anomalies, geopotential (Φ, m^2 s^{-2}) used to derive the geopotential height ($Z=\Phi/g_0$ where g_0=9.81 m s^{-2} is the Earth's

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mean gravitational acceleration) to detect weather synoptic systems, and specific humidity (q, kg kg^{-1}) to assess the moisture-related thermodynamic properties of the air masses.

Data extraction was centred on the metropolitan area of Rome. Given the native ERA5 horizontal resolution (~0.25° × 0.25°; ~31 km), the extracted fields should be interpreted as spatially representative atmospheric conditions over the broader urban-coastal environment. This approach is particularly suitable for investigating large-scale and vertically integrated atmospheric structures, while local urban-scale processes remain only partially resolved within the reanalysis framework (Jiaheng et al., 2021; Nogueira et al., 2022; Hersbach and NCAR staff, 2025).

2.3 Evaluation of long-term temporal trends

The long-term evolution of the vertical atmospheric structure over Rome was evaluated by applying the Mann-Kendall (MK) test (Mann, 1945; Kendall and Gibbons, 1962) to the timeseries of monthly anomalies of air temperature, geopotential height, and specific humidity at four representative pressure levels: 1000, 850, 500, and 300 hPa, chosen to characterize the entire tropospheric column.

As recommended by the World Meteorological Organization (WMO), monthly anomalies were calculated with respect to the reference climatological period 1991-2020 (World Meteorological Organization, 2017; World Meteorological Organization, 2022). For each specific calendar month, the anomaly was derived by subtracting the corresponding multi-year monthly mean from the individual monthly value. This procedure effectively eliminates the dominant annual cycle, allowing for a robust assessment of the underlying forced climatic signal (Yue and Wang, 2004; Sadhukhan et al., 2022). Therefore, the original MK test was applied (rather than its seasonal version) as the prior removal of the monthly mean ensures that the test detects monotonic tendencies in the residuals.

The magnitude of the temporal trend was quantified using Sen's Slope estimator (Hirsch and Slack, 1984), providing the rate of change per decade. All statistical assessments were carried out with a significance level $\alpha = 0.05$ (the null hypothesis of no-trend is rejected if the p-value is less than 5%).

2.4 Identification and classification of Extreme Warm Events (EWEs)

To characterize the three-dimensional structure of EWEs, a multi-level identification framework based was developed. The climatological reference period follows the 1991-2020 WMO standard normal, which is used to derive the pressure-level-specific temperature thresholds described below. The detection algorithm is applied to daily mean temperature (T_{mean}) at three pressure levels (p): 1000, 500, and 300 hPa, selected to represent the near-surface, middle, and high troposphere, as discussed above. Unlike conventional HW detection methods, the proposed framework also identifies persistent warm anomalies confined to the middle or high troposphere. This allows the simultaneous identification of both vertically coupled and decoupled warm events, thereby capturing the full three-dimensional structure of atmospheric thermal extremes.

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For each day of the year (d) and pressure level (p), a dynamical threshold (THR_p) was defined using the 90th percentile ($T_{p,90,ref}$) of the daily mean temperature distribution during the 1991-2020 reference period, using a 21-day moving window ($d \pm 10\ days$) centred on each calendar day:

$$THR_p(d) = T_{p,90,ref}(d \pm 10)\ , \tag{1}$$

This moving-window approach reduces the influence of short-lived weather systems while providing a smooth representation of the seasonal cycle. Consequently, thermal extremes are evaluated relative to the evolving climatological background, allowing robust identification of anomalously warm conditions throughout the year (Di Bernardino et al., 2023; Di Bernardino et al., 2024).

An EWE is identified when the following two conditions are simultaneously satisfied:

1) Intensity: T_{mean} exceeds THR_p at least at one of the three reference pressure levels p (1000, 500, and 300 hPa)
2) Persistence: the intensity criterion is satisfied, at the same pressure level, for at least four consecutive days.

The four-day persistence criterion was adopted to ensure that only sustained warm anomalies are retained, in line with the persistence requirements commonly used in HW identification, while excluding short-lived warm episodes. Consequently, events interrupted by one or more days below the corresponding threshold are treated as separate EWE rather than a single continuous event. Event persistence was first assessed independently at each pressure level. Warm episodes occurring simultaneously or with temporal overlap across different layers were then combined into a single EWE, enabling the characterization of its evolving three-dimensional structure throughout the tropospheric column.

Finally, to disentangle the relative contributions of synoptic-scale atmospheric processes and near-surface feedback, each day within an identified EWE was assigned to one of five mutually exclusive classes according to the hierarchical classification presented in Table 1.

Table 1: Vertical classification of EWE categories.

EWE Category	Temperature condition	Meteorological interpretation
Surface Only	$T_{mean,1000} > THR_{1000}\ \land$ $T_{mean,500} \leq THR_{500} \land$ $T_{mean,300} \leq THR_{300}$	boundary layer-confined extremes (local thermodynamic feedback, typical surface HW)
Mid Troposphere	$T_{mean,1000} \leq THR_{1000}\ \land$ $T_{mean,500} > THR_{500} \land$ $T_{mean,300} \leq THR_{300}$	mid-level anomalies (warm-air advection from Saharan region)

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High Troposphere	$T_{mean,1000} \leq THR_{1000} \wedge$ $T_{mean,500} \leq THR_{500} \wedge$ $T_{mean,300} > THR_{300}$	high troposphere anomalies (high troposphere dynamical perturbations or Rossby-wave activity)
Full Column	$T_{mean,1000} > THR_{1000} \wedge$ $T_{mean,500} > THR_{500} \wedge$ $T_{mean,300} > THR_{300}$	deep tropospheric warming (heat dome, severe blocking)
Transition	Other combinations of $T_{mean,p} > THR_p$	transition phases or complex vertical decoupling

To quantitatively assess each EWE, the daily mean temperature deviation from the 21-day running climatological mean for each day (t) belonging to a single event for each pressure level p for $p \in \{1000, 500, 300\ hPa\}$ is defined as:

$$\Delta T_{mean,p}(t) = T_{mean,p}(t) - T_{mean,p,ref}(t), \qquad (2)$$

In addition, the event-averaged temperature deviation relative to each pressure level p is denominated as $\overline{\Delta T_p}$. To complement this intensity metric and better discriminate among different event structures, the intra-event temporal variability of the anomaly at each pressure level is quantified by computing its standard deviation σ_{Tp}.

2.5 Identification and classification of Extreme Warm Regimes (EWRs)

To objectively identify and characterize the distinct three-dimensional atmospheric configurations associated with EWEs, a K-means clustering analysis was applied to the population of identified EWE days using daily temperature anomalies at the three reference pressure levels (1000, 500, and 300 hPa). The identified clusters correspond to recurrent vertical profiles of temperature anomalies, representing both vertically coupled and vertically decoupled warm regimes. The optimal number of clusters was determined using a dual-metric approach, combining the Elbow Method (to assess the within-cluster sum of squares) and the Silhouette Analysis (to evaluate cluster separation and cohesion), as shown in Fig. A1. To further investigate potential climate-driven shifts in the distribution of the identified EWRs, the 35-year study period was subdivided into 5-year intervals, and the specific metrics presented in Table 2 were derived for each cluster (i.e., for each EWR) and temporal window. Once the EWRs were clusterized, synoptic composite maps were generated using the ERA5 dataset to disentangle the synoptic atmospheric configurations and physical drivers associated with each EWR, using the geopotential height at 500 hPa (Z_{500}) and air temperature anomaly at 850 hPa (ΔT_{850}). Specifically, the Z_{500} field reflects the large-scale atmospheric circulation and provides information on whether the identified EWRs are associated with mid-tropospheric ridges, atmospheric blocking, troughs, or their synoptic-scale circulation features. ΔT_{850} is utilized as a standard diagnostic for identifying air-mass characteristics unaffected by immediate surface diurnal cycles, serving to detect the origin and intensity of lower-tropospheric

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warm-air advection. The use of the thermal anomaly rather than absolute temperature allows for a clear discrimination of the synoptic forcing from the strong seasonal cycle characteristic of the Mediterranean climate. Therefore, ΔT_{850} serves as a reliable proxy for the thermal core of the air mass: high positive values associated with a Z_{500} ridge indicate a synergy between Saharan air intrusion and adiabatic compression, whereas lower ΔT_{850} values in the presence of high Z_{500} suggest that the extreme is primarily driven by local vertical dynamics rather than the arrival of a distinct sub-tropical air mass.

Table 2: List of the metrics adopted for the characterization of EWRs.

Metric	Definition
EWEs frequency (n. days)	total number of EWE days
EWEs duration (n. days)	average persistence of EWEs
Average temperature anomaly ($\overline{\Delta T}$, °C)	event-averaged temperature deviation relative to each pressure level p with respect to the reference climatological period
Cumulative Heat Index (CHI, °C·day)	time-integral of temperature anomalies, evaluated over the entire duration of each EWE, used as a proxy of the thermodynamic load within the atmospheric column

2.6 Temporal evolution of precursor thermal anomaly

To characterize the evolution of multi-level vertical features in the tropospheric column preceding the onset of EWEs, a precursor analysis was developed. This approach tracks the progressive intensification, vertical alignment, and thermodynamic precursory pathways of the warming signal across different tropospheric layers during the days immediately leading up to the event initiation. For each EWE, the onset date (t_0) is defined as the first day of a persistent sequence (minimum 4 consecutive days) during which $T_{mean,p}(t) > THR_p\ (t)$ at least at one of the target pressure levels p (1000, 500, and 300 hPa). The temporal window for the analysis of the preceding conditions spans a 4-day frame from t_{-3} to t_0, where t_{-n} represents the *n*-th day prior to the official event onset (with n = 1, 2, 3).

