

RESEARCH ARTICLE

Dry intrusions and warm-core development in Medicanes: Insights from a multi-case analysis and the peculiar evolution of *Ianos*

Daniele Nigro¹  | Lorenzo Giovannini²  | Simona Bordoni^{1,2}  | Stavros Dafis³  | Mario Marcello Miglietta⁴ 

¹Center Agriculture Food Environment, University of Trento, Trento, Italy

²Department of Civil, Environmental and Mechanical Engineering, University of Trento, Trento, Italy

³National Observatory of Athens, Institute for Environmental Research and Sustainable Development, Athens, Greece

⁴Institute of Atmospheric Sciences and Climate, National Research Council of Italy, CNR-ISAC, Padua, Italy

Correspondence

Daniele Nigro, Centro Agricoltura Alienti Ambiente (C3A), Università di Trento, 38010 San Michele all'Adige (TN), Italy.
Email: daniele.nigro@unitn.it

Abstract

We analyse 17 Mediterranean cyclones with tropical-like characteristics using European Centre for Medium-Range Weather Forecasts (ECMWF) Reanalysis Version 5 (ERA5) reanalysis data to investigate the role of upper-tropospheric processes and their seasonal variations in cyclone development. Our results show that cyclones occurring in September exhibit the most intense convection, with *Ianos*, one of the strongest medicanes on record, representing an extreme case. Using correlation coefficients between $-V_T^U$ and upper-level relative humidity (r_1) and potential vorticity (r_2), we find that warm-core strengthening is systematically linked to upper-tropospheric moistening. While r_2 is generally negative, consistent with diabatic erosion/decoupling of the upper-level PV anomaly during warm-core growth, both its magnitude and the level of maximum anti-correlation H vary across cyclones. Using back-trajectory analyses, we investigate the presence of dry intrusions in the early and mature cyclone phases. We show that one or more dry intrusions are common in medicanes, with an intensity that is case-dependent. Consistently, 700-hPa equivalent potential temperature (θ_e) fields show that descending trajectories correspond to low- θ_e filaments wrapping around the cyclone, and that a warm-seclusion-like θ_e structure is visible during warm-core onset. While dry intrusions can accelerate warm-core formation by favouring convection, the eventual warm-core intensity depends critically on diabatic processes near the cyclone centre, as exemplified by *Ianos*. In fact, despite only marginally descending flows before the main tropical-like phase, this cyclone develops the strongest warm core among the cyclones analysed. This motivates us to examine *Ianos* in detail using ERA5 and a Weather Research and Forecasting (WRF) simulation with a grid spacing of 3 km, which confirms the need for high resolution to represent the cyclone intensity correctly, highlights the dominant contribution of diabatic heating to cyclone deepening, and suggests a secondary role of the weak descending branch of the PV streamer.

KEYWORDS

diabatic heating, dry intrusions, *Ianos*, medicanes, pressure tendency equation, PV streamer, tropical-like cyclones, WRF

1 | INTRODUCTION

The Mediterranean region is one of the most favourable cyclogenetic areas on Earth due to its complex orography and the presence of numerous mountain ranges (Buzzi *et al.*, 2020; Rousseau-Rizzi *et al.*, 2024; Ulbrich *et al.*, 2009). Cyclones in the region often cause significant damage through strong winds, heavy precipitation, and flooding (Giovannini *et al.*, 2021; Hewson *et al.*, 2024; Lagouvardos *et al.*, 2022). Most of these systems are baroclinic in nature, typically characterised by frontal structures, dry intrusions, thermal asymmetries, and a deep cold core (Browning, 1993; Raveh-Rubin, 2017).

Occasionally, a subset of cyclones, commonly referred to as Mediterranean tropical-like cyclones or *medicanes* (Miglietta *et al.*, 2025), exhibit features typical of tropical cyclones, such as thermal symmetry, an eyewall, and a deep warm core (Emanuel, 2005; Miglietta *et al.*, 2013). Medicanes are relatively rare, with an average occurrence of 1–2 cases per year (Cavicchia *et al.*, 2014; Tous & Romero, 2013), but they can reach intensities comparable with Category 1 hurricanes on the Saffir–Simpson scale (Lagouvardos *et al.*, 2022).