To quantify the pre-onset thermodynamic behaviour, the cluster-averaged mean thermal anomaly ($\overline{\Delta T_p(t_{-n})}$) is computed by averaging at each level p the temperature anomalies across all N_C events belonging to a specific cluster:

$$\overline{\Delta T_p(t_{-n})} = \frac{1}{N_C}\sum_{i=1}^{N_C} \Delta T_{p,i}(t_{-n}), \qquad (3)$$

where $\Delta T_{p,i}(t_{-n})$ represents the daily temperature anomaly recorded on day t_{-n} at pressure level p for the i-th event belonging to a selected cluster.

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2.7 Investigation of selected case studies

To bridge the gap between statistical clustering and atmospheric dynamics, a representative case study was selected for each EWR identified following the approach in Sect. 2.5. It is worth noticing that, since EWEs are transient phenomena, their vertical structure can dynamically evolve through different categories over time. To isolate the most representative and persistent fingerprint for each EWR, the chronologically continuous event exhibiting the maximum CHI value across the reference levels (1000, 500, and 300 hPa) was selected, prioritizing episodes where the dominant daily cluster ID matched the prevailing vertical category of the entire event.

The vertical evolution of each case study was investigated using the time-height cross-sections (Hovmöller diagrams) of temperature anomalies and equivalent potential temperature (θ_e). Temperature anomalies were calculated relative to the local mean of the 21-day window to isolate the warm core of the event. θ_e, assumed as a conservative tracer for both dry and pseudo-adiabatic processes, was calculated following the classical thermodynamic formulation as in Bolton (1980):

$$\theta_e = \theta \exp\left(\frac{L_v q}{c_p T}\right) \tag{4}$$

where θ is the potential temperature for dry air in K, L_v is the latent heat of evaporation (2406 kJ kg^{-1} at 313.15 K and 2501 kJ kg^{-1} at 273.15 K) and c_p is the specific heat of dry air at constant pressure (1005.7 J kg^{-1} K^{-1}).

The combined analysis of θ_e and temperature anomalies allows for the identification of air mass origins. Specifically, high θ_e values suggest the intrusion of moist tropical air masses, while relatively low θ_e values, concurrent with high thermal anomalies, indicate large-scale atmospheric subsidence, where the air mass warms via vertical compression while remaining significantly dry.

In addition, to disentangle the large-scale forcing, the synoptic-scale drivers of each event were characterized using ERA5 composite maps of Z_{500} and ΔT_{850}, averaged over the specific event duration.

Finally, to identify the geographical origin of the air masses and their vertical displacement, the Hybrid Single-particle Lagrangian Integrated Trajectory (HYSPLIT) model (Version 4.8), developed by the National Oceanic and Atmospheric Administration Air Resources Laboratory (NOAA ARL), was used to retrieve the backward trajectories of the air parcels arriving in Rome at 12:00 UTC of the day of maximum ΔT_{850} (Draxel and Rolph, 2010). Each backward trajectory was calculated for a 96-hour duration, with arrival altitudes set at 500 m, 1500 m, and 5500 m above ground level to comprehensively sample the PBL, the lower troposphere, and the mid-tropospheric flow.

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3 Results and discussion

3.1 Long-term temporal trends

The progressive warming observed over Rome is consistent with the accelerated climate change regional trends documented across the Mediterranean basin, as clearly reflected in the results from the MK test and Sen's slope estimates summarized in Table 3. According to the results of the MK test, all positive trends detected are statistically significant (p-value < 0.05). The analysis, conducted on monthly anomalies across the 1991-2025 period, and subsequently partitioned into meteorological seasons (winter: DJF, spring: MAM, summer: JJA, autumn: SON), highlights a robust, statistically significant upward trend in thermal anomalies (ΔT) throughout the entire tropospheric column on an annual basis, with warming rates ranging from +0.427 °C decade^{-1} at 300 hPa to +0.457 °C decade^{-1} close to the surface (1000 hPa).

This relatively uniform warming throughout the troposphere suggests that the observed climate signal is not confined to the boundary layer but affects the entire atmospheric column over the metropolitan area. However, the seasonal breakdown unveils a more complex picture. The summer season (JJA) exhibits the most intense warming across the vertical profile, with thermal anomaly trends peaking at +0.587 °C decade^{-1} at 300 hPa and remaining remarkably high down to the surface (+0.554 °C decade^{-1}). In addition, a significant warming signal is also observed in autumn (SON) and winter (DJF), with decadal trends paralleling summer values. These outcomes support the hypothesis of a seasonal stretching of summer-like synoptic configurations in autumn, effectively expanding the temporal window of regional vulnerability to EWEs.

This thermodynamic evolution is further supported by trends in geopotential-height anomalies (ΔZ). Marked positive trends are heavily concentrated in the mid-to-upper levels during both summer and autumn, peaking in the high troposphere (300 hPa) at +19.502 gpm decade^{-1} in autumn and +18.640 gpm decade^{-1} in summer. Notably, the absence of significant trends for ΔZ at 1000 hPa across all seasons suggests that the increasing frequency and severity of EWEs over the region are primarily governed by high troposphere dynamical intensification and enhanced synoptic-scale subsidence (ridge deepening), rather than shifts in mean surface pressure.

Specific humidity anomalies (Δq) show widespread and significant increases across almost all pressure levels and seasons. The annual near-surface trend (+0.265 g kg^{-1} decade^{-1}) nearly doubles during summer (+0.441 g kg^{-1} decade^{-1}), consistent with the increased water-holding capacity of a warming atmosphere. This provides a higher latent heat content, which may critically alter atmospheric stability and amplify the overall intensity of EWEs (Di Bernardino et al., 2023).

Table 3: Decadal Sen's slope estimates obtained from the MK test applied to monthly atmospheric anomalies (1991-2025) relative to the 1991-2020 climatology. Sen's slopes are expressed as °C decade^{-1} for ΔT), gpm decade^{-1} for ΔZ, and g kg^{-1} decade^{-1} for Δq. Trends are denoted by symbols: ↑ (positive trend), ↓ (negative trend), and ↔ (no trend).

Variable	All year		Winter		Spring		Summer		Autumn	
	Slope	Trend	Slope	Trend	Slope	Trend	Slope	Trend	Slope	Trend
ΔT_{1000}	0.457	↑	0.494	↑	0.273	↑	0.554	↑	0.424	↑

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ΔT_{850}	0.453	↑	0.496	↑	0.154	↔	0.582	↑	0.445	↑
ΔT_{500}	0.447	↑	0.393	↔	0.336	↑	0.496	↑	0.480	↑
ΔT_{300}	0.427	↑	0.290	↔	0.292	↑	0.587	↑	0.441	↑
ΔZ_{1000}	-0.138	↔	-3.075	↔	0.798	↔	-1.302	↔	1.750	↔
ΔZ_{850}	2.298	↑	-0.920	↔	2.386	↔	1.827	↔	3.988	↔
ΔZ_{500}	9.160	↑	5.415	↔	7.244	↔	10.250	↑	11.961	↑
ΔZ_{300}	15.795	↑	6.607	↔	12.313	↑	18.640	↑	19.502	↑
Δq_{1000}	0.265	↑	0.227	↑	0.174	↑	0.441	↑	0.273	↑
Δq_{850}	0.180	↑	0.134	↑	0.169	↑	0.295	↑	0.162	↑
Δq_{500}	0.033	↑	0.222	↑	0.034	↑	0.043	↑	0.046	↑
Δq_{300}	0.004	↑	0.002	↔	0.003	↑	0.004	↑	0.007	↑

3.2 Identification and classification of Extreme Warm Events (EWEs)

The application of the multi-level identification framework reveals substantial heterogeneity in the vertical structure of EWEs affecting the metropolitan area of Rome. According to the criteria summarized in Table 1, five mutually exclusive EWE categories were identified. A total of 1371 days were classified as EWE during the study period.

The thermodynamic nature of these classes is inferred from the vertical alignment of thermal anomalies. *Surface Only* EWEs point toward a vertical decoupling from the high troposphere synoptic circulation, where extremes might be amplified by local diabatic processes, such as UHI or soil moisture-temperature feedback. On the contrary, *Full Column* events are characterized by concurrent thermal anomalies across all atmospheric layers, from 1000 to 300 hPa. From a dynamic perspective, this configuration is consistent with deep-column warming, potentially associated with persistent subsidence and large-scale anticyclonic circulation. The *Mid Troposphere* and *High Troposphere* EWE categories serve as indicators of stratified forcing, such as warm-air advection driven by the northward extension of the North African High (typically peaking at 500 hPa) or transient dynamical pulses associated with jet-stream perturbations in the high troposphere. Finally, the *Transition* class successfully captures the complex structural evolution during the growth and decay phases of individual EWE.

The temporal evolution of EWE typologies, presented in Fig. 2, shows a marked increase over the 1991-2025 period. While the early decades (1991-2010) are characterized by sporadic events dominated primarily by *Surface Only* or *High Troposphere* anomalies, the last decade (2015-2025) exhibits a marked change in the frequency and composition of EWE categories. Specifically, the total annual number of EWE days has escalated from 20-40 days per year in the 1990s to unprecedented peaks in recent years, exceeding 120 days in 2022, 130 days in 2023, and culminating in a historical maximum of over 160 days in 2024, i.e., more than four times the values observed during most of the 1990s. This rise is primarily driven by an unprecedented increase in the frequency of *Full Column* and *High Troposphere* events, which were comparatively rare in the first two decades of the study period. The increasing contribution of the *Full Column* category suggests a growing prevalence of vertically

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coupled warm anomalies over the study region, where synoptic-scale dynamical intensification dominates over localized boundary layer responses.

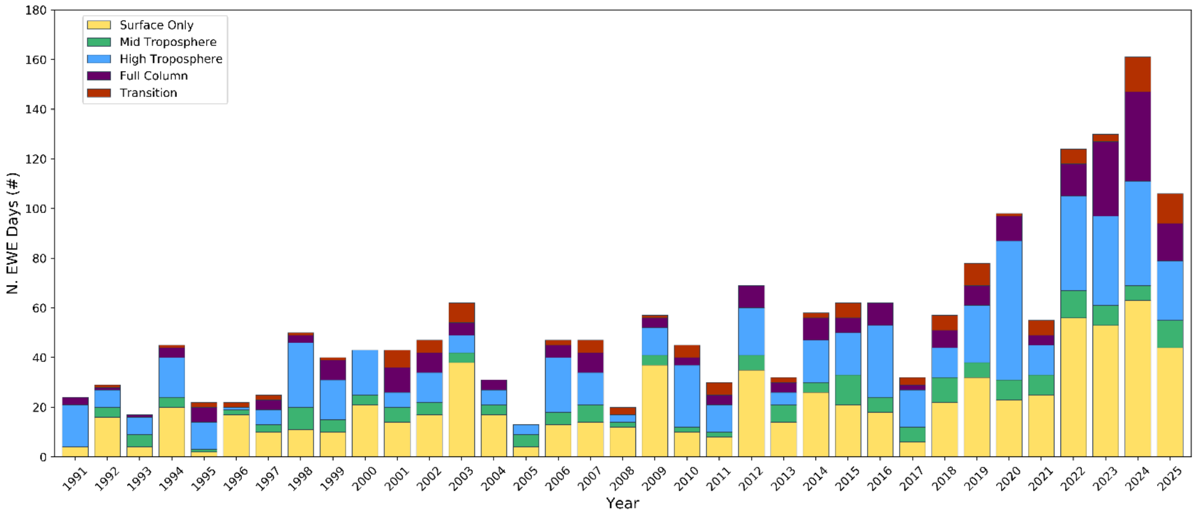

Figure 2: Timeseries of the EWE days divided into the five vertical categories described in Table 1.

The seasonal distribution of these events is further detailed in the daily heatmaps presented in Fig. 3, which illustrate a simultaneous increase in frequency, seasonal expansion, and vertical deepening of thermal extremes during the 2015-2025 decade. The heatmap reveals a clear expansion of the seasonal window favourable to EWE occurrence, with progressively extending into spring (MAM) and autumn (SON). Furthermore, the plot highlights an increase in vertical coupling: while early events were often transient and confined to a single layer, recent EWEs (see, for example, 2022, 2023, and 2025) frequently exhibit transitions from *High Troposphere* precursor stages to prolonged *Full Column* configurations. This behaviour is consistent with enhanced vertical coupling between upper- and lower-tropospheric thermal anomalies, potentially associated with persistent ridging and prolonged subsidence.

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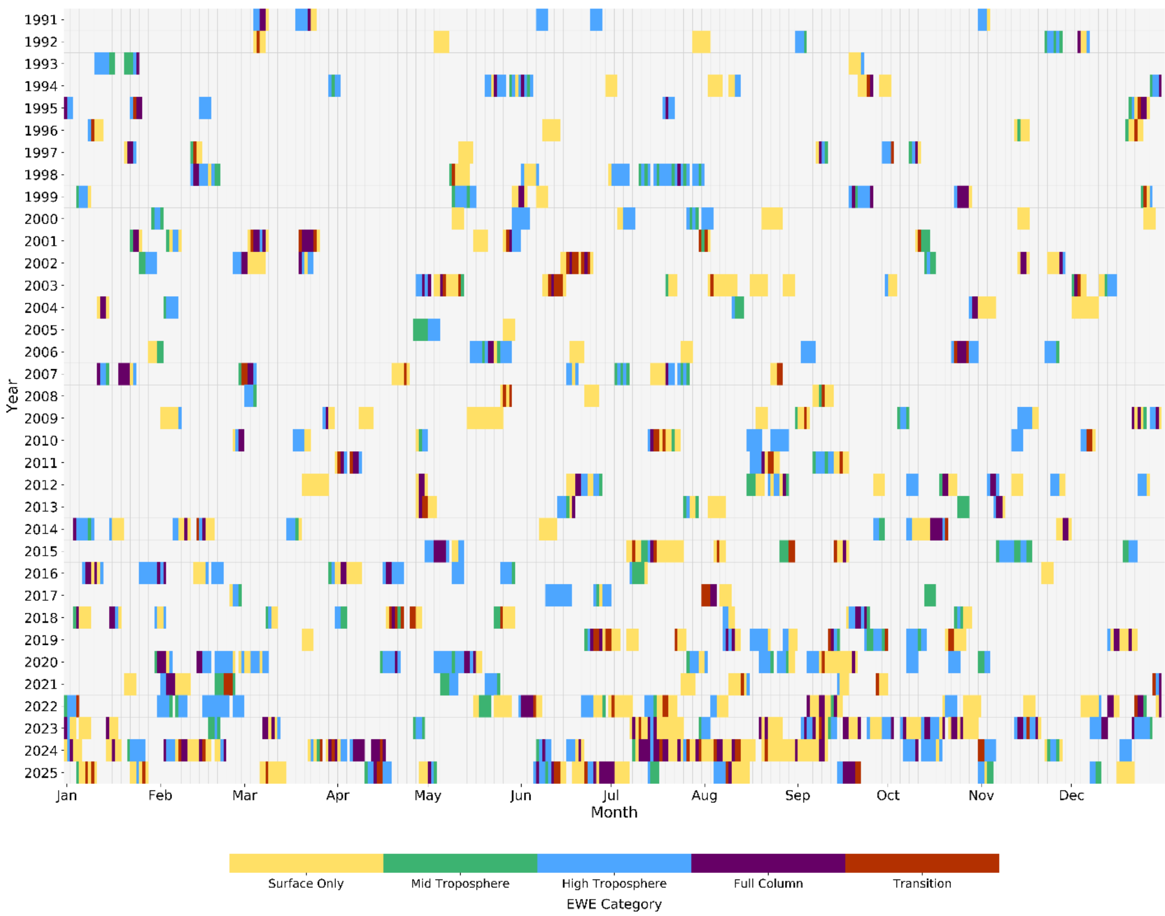

Figure 3: Heatmaps of EWEs classified into the five mutually exclusive categories described in Table 1.

3.3 Identification and classification of Extreme Warm Regimes (EWRs)

To objectively categorize the diverse atmospheric structures associated with EWEs over Rome, a K-means clustering analysis was performed using temperature anomalies at 1000, 500, and 300 hPa. The combined application of the Elbow Method and the Silhouette Analysis identified five clusters as the optimal partition of the dataset (Fig. A1), composed of a total of 1371 days. Each cluster represents a distinct vertical thermodynamic structure, hereafter referred to as an EWR.

The mean vertical profiles of thermal anomalies ΔT, obtained by averaging all days assigned to each cluster, are shown in Fig. 4 and reveal substantial variability in the vertical distribution and intensity of atmospheric warming, as detailed in the following:

i. *Extreme Deep* (n. days=294): the strongest and most vertically coupled EWR, characterized by intense warming throughout the tropospheric column. Temperature anomalies exceed 6 °C in the middle troposphere and remain

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strongly positive at all analysed pressure levels, indicating a highly coupled warm structure extending from the lower to the high troposphere;

ii. *Standard Deep* (n. days=553): a vertically consistent warming profile with temperature anomalies of approximately 3-4 °C. This regime represents a moderate-intensity deep-warming configuration affecting most of the tropospheric column;

iii. *Mid Troposphere* (n. days=529): warming reaches its maximum in the middle troposphere (500 hPa), while anomalies progressively weaken toward both the surface and upper atmospheric levels. This pattern indicates a partially decoupled vertical structure, with anomalous heating concentrated primarily in intermediate layers;

iv. *Low Troposphere* (n. days=459): temperature anomalies peak near the surface (about 3.0 °C) and decrease as the altitude increases. The resulting profile suggests a warm structure largely confined to the lower troposphere, with limited extension into the free atmosphere;

v. *High troposphere* (n. days=65): a highly stratified thermal profile, where anomalies are negligible at the surface but exceed 4.5 °C at 300 hPa. These relatively infrequent events are likely associated with high troposphere dynamical perturbations or Rossby-wave activity with limited coupling to the lower troposphere.