Global climate models (GCMs) suggest that, while the overall frequency of medicanes may decrease in the future, their intensity is likely to increase due to climate change (González-Alemán *et al.*, 2019; Romero & Emanuel, 2013). However, these projections remain uncertain due to the limited ability of coarse-resolution GCMs to simulate the small-scale structure and convection within medicanes accurately (Pantillon *et al.*, 2024).

Sea-surface temperature (SST) is a critical factor for medicane intensity, as higher SST enhances surface fluxes and latent heat release. For example, Miglietta *et al.* (2011) showed that reducing SST by a few degrees leads to a progressive loss of tropical cyclone features due to weaker surface fluxes. More recently, Varlas *et al.* (2023) demonstrated that modifying the SST by $\pm 2^\circ\text{C}$ can alter enthalpy fluxes by -39% and $+50\%$, respectively, with significant impacts on wind speed and precipitation. These findings highlight the sensitivity of medicanes to SST changes, with potential implications for their future behaviour under global warming.

The mechanisms responsible for the development and intensification of medicanes have been extensively investigated (Emanuel, 2005; Homar *et al.*, 2003; Miglietta & Rotunno, 2019). Most Mediterranean cyclones develop via baroclinic instability, often triggered by the descent of upper-level potential vorticity (PV) into the lower troposphere, forming a dry intrusion (Fita *et al.*, 2006; Raveh-Rubin & Flaounas, 2017). Givon *et al.* (2024) analysed thousands of Mediterranean cyclones, revealing nine classes associated with different Rossby-wave breaking

patterns and different upper-level PV structures. Indeed, several studies have identified the presence of PV streamers in the early stages of medicanes (Cioni *et al.*, 2016; Miglietta *et al.*, 2017; Miglietta *et al.*, 2021). Flaounas *et al.* (2021) confirmed that many, if not all, medicanes are associated with PV streamers in their early evolution, reinforcing the importance of upper-level dynamics.

However, the precise role of upper-tropospheric dry air remains ambiguous. While PV streamers can favour cyclone development by enhancing surface fluxes and creating potential instability through dry air overriding moist and warm air at lower levels, the accompanying dry air may conversely inhibit intensification. Miglietta *et al.* (2021) found that dry-air advection decreases equivalent potential temperature (θ_e) near the cyclone core, ultimately weakening the storm. Despite these findings, a comprehensive quantitative analysis of dry intrusions in medicanes is still lacking. Raveh-Rubin (2017) proposed a Lagrangian definition of dry intrusions, based on a descent of at least 400 hPa in 48 hours along a parcel trajectory. To the best of our knowledge, this criterion has not yet been applied systematically to medicanes.

The origin of low-tropospheric PV anomalies in Mediterranean cyclones was investigated in Scherrmann *et al.* (2022), who find that in most cases the PV anomaly forms within the cyclone a few hours before the mature stage, while in some cases PV production occurs due to orographic effects. The warm-core development of medicanes during their tropical-like phase and the eventual formation of a PV tower are often attributed to latent heat release and air–sea interaction, with the Wind-Induced Surface Heat Exchange (WISHE) mechanism potentially playing a crucial role in maintaining the vortex, as in tropical cyclones (Miglietta & Rotunno, 2019). Nevertheless, some authors argue that warm-air seclusion into the core or the interplay of air–sea interaction and baroclinic processes can also explain the deep warm core in some cyclones (Fita & Flaounas, 2018; Mazza *et al.*, 2017).

Miglietta and Rotunno (2019) demonstrated this diversity by analysing two medicanes: one where WISHE was critical for intensification and another sustained by persistent interaction with a PV streamer, highlighting a dominant baroclinic component even in the mature phase. Additionally, Fita and Flaounas (2018) applied the pressure tendency equation (PTE: Fink *et al.*, 2012) analysis to medicane *Zeo*, showing that both diabatic heating and warm-air advection contribute to the cyclone's life cycle. These results highlight that medicane intensification mechanisms are case-dependent, influenced by factors such as the time of year, genesis location, and specific meteorological conditions. To classify this diversity of medicane behaviours, Miglietta and Rotunno (2019) proposed three categories: category A for cyclones where

WISHE dominates in the mature phase; category B for cyclones where both WISHE and baroclinic processes are active; and category C for cyclones where intensification occurs well after cyclogenesis through interaction with an upper-level PV streamer.