The physical consistency of the clustering framework is further supported by Fig. A2, which shows the relative contribution of the EWE categories introduced in Sect. 3.2 within each statistically derived EWR. Among all EWRs, the *Extreme Deep* regime exhibits the largest percentage of EWEs classified as *Full Column*, highlighting that the most intense events are typically associated with vertically coupled warming throughout most of the tropospheric column. Similarly, the *Standard Deep* regime includes substantial contributions from *Surface Only* and *Full Column* EWEs, suggesting a mixed regime where both lower-tropospheric thermodynamic feedback and large-scale subsidence contribute to EWEs development. The *Mid Troposphere* regime is primarily associated *with High Troposphere* and *Low Troposphere* categories, highlighting the prevalence of vertically decoupled atmospheric configurations. Conversely, the *Low Troposphere* regime is almost entirely associated with *Surface Only* events, reinforcing its interpretation as a shallow, PBL-confined EWR. Finally, the *High troposphere* regime is overwhelmingly dominated by *High Troposphere* events, confirming that these cases remain largely confined to upper atmospheric levels.

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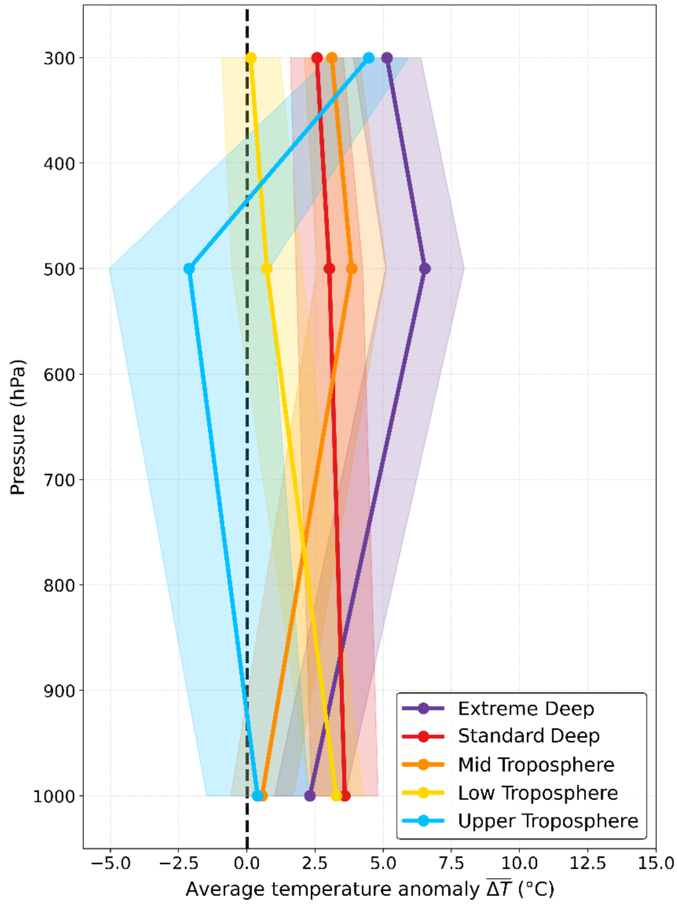

Figure 4: Vertical profiles of thermal anomalies $\overline{\Delta T}$, obtained by averaging profiles of all days belonging to each EWR. Horizontal shaded regions depict ±1 standard deviation σ_{Tp}.

To characterize the large-scale atmospheric configurations associated with each EWR, Fig. 5 shows the ERA5 composite maps of geopotential height at 500 hPa, Z_{500}, and temperature anomaly at 850 hPa, ΔT_{850}, averaged across all days belonging to each specific EWR. Although all regimes are associated with positive thermal anomalies over the central Mediterranean, substantial differences emerge in their spatial organization and vertical structure.

The *Extreme Deep* EWR is associated with a pronounced Z_{500} ridge centred over the central Mediterranean and extending across much of southern Europe (Fig. 5a). Although the ΔT_{850} maximum is slightly displaced toward central-western Mediterranean, the overall structure suggests intense subsidence-driven warming and an efficient vertical propagation of thermal anomalies throughout the atmospheric column. The *Standard Deep* EWR presents a similar anomaly structure. Z_{500} peaks over the Central Mediterranean, while the temperature anomaly field exhibits a maximum (up to +6 °C) over Italy (Fig. 5b), consistent with combined contributions from warm-air advection and large-scale subsidence. The *Mid Troposphere* EWR is characterized by a ridge configuration, with maximum ΔT_{850} confined over North Africa and the western Mediterranean (Fig. 5c). This configuration is consistent with atmospheric conditions in which warming is experienced in intermediate

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tropospheric layers without the development of a fully coupled deep-column structure. The *Low Troposphere* EWR presents a synoptic configuration similar to that of *Standard Deep* (Fig. 5d). In this case, ΔT_{850} assumes the highest value over Italy (about +6 °C), suggesting a predominantly shallow warm advection and enhanced PBL heating rather than intense free-tropospheric subsidence. In contrast, the *High troposphere* EWR exhibits the weakest surface signature among all EWRs (Fig. 5e). The ΔT_{850} field remains close to climatological conditions over Italy, indicating that the thermal anomalies identified in the vertical profiles are confined to upper atmospheric levels and likely associated with transient jet-stream perturbations or Rossby-wave activity.

Overall, the composite analysis indicates that the statistically derived EWRs correspond to physically meaningful atmospheric configurations rather than purely statistical partitions of the dataset, thereby providing a synoptic-scale interpretation of the vertical thermal structures identified by the clustering analysis.

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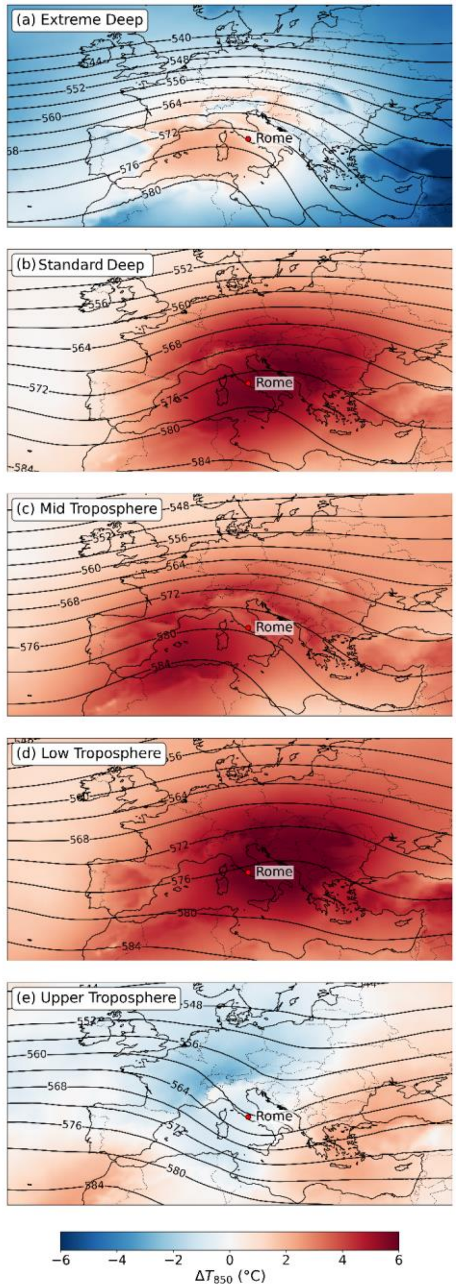

Figure 5: ERA5 composite maps for the five EWRs identified. Each map represents the average atmospheric state obtained by coupling temperature anomaly at 850 hPa, ΔT_{850}, (shaded contours) and geopotential height at 500 hPa, Z_{500} (solid, black lines).

The temporal evolution of the EWR metrics (Table 2) over the 1991-2025 period (Fig. 6) reveals substantial changes in the frequency and thermodynamic contribution of the different atmospheric configurations associated with EWEs over Rome. The most evident signal emerges from the quinquennial evolution of the EWRs frequency (Fig. 6a), which shows a marked increase in the occurrence of all EWRs during the last decade, particularly after 2015. The strongest growth is observed for

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the *Standard Deep* and *Extreme Deep* regimes, whose combined frequency increases sharply during 2021-2025 and accounts for a large fraction of all identified EWR days. In contrast, the mean duration of individual episodes exhibits limited long-term variability (Fig. 6b). Although minor fluctuations are evident among quinquennia, average durations remain relatively stable across all EWRs, generally ranging between approximately 1.5 and 3.5 days. The *Mid Troposphere* and *Low Troposphere* EWRs consistently display slightly longer durations than the Deep EWR, while the *High troposphere* regime remains the shortest-lived configuration throughout the study period. Similarly, the mean temperature anomaly associated with each EWR remains remarkably stable over time (Fig. 6c). The *Extreme Deep* regime consistently exhibits the highest anomalies (~4.5 °C), followed by *Standard Deep* (~3 °C) and *Mid Troposphere* (~2.5 °C). Lower anomaly intensities characterize the *Low Troposphere* EWR, whereas the *High troposphere* EWR displays greater temporal variability, likely reflecting its relatively small sample size. A different behaviour emerges from the evolution of the CHI metric (Fig. 6d). The largest CHI values are consistently associated with the *Extreme Deep* EWR, followed by *Standard Deep* and *Mid Troposphere*. Notably, both Deep EWRs show a substantial increase in CHI during the most recent decades, indicating that their contribution to the overall thermodynamic burden of EWEs has become progressively more important over time.