In this work, we investigate 17 Mediterranean cyclones exhibiting warm-core characteristics across different seasons, with the aim of identifying seasonal patterns and examining the influence of upper-level dynamics. We focus specifically on a quantitative assessment of dry intrusions and their influence on warm-core development using a back-trajectory analysis with the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLOT) model. Among the cases analysed, Medican *Ianos* stands out and is therefore studied in greater detail using a high-resolution simulation with the Weather Research and Forecasting (WRF) model.

This study is structured as follows. Section 2 describes the cyclone dataset, analysis methodologies, back-trajectory approach for the detection of dry intrusions, and WRF model setup for simulating *Ianos*. Section 3 details the correlation of upper-level quantities across all 17 cyclones. Section 4 discusses the results of the dry intrusion analysis performed using HYSPLOT. Section 5 focuses on *Ianos*, including European Centre for Medium-Range Weather Forecasts (ECMWF) Reanalysis Version 5 (ERA5) reanalysis, WRF simulation results, and PTE diagnostics. Finally, in Section 6

we offer some discussion and conclusions of this study. An Appendix provides a detailed explanation of the PTE analysis.

2 | MATERIALS AND METHODS

2.1 | Definition and tracking of Mediterranean cyclones

The 17 Mediterranean tropical-like cyclones analysed in this study are listed in Table 1. Cyclones are classified according to their time of occurrence into three seasonal groups: September cyclones (*Callisto*, *Maria*, *Zorbas*, *Ianos*, *Daniel*), autumn cyclones (October–November: *Cornelia*, *Rolf*, *Qendresa*, *Numa*, *Apollo*, *Blas*), and winter cyclones (December–March: *Leucosia*, *Celeno*, *Zeo*, *Ilona*, *Helios*, *Juliette*).

The purpose of the analysis is to identify similarities and differences in terms of PV streamers and convection development for each group. To this aim, we use hourly ERA5 reanalysis data (Hersbach *et al.*, 2020), with grid spacing of $0.25^\circ \times 0.25^\circ$ at 37 pressure levels. Cyclone tracks are computed by identifying the displacement of the mean sea-level pressure (MSLP) minimum. To define the initial centre, the cyclonic region is first identified visually based on sea-level isobars. The centre is then assigned to the grid point within this region that exhibits the lowest

TABLE 1 List of Mediterranean cyclones considered in this study, including their ID, name, start and end times (UTC), and minimum pressure.

ID	Name	Start	End	Min MSLP [hPa]
1	<i>Leucosia</i>	1982/01/23 0100 UTC	1982/01/28 1400 UTC	994.5
2	<i>Callisto</i>	1983/09/26 2000 UTC	1983/10/02 1300 UTC	1002.3
3	<i>Celeno</i>	1995/01/13 0200 UTC	1995/01/18 1000 UTC	989.3
4	<i>Cornelia</i>	1996/10/06 0900 UTC	1996/10/11 0600 UTC	1000.0
5	<i>Zeo</i>	2005/12/13 0200 UTC	2005/12/16 1000 UTC	989.5
6	<i>Maria</i>	2006/09/25 0000 UTC	2006/09/27 2100 UTC	996.8
7	<i>Rolf</i>	2011/11/05 1000 UTC	2011/11/09 1300 UTC	996.1
8	<i>Ilona</i>	2014/01/18 2200 UTC	2014/01/22 0800 UTC	989.5
9	<i>Qendresa</i>	2014/11/06 0900 UTC	2014/11/10 1200 UTC	992.0
10	<i>Numa</i>	2017/11/14 2300 UTC	2017/11/19 1500 UTC	1004.0
11	<i>Zorbas</i>	2018/09/27 0300 UTC	2018/09/30 1500 UTC	994.9
12	<i>Ianos</i>	2020/09/13 1300 UTC	2020/09/21 0400 UTC	1000.3
13	<i>Apollo</i>	2021/10/24 1700 UTC	2021/10/31 2100 UTC	1003.1
14	<i>Blas</i>	2021/11/07 1600 UTC	2021/11/14 1800 UTC	1004.9
15	<i>Helios</i>	2023/02/08 0800 UTC	2023/02/11 0400 UTC	1007.4
16	<i>Juliette</i>	2023/02/26 1900 UTC	2023/03/03 0800 UTC	997.7
17	<i>Daniel</i>	2023/09/04 2000 UTC	2023/09/12 1100 UTC	995.4