Overall, these results suggest that the recent intensification of EWEs over the study area is primarily linked to the increasing occurrence of Deep EWRs rather than to systematic changes in their duration or mean thermal intensity.

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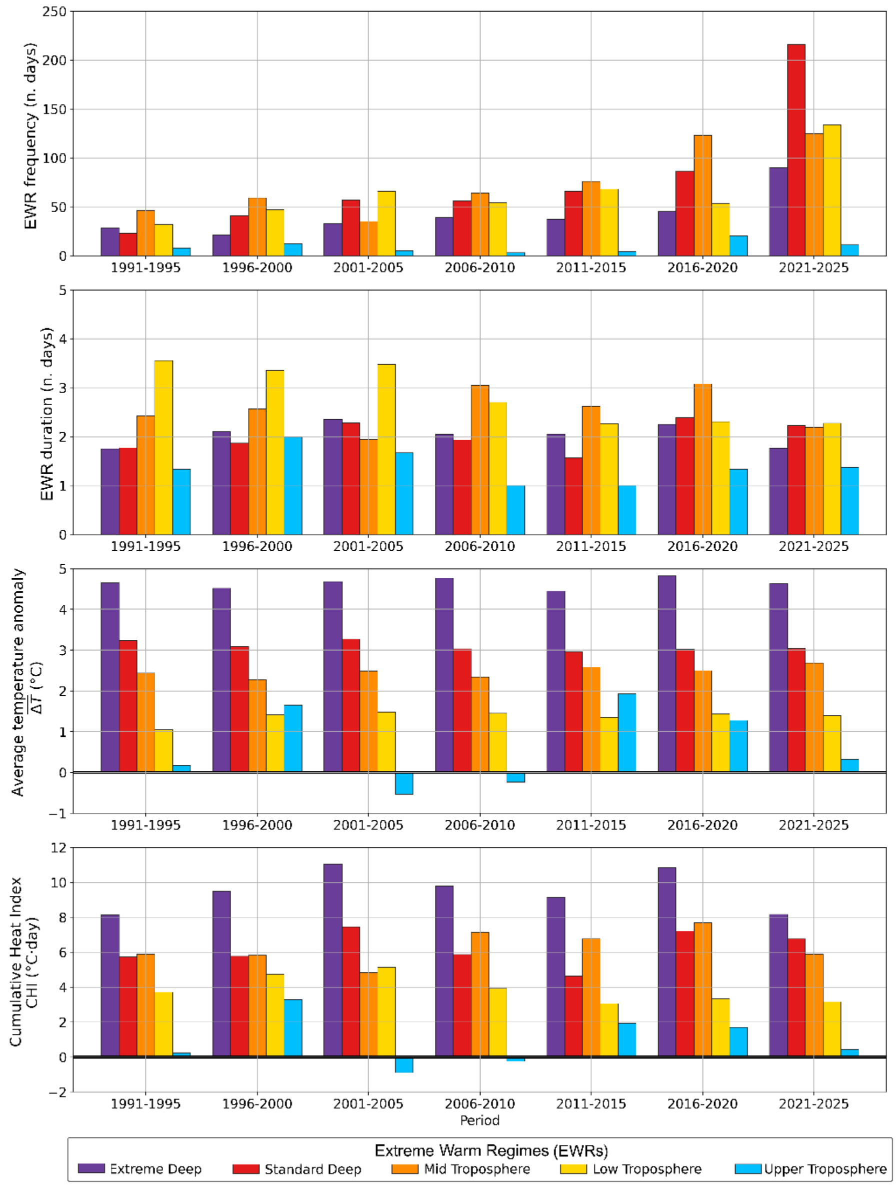

Figure 6: Quinquennial variability of EWR metrics across the five identified clusters for the period 1991-2025.

To investigate the dynamic mechanisms and vertical structures driving the onset of the different atmospheric configurations, Fig. 7 depicts the temporal evolution of cluster-averaged temperature anomalies $\overline{\Delta T_p(t)}$ at 1000, 500, and 300 hPa from three days prior to the event (t_{-3}) up to the onset day (t_0). This lagging framework highlights the distinct precursory pathways and vertical coupling modes that characterize each extreme regime.

All EWRs exhibit a shared behaviour in the upper atmospheric layers during the earliest precursor phase (t_{-3} to t_{-2}), where the upper (300 hPa) and middle troposphere (500 hPa) track each other closely, displaying well-defined, parallel warm

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anomalies ranging between +1.2 °C and +3.0 °C. This widespread high troposphere initialization confirms that the vast majority of EWEs over the region possess a distinct free-tropospheric signature well before appearing at the surface. However, their evolutionary pathways structurally diverge as the onset approaches. Specifically, for the *Extreme Deep* EWR, a powerful top-down intensification mechanism occurs as t_0 approaches; the mid-tropospheric warm core surges abruptly from t_{-2} onward, with the 500 hPa anomalies exceeding +6.0 °C at t_0, while the 300 hPa layer reaches approximately +5.0 °C. Conversely, the lowest tropospheric layer (1000 hPa) undergoes a steady but more gradual warming, reaching +2.3 °C at t_0. This behavior demonstrates that these severe events are initiated by macro-scale synoptic ridging and intense adiabatic compression under strong subsidence, which progressively forces the thermal anomaly downward until full vertical alignment is achieved at t_0. The *Standard Deep* EWR presents a similar but more moderate top-down development, where all three levels converge symmetrically at t_0 within a modest anomaly range of +2.5-3.5 °C. The *Mid Troposphere* EWR exhibits a remarkable thermodynamic decoupling of the surface layer throughout the precursor window. This is evidenced by the contrasting evolution of the vertical temperature anomalies: from t_{-3} to t_{-1}, the 300 and 500 hPa levels show a progressive increase in their warm anomalies, whereas the near-surface layer remains stationary or drops slightly toward the climatological baseline (around +0.7 °C). This pattern indicates that the precursory warming is initially confined to the free atmosphere, likely associated with elevated warm advection or persistent high troposphere ridging that has not yet coupled with the PBL. In stark contrast to the top-down regimes, the *Low Troposphere* EWR is driven by a clear bottom-up warming. At t_{-3} and t_{-2}, the entire tropospheric column appears moderately and homogeneously warm (+1.5-2.5 °C). From t_{-1} onward, however, the vertical structure undergoes a radical stratification: the middle and high troposphere undergo a rapid cooling trend, dropping to +1.0 °C (500 hPa) and +0.4 °C (300 hPa) at t_0. Conversely, a localized thermal intensification occurs exclusively near the surface, with the 1000 hPa anomaly climbing steadily to exceed +3.2 °C at t_0. This clean structural divergence confirms that *Low Troposphere* events are dictated by surface-driven thermal processes, such as enhanced sensible heat fluxes, localized land-atmosphere feedback, or shallow, PBL-confined warm air masses. Finally, the *High troposphere* EWR represents a highly isolated, high-altitude extreme structure. Throughout the precursor window, the 300 hPa level maintains a steadily increasing warm anomaly that reaches +4.5 °C at t_0. In contrast, the middle and lower troposphere display a striking downward trend. At t_0, the vertical decoupling across the column becomes pronounced. Indeed, the high troposphere reaches its thermal peak, the near-surface anomaly drops below +1.0 °C, and the mid-troposphere (500 hPa) undergoes a prominent collapse, falling well below the climatological baseline to approximately -1.6 °C.

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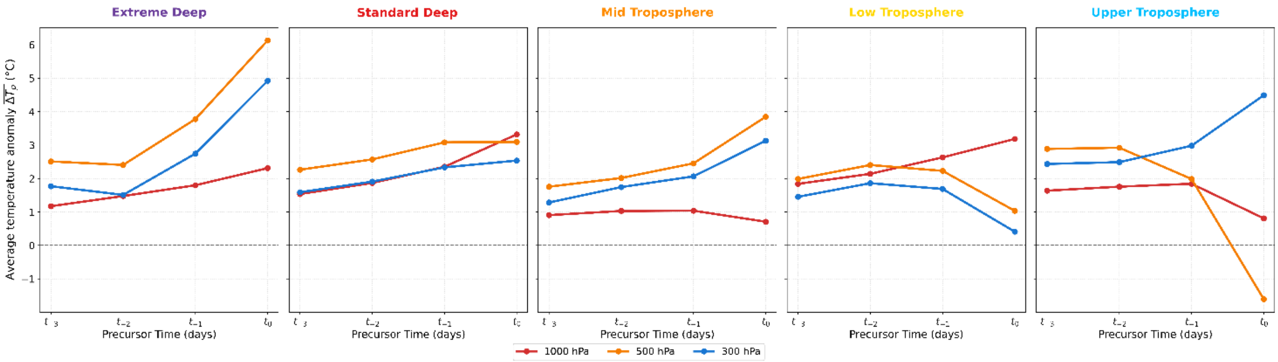

Figure 7: EWR-averaged thermal anomalies ($\overline{\Delta T_p}$) computed over the 4-day precursor temporal window for the five identified EWRs. The temporal evolutions refer to 1000 hPa (red lines), 500 hPa (orange lines), and 300 hPa (blue lines). The dashed black horizontal line depicts the zero-anomaly climatological baseline.

3.4 Spatiotemporal characterization of case studies

To validate the physical interpretation of the statistically derived EWRs, one representative event was selected for each cluster following the criteria detailed in Sect. 2.7. The selected episodes maximize the CHI values while preserving the dominant EWE category associated with each regime (Table 4).

Together, the time-height cross-section of ΔT and θ_e (Fig. 8), the corresponding synoptic configurations, and the HYSPLIT backward trajectories (Fig. 9) provide a process-based validation of the physical mechanisms governing each EWR.

Table 4: Summary of the representative case studies selected for each EWR. For each event, the dominant EWE category, period of occurrence, total duration, mean temperature anomalies at the three reference pressure levels ($\overline{\Delta T_{1000}}$, $\overline{\Delta T_{500}}$, and $\overline{\Delta T_{300}}$), and the Cumulative Heat Index (CHI) are reported.

EWR category	EWE category	EWE Period	Duration (n. days)	$\overline{\Delta T}_{1000}$ (°C)	$\overline{\Delta T}_{500}$ (°C)	$\overline{\Delta T}_{300}$ (°C)	***CHI*** (°C·day)
Extreme Deep	*Full column*	19/01/1997-22/01/1997	4	3.24	8.25	5.84	69.32
Standard Deep	*Full column*	02/06/2022-05/06/2022	4	6.11	3.30	3.61	52.10
Mid Troposphere	*High troposphere*	03/05/2020-12/05/2020	10	0.35	3.43	4.08	72.29
Low Troposphere	*Surface only*	01/12/2004-09/12/2004	9	3.65	1.85	-0.31	43.72
High troposphere	*High Troposphere*	02/07/1998-07/07/1998	6	0.01	0.92	4.87	23.48

The *Extreme Deep* case (19-22 January 1997) is characterized by exceptionally strong mid-tropospheric warming, with mean anomalies reaching +8.25 °C at 500 hPa decreasing to +5.84 °C at 300 hPa, while remaining positive near the surface ($\overline{\Delta T_{1000}}$ = +3.24 °C; Table 4). The time-height evolution (Fig. 8a) indicates that warming first intensifies above approximately 600-700 hPa and progressively propagates downward over the following days, leading to the development of a vertically coupled warm anomaly. Throughout the event, θ_e exhibits only limited temporal variability and does not develop a pronounced elevated

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maximum (Fig. 8b), suggesting that the event is not associated with a substantial increase in the thermodynamic content of the atmospheric column. This interpretation is supported by the large-scale circulation, which is dominated by a compact blocking anticyclone over the central Mediterranean (Fig. 9a), while the backward trajectories reveal descending continental air masses arriving over Rome from the European sector (Fig. 9b). The close agreement between the vertical thermal evolution, the synoptic configuration and the transport pathways indicates that this winter event is primarily sustained by persistent subsidence and adiabatic compression rather than by long-range warm-air advection.

The *Standard Deep* event (02-05 June 2022) also evolves toward a vertically coupled warm column, although within a substantially different thermodynamic environment. Even if positive anomalies extend throughout the atmospheric column, the largest warming is concentrated in the lower troposphere, where $\overline{\Delta T_{1000}}$ reaches +6.11 °C, while anomalies remain close to +3.50 °C at both 500 and 300 hPa (Table 4). Unlike the winter case, the θ_e field evolves rapidly after the onset, developing a pronounced maximum within the middle troposphere (Fig. 8d), indicative of a progressive increase in the thermodynamic content of the air mass. At the synoptic scale, the event coincides with a broad subtropical ridge extending from North Africa across the central Mediterranean (Fig. 9c). Consistently, the HYSPLIT trajectories trace the lower-to-mid tropospheric air parcels back to northern Africa after crossing the Mediterranean Sea (Fig. 9d), highlighting the significant contribution of subtropical air-mass advection to the development of the vertically coupled warm structure. In contrast to the winter *Extreme Deep* case, the *Standard Deep* event develops under much stronger advective forcing, producing the strongest lower-tropospheric warming among the five representative events. Despite their contrasting seasonal environments, both events evolve toward a vertically coupled warm column, supporting the interpretation that the Deep EWRs represent dynamically coupled atmospheric structures, although sustained by different large-scale processes.

In contrast, the remaining three case studies are characterized by persistent vertical decoupling, although the altitude at which the thermal anomaly develops differs substantially among the regimes.

The *Mid Troposphere* case (03-12 May 2020) illustrates a vertically decoupled configuration in which warming remains largely confined to the free troposphere. Mean temperature anomalies reach +3.43 °C at 500 hPa and +4.08 °C at 300 hPa, whereas the lower troposphere experiences only weak warming **(**+0.35 °C at 1000 hPa; Table 4). The time-height evolution (Fig. 8e) shows that the warm core remains centred between approximately 800 and 400 hPa for most of the event, with only limited downward propagation towards the lowest portion of the troposphere. A comparable vertical organization is evident in the θ_e field (Fig. 8f), where the highest values persist aloft while the lower troposphere undergoes only modest temporal variations, suggesting that the thermodynamic anomaly remains largely confined to the free atmosphere. This behaviour is consistent with the synoptic configuration (Fig. 9e), which places Rome along the northern flank of a subtropical ridge extending across North Africa and the western Mediterranean. The backward trajectories further support this interpretation (Fig. 9f), showing that the upper-level air parcels remain elevated throughout their transport, whereas the lower-level trajectories are comparatively short and predominantly regional. The persistence of this vertically decoupled structure closely matches the precursor evolution identified in Sect. 3.3, confirming that the anomalous warming remains dynamically confined to the free troposphere throughout the event.

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The *Low Troposphere* event (01-09 December 2004) is characterized by warming almost entirely confined up to 950 hPa. The strongest anomalies occur near the surface, reaching +3.65 °C at 1000 hPa, while they rapidly decrease with height (+1.85 °C at 500 hPa) and become slightly negative at 300 hPa (−0.31 °C; Table 4). The time-height evolution (Fig. 8g) shows that the positive anomaly remains largely confined below approximately 600 hPa throughout the event. Unlike the Deep regimes, the θ_e field (Fig. 8h) displays relatively weak vertical organization, without the development of an elevated thermodynamic maximum in the free troposphere. At the synoptic scale, the event is associated with the transition from a high to low pressure system over the central Mediterranean (Fig. 9g), accompanied by only modest positive temperature anomalies at 850 hPa, suggesting that large-scale dynamical forcing provides only a limited background contribution. Consistently, the HYSPLIT trajectories (Fig. 9h) indicate predominantly short transport pathways with little vertical displacement before reaching Rome. Together, these features indicate that the thermal anomaly is primarily generated and maintained within the PBL, with only limited interaction with the overlying free atmosphere.

The *High Troposphere* event (02-07 July 1998) represents a pronounced example of persistent upper-level warming without effective coupling to the lower troposphere. The strongest anomalies remain confined to the upper atmospheric layers, where the mean temperature anomaly reaches +4.87 °C at 300 hPa, while the lower troposphere remains close to climatological conditions ($\overline{\Delta T_{1000}}$ = +0.01 °C) and only weak warming develops at mid-levels ($\overline{\Delta T_{500}}$ = +0.92 °C; Table 4). The time-height evolution (Fig. 8i) shows that the warm anomaly is initially restricted above approximately 500 hPa and only marginally extends downward during the later stages of the event, without establishing a vertically coupled structure. The θ_e field exhibits a comparable evolution (Fig. 8j), with its largest values persistently located in the upper troposphere and only limited temporal variability within the PBL, further highlighting the strong vertical separation between the upper and lower atmosphere. The associated synoptic configuration (Fig. 9i) is characterized by a broad subtropical ridge centred over North Africa, while the strongest low-level thermal anomalies remain displaced south of the central Mediterranean. Likewise, the backward trajectories (Fig. 9j) show that only the highest air parcels originate from subtropical latitudes and remain aloft throughout their transport, whereas the lower-level trajectories remain comparatively local and experience minimal vertical displacement. The close correspondence between the vertical thermal evolution, the synoptic configuration, and the transport pathways confirms that the anomalous warming remains effectively isolated within the upper troposphere, preventing the establishment of the vertically coupled warm column that characterizes the Deep EWRs.