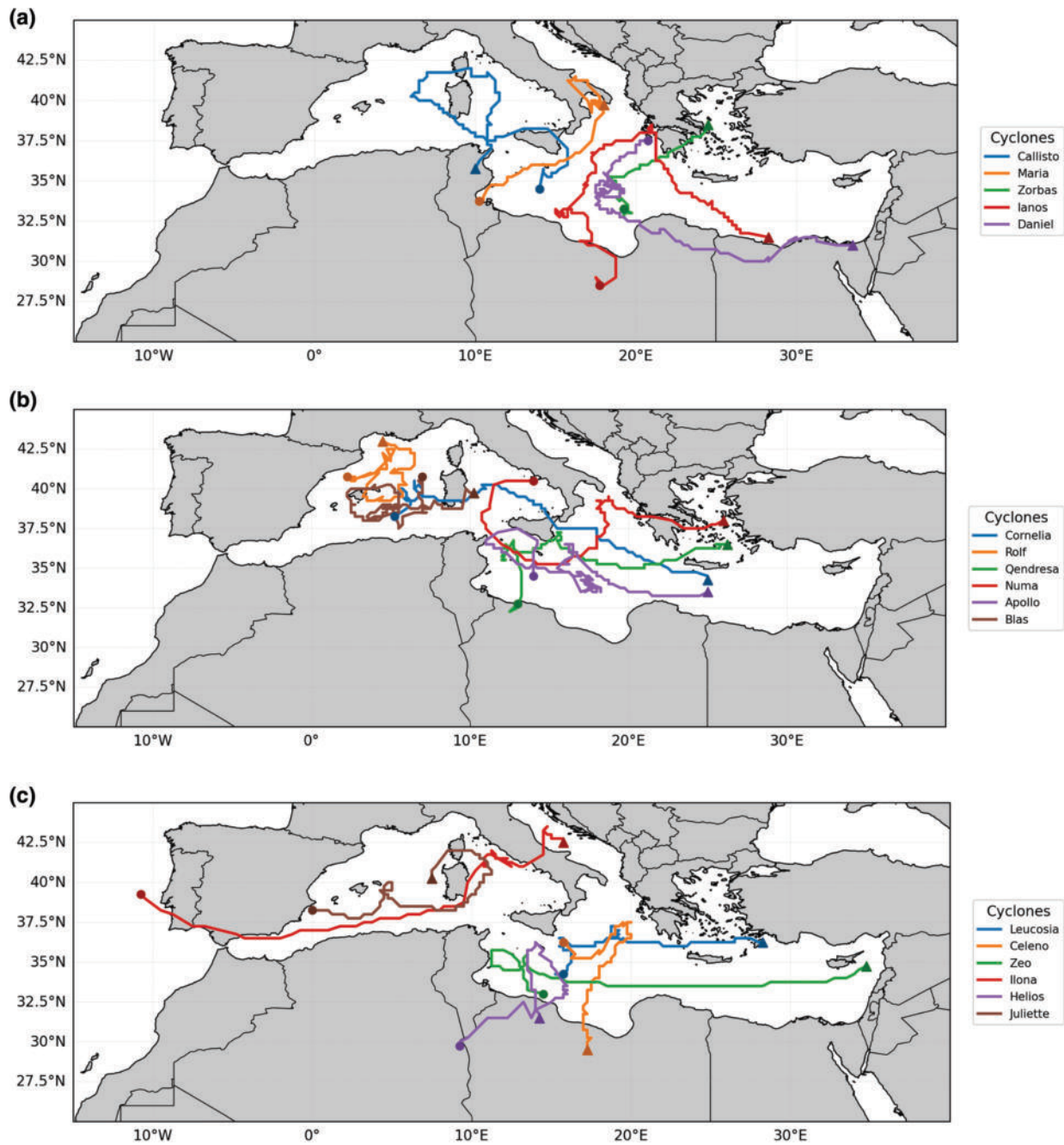


FIGURE 1 Trajectories of the medicanes listed in Table 1 obtained from ERA5 reanalysis: (a) September cyclones, (b) autumn cyclones, and (c) winter cyclones. Dots and triangles represent the trajectory start and end points, respectively.