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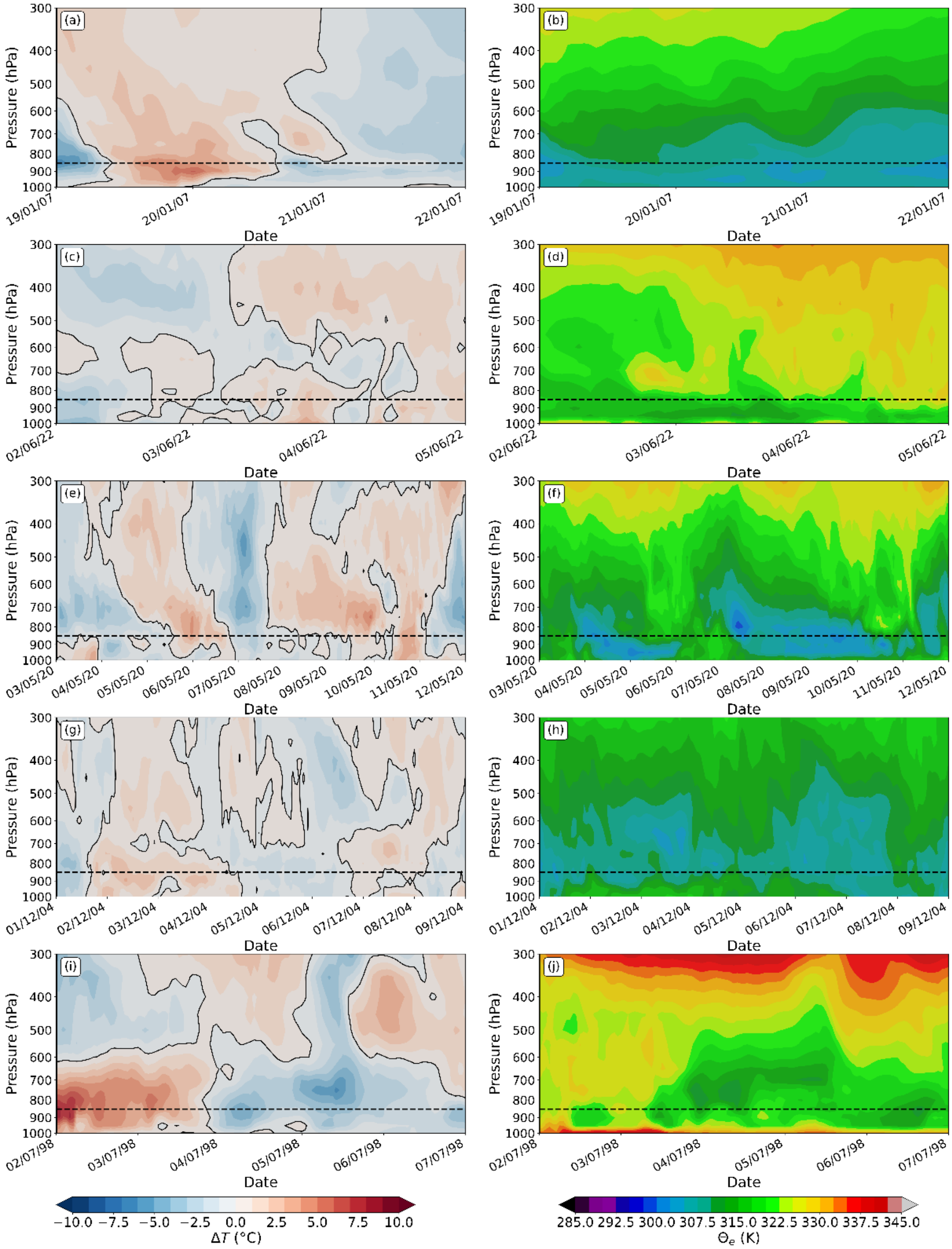

545 **Figure 8: Time-height cross-sections of the selected case studies. Left panels: temperature anomalies (ΔT, °C) calculated relative to the 21-day local climatological window. Right panels: equivalent potential temperature (θ_e, K). From top to bottom, rows correspond to the identified EWRs: *Extreme Deep*, *Standard Deep*, *Mid Troposphere*, *Low Troposphere*, and *High troposphere*. Horizontal, black dashed line refers to the 850 hPa level shown in the composite maps in Fig. 9.**

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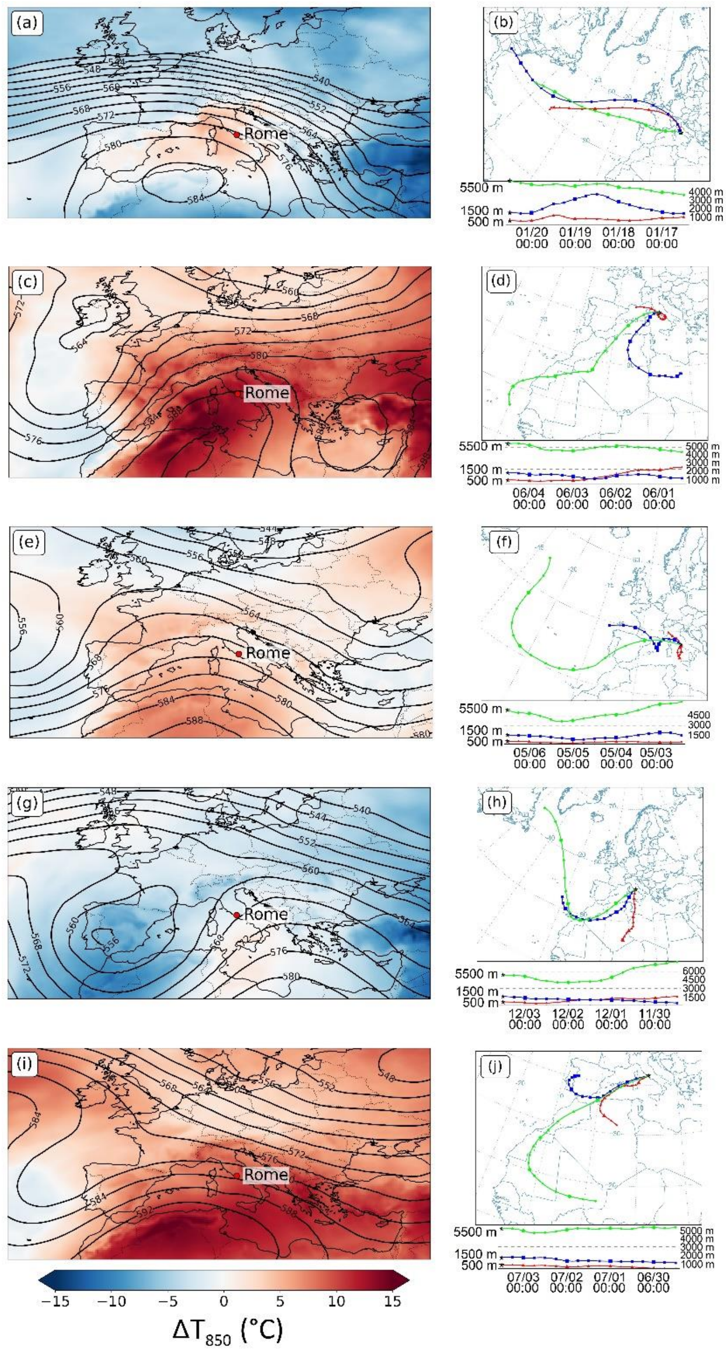

Figure 9: Spatial synoptic characterization of the selected case studies. Left panels: ERA5 composite maps of geopotential height at 500 hPa (Z_{500}, gpm, black solid lines) and temperature anomaly at 850 hPa ΔT_{850}, °C, colour shading) averaged over the respective EWE duration. Right panels: 144-hour HYSPLIT backward trajectories arriving in Rome at 12:00 UTC of the day of maximum thermal anomaly. Arrival altitudes are set at 500 m (red lines), 1500 m (blue lines), and 5500 m (green lines) above ground level (agl), with respective vertical displacement profiles reported in the bottom sub-panels.

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4 Discussion

The results highlight a substantial change not only in the frequency of EWEs but also in their vertical thermodynamic structure. Although the increase in EWE frequency aligns with broader Mediterranean climate change trends (Perkins-Kirkpatrick and Lewis, 2020; Seneviratne et al., 2021; Rousi et al., 2022), the present multi-level framework demonstrates that this increase is not homogeneous across the different EWRs. The strongest rise is associated with vertically coupled regimes (*Full Column* and *Standard Deep* EWRs), suggesting that large-scale dynamical forcing is playing a progressively greater role in shaping Mediterranean heat extremes than shallow, near-surface processes alone.

This interpretation is consistent with the long-term temporal trends identified throughout the tropospheric column. The pronounced positive trends observed during summer and autumn suggest a seasonal stretching of summer-like atmospheric configurations, likely associated with the increased persistence and expansion of subtropical ridging over the Mediterranean basin (Cramer et al., 2018; Cos et al., 2022). This behaviour agrees with previous studies linking Mediterranean warming to large-scale circulation changes and enhanced atmospheric blocking weather patterns (Giannakopoulos et al., 2009; Molina et al., 2020; Zittis et al., 2021).