MSLP. Subsequent positions are assigned as the grid point with the lowest MSLP within a 1.0° radius of the previously detected location. The resulting tracks are shown in Figure 1.

To detect the warm core, Hart parameters (Hart, 2003) $-V_T^L$ and $-V_T^U$ are evaluated. We apply the modified definition proposed in Picornell *et al.* (2014) for medicanes:

$$-V_T^L = \left(\frac{\partial(\Delta z)}{\partial \ln p} \right)_{925 \text{ hPa}}^{700 \text{ hPa}}, \quad -V_T^U = \left(\frac{\partial(\Delta z)}{\partial \ln p} \right)_{700 \text{ hPa}}^{400 \text{ hPa}}. \quad (1)$$

These parameters are computed within a radius of 2.0° around each cyclone centre. Positive values of $-V_T^U$ ($-V_T^L$) indicate the presence of a deep (shallow) warm core, that is, a warm anomaly extending into the upper (lower) troposphere. The thermal symmetry parameter B is not considered, as the focus here is solely on the presence or absence of a warm core.

To assess the relationship between upper-tropospheric conditions and warm-core development, we compute for each cyclone the Pearson correlation coefficients between

$-V_T^U$ and relative humidity (RH), hereafter r_1 , and between $-V_T^U$ and PV, hereafter r_2 . Hourly values of each field are obtained by averaging over a 2.0° radius around the cyclone centre at 250, 300, 350, and 400 hPa along the cyclone track. These values are stored as time series, and the correlation coefficients are calculated by comparing the corresponding time series of the different variables.

2.2 | Back-trajectory analysis

Given the well-known role of baroclinic processes in the development and initial evolution of medicanes (Flaounas *et al.*, 2021), we compute kinematic back-trajectories from ERA5 using HYSPLIT (Stein *et al.*, 2015) to investigate the occurrence and characteristics of dry intrusions during the life cycles of the cyclones analysed. To handle the large number of trajectories analysed, we developed a Python-based workflow that automates the generation and visualisation of back-trajectories for all cyclones. This workflow leverages the Pysplit package (Warner, 2018), which facilitates HYSPLIT execution within Python.

The script performs trajectory calculations at individual grid points and iterates over all selected spatial and temporal domains. Each trajectory is computed 48 hours backward in time, with a temporal resolution of 1 hour. Horizontal starting points are spaced at 1.0° intervals within a subdomain encompassing most of the Mediterranean basin where the cyclones developed (latitudes 21°N – 46°N , longitudes 10°W – 25°E). For cyclones *Rolf* and *Ilonia*, which formed in the western Mediterranean, the domain is adjusted to 20°W – 15°E . Trajectories are initialised between 1000 and 5500 m above sea level, with a vertical spacing of 500 m.

To identify dry-intrusion-like descending airstreams, we follow a Lagrangian approach based on the magnitude of descent over the 48-hour window considered (Raveh-Rubin, 2017). Because the strength and depth of descent near Mediterranean cyclones can be weaker than in midlatitude oceanic storms, we test multiple descent thresholds (400, 350, and 300 hPa in 48 hours) and evaluate how sensitive the diagnosed occurrence of intrusions is to this choice. Subsequently, trajectories that meet these criteria and lie within 5° of the cyclone centre are counted.

2.3 | Numerical simulation

A numerical simulation was carried out exclusively for Medicanes *Ianos* using the Advanced Research WRF