Combining clustering, precursor analysis, and case studies, the five EWRs can be grouped into two main dynamical classes:

- Coupled events (*Extreme Deep* and *Standard Deep EWRs*): both regimes evolve toward a vertically coherent warm column, but through partly different pathways. As the ridge deepens, intense synoptic-scale subsidence and adiabatic compression force the warm anomaly downward until full vertical alignment is achieved at the EWE onset, overriding local mitigating factors (Lhotka et al., 2018; Sousa et al., 2018; Zschenderlein et al., 2019). The *Extreme Deep* precursor is characterized by the progressive downward extension of a mid-tropospheric warm anomaly, consistent with persistent blocking, subsidence, and adiabatic warming. In contrast, the *Standard Deep* regime develops within a subtropical ridge and is accompanied by low-level warm-air advection from North Africa, favouring rapid warming of the lower troposphere and the establishment of a vertically coupled atmospheric structure. Despite these differences, both regimes ultimately evolve toward a fully coupled tropospheric column dominated by large-scale forcing.
- Decoupled events (*Mid Troposphere*, *Low Troposphere*, and *High Troposphere* EWRs): unlike the Deep EWRs, these events never develop a vertically coupled warm column. Instead, the thermal anomaly remains confined to a limited portion of the troposphere, indicating that the large-scale forcing is either insufficient or unable to establish effective vertical coupling. In the *Mid Troposphere* case, the anomaly is confined to the free troposphere throughout the event, indicating limited penetration toward the PBL. The *Low Troposphere* EWR shows the opposite behaviour, with warming restricted to the PBL and weak anomalies aloft, mainly attributable to surface-driven processes, such as enhanced sensible heat fluxes, shallow warm advection, and local land-atmosphere feedback (Seneviratne et al., 2010; Stéfanon et al., 2014; Hirsch and King, 2020). The *High Troposphere* EWR remains isolated in the upper troposphere,

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likely associated with transient upper-level dynamical disturbances that do not project onto the surface. Together, these cases show that strong warming aloft does not necessarily translate into near-surface extremes.

The increasing frequency of Deep EWRs has relevant implications for Mediterranean coastal cities. Under typical summer conditions, sea-breeze circulations can mitigate daytime heat by importing cooler marine air inland (Bedoya-Valestt et al., 2026). During Deep events, however, the persistence of large-scale warming throughout much of the tropospheric column may weaken these mesoscale cooling mechanisms. Although sea-breeze dynamics are not explicitly resolved here, the synoptic patterns suggest conditions less favourable to their development, with strong anticyclonic control and reduced pressure gradients. This may enhance the persistence of heat over coastal urban areas such as Rome.

Several limitations of the present study must, however, be recognized. First, the analysis relies on ERA5 reanalysis data, which lacks the horizontal resolution necessary to explicitly resolve fine-scale urban canopy dynamics, UHI, or complex mesoscale coastal circulations. Second, the multi-level clustering framework is inherently sensitive to the choice of the specific pressure levels (1000, 500, and 300 hPa) and the determination of thresholds utilized for EWE identification.

Despite these limitations, the proposed three-dimensional framework provides a physically consistent and structurally robust methodology for investigating the vertical structure of atmospheric extremes. By moving beyond the traditional surface-based perspective toward a vertically stratified diagnostic framework, this study shows that the vertical organization of the atmospheric column provides key information on the physical nature of Mediterranean heat extremes that cannot be inferred from near-surface temperature alone. Distinguishing between vertically coupled and decoupled regimes offers a physically based framework for interpreting the processes leading to the development of EWEs and may support future improvements in event classification, forecasting, and impact assessment.

5 Conclusions

This study investigated the three-dimensional structure of EWEs over Rome using ERA5 pressure-level data over the 1991-2025 period. By combining vertical anomaly diagnostics, multivariate analysis, synoptic composite maps, precursor thermal anomaly evolution, and air-mass backward trajectories, this study identified distinct thermodynamic and dynamical regimes governing Mediterranean EWEs. In this context, the precursor analysis successfully unveiled the vertically decoupled or aligned thermodynamic pathways that precede each regime, providing a process-oriented understanding of extreme heat development prior to its surface onset.

The long-term analysis reveals a stark, non-linear increase in EWE frequency over recent decades, with a significant acceleration observed after 2015. This trend is systematically driven by a growing occurrence of vertically coupled events, specifically the *Full Column* category corresponding to the *Extreme Deep* and *Standard Deep* EWRs, characterized by significant warming extending to a large portion of the tropospheric column. Conversely, the average duration and mean thermal intensity of individual events have remained relatively stable over the 35-year period. This implies that the recent

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growth in regional thermal stress is primarily driven by a higher recurrence frequency of deep-column anomalies rather than by the systematic prolongation or amplification of single episodes.

Overall, these findings suggest a progressive transition toward more vertically coupled and synoptically controlled EWRs in the central Mediterranean. This evolution has important implications for climate-risk assessment, as vertically coupled events sustain tropospheric thermal loads more efficiently and can suppress mesoscale pressure gradients, thereby reducing the cooling effectiveness of local mitigating mechanisms such as sea-breeze circulations.

Future work should evaluate the robustness of this three-dimensional framework across different Mediterranean sectors to assess its regional scalability. Furthermore, utilizing higher-resolution urban climate models and convection-permitting simulations will be essential to clarify the precise, fine-scale contributions of urban canopy processes and complex coastal circulations to the vertical structure of extreme heat.

Code and data availability

The detection and analysis scripts rely on standard Python libraries, including xarray, numpy, scipy, pandas, sklearn, matplotlib, and cartopy, and are designed to process ERA5 reanalysis data in NetCDF format. Codes are available upon request. All data used in this study are publicly available. Reanalysis products can be found in the Copernicus Data Store repository, accessible at https://cds.climate.copernicus.eu/ (last access: 07 July 2026).

Author contributions

ADB: conception, formal analysis, methodology, resources, data curation, investigation, software, writing (original draft preparation, review & editing), funding acquisition

SC: conception, formal analysis, methodology, writing (review & editing);

AMI: conception, methodology, writing (review & editing);

AMS: conception, formal analysis, methodology, supervision, writing (review & editing)

Competing interests

The authors declare they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A

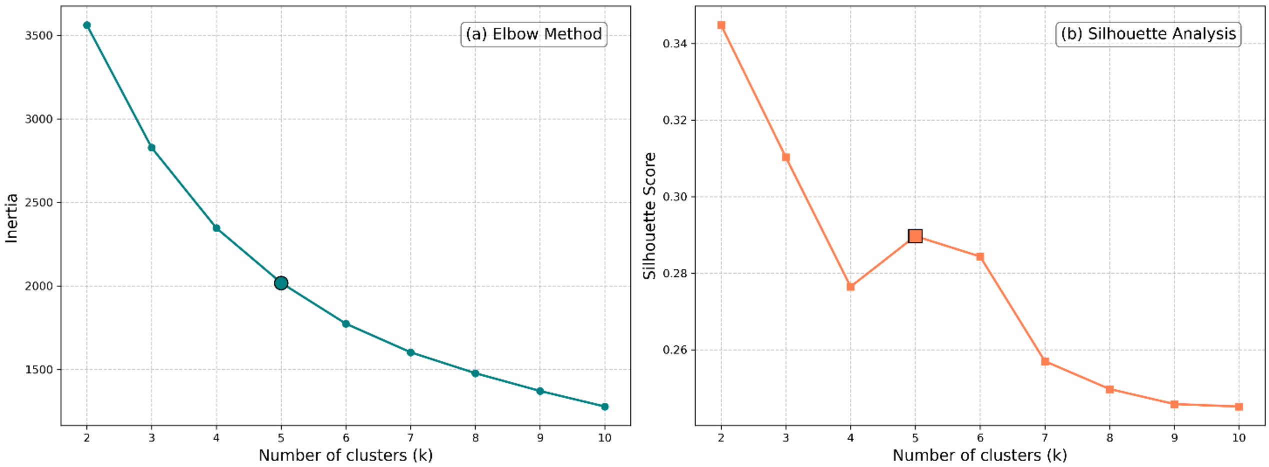

Figure A1: Results of (a) Elbow Method and (b) Silhouette Analysis used for the identification of the correct number of clusters.

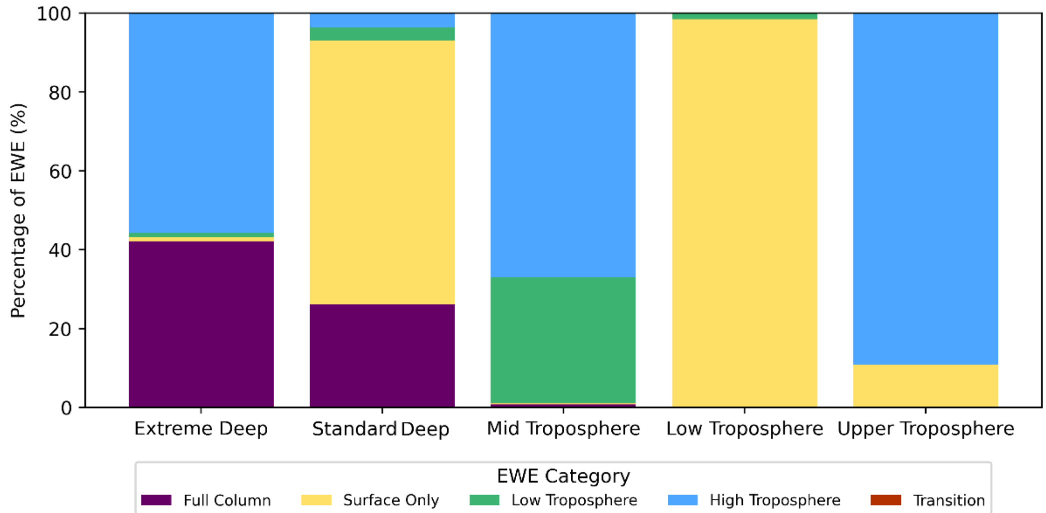

Figure A2: Relative distribution (%) of the five EWE categories within each K-means cluster identified from the vertical temperature anomaly profiles.