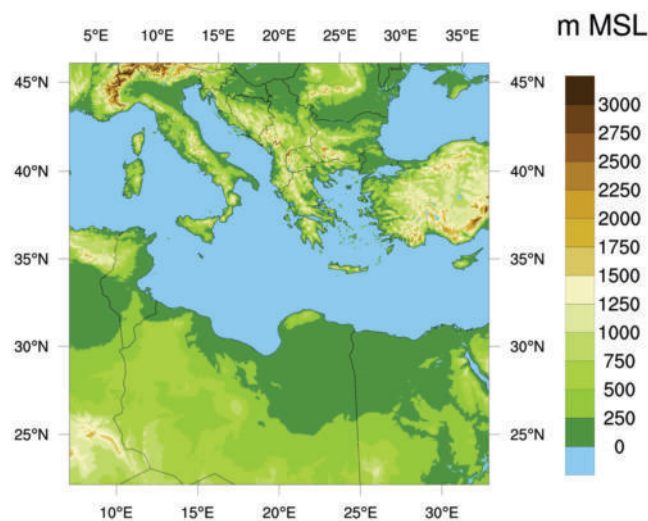


FIGURE 2 Orography of the domain of the WRF simulation.

(WRF-ARW) model, version 4.5 (Skamarock *et al.*, 2019). Initial and boundary conditions, with hourly updates, are provided by ECMWF operational analysis and forecast data from the Integrated Forecasting System (IFS) model. The simulation employs a single domain with a horizontal grid spacing of 3 km, allowing for explicit resolution of deep convection. For the vertical grid, we use 60 levels, with higher resolution in the lower layers and the model top at 10 hPa. The domain orography is shown in Figure 2.

The simulation is initialised on September 15, 2020, at 000 UTC. The following physical parameterisations are employed: WRF Single-moment 7-class (WSM7) for microphysics (Bae *et al.*, 2019), Rapid Radiative Transfer Model for General Circulation Models (RRTMG) for longwave and shortwave radiation (Iacono *et al.*, 2008), Asymmetric Convective Model 2 (ACM2) for the planetary boundary layer (Pleim, 2007), Noah as land-surface model (Tewari, 2004), and the revised MM5 Monin–Obukhov model for the surface layer (Jiménez *et al.*, 2012). The topography and land-cover (Moderate Resolution Imaging Spectroradiometer (MODIS)-based) datasets used have a spatial resolution of 30 arcsec. Since SST is important for the cyclone evolution (Mahmood *et al.*, 2021), as cyclones can extract substantial energy from water, SST fields are updated every 24 hours using the NASA Dataset Discovery (Chin *et al.*, 2017).

To investigate further the mechanisms responsible for cyclone intensification, we apply a diagnostic analysis to the WRF results based on the PTE. This allows for a quantitative evaluation of the contribution of different processes to the deepening of extratropical cyclones (see Appendix for details).

3 | SEASONAL VARIABILITY OF UPPER-LEVEL DYNAMICS IN MEDICANES: A CORRELATION ANALYSIS

The cyclones analysed in this study developed in different months of the year and in distinct locations across the Mediterranean, thus experiencing different environmental conditions. An important feature characterising the upper-level dynamics is the height of the dynamical tropopause, commonly defined as the 1.5 or 2.0 potential vorticity units (PVU) isosurface (Holton *et al.*, 1995). This surface is typically higher in the Tropics than in midlatitudes and in summer than in winter, and it is also sensitive to meteorological conditions, such as stratospheric air intrusions associated with cut-off lows and PV streamers, which can lower the tropopause height locally.

To quantify the link between the warm-core development and the upper-tropospheric PV structure, we use the

Pearson correlation coefficients introduced in Section 2.1: r_1 (between $-V_T^U$ and RH) and r_2 (between $-V_T^U$ and PV) computed along each track at 400, 350, 300, and 250 hPa. First, r_1 indicates whether warm-core strengthening is accompanied by moistening ($r_1 > 0$) or drying ($r_1 < 0$) at a given isobaric level, while r_2 measures whether PV tends to decrease ($r_2 < 0$) or increase ($r_2 > 0$) as the warm core strengthens.

Figure 3a shows that the sign and magnitude of r_1 depend strongly on both season and isobaric level. At 250 hPa, r_1 is negative for all winter cyclones, as well as for *Qendresa* and *Maria*, but positive for the remaining cases. Notably, high r_1 values exceeding 0.5 are observed in *Rolf*, *Numa*, *Zorbas*, *Ianos*, and *Apollo*, which are among the strongest medicanes, with *Ianos* featuring the highest value (0.80). This behaviour is consistent with a seasonal shift in the vertical reach of moist convection: in September/early autumn, the convective outflow and moist plume extend more frequently to 250 hPa, while in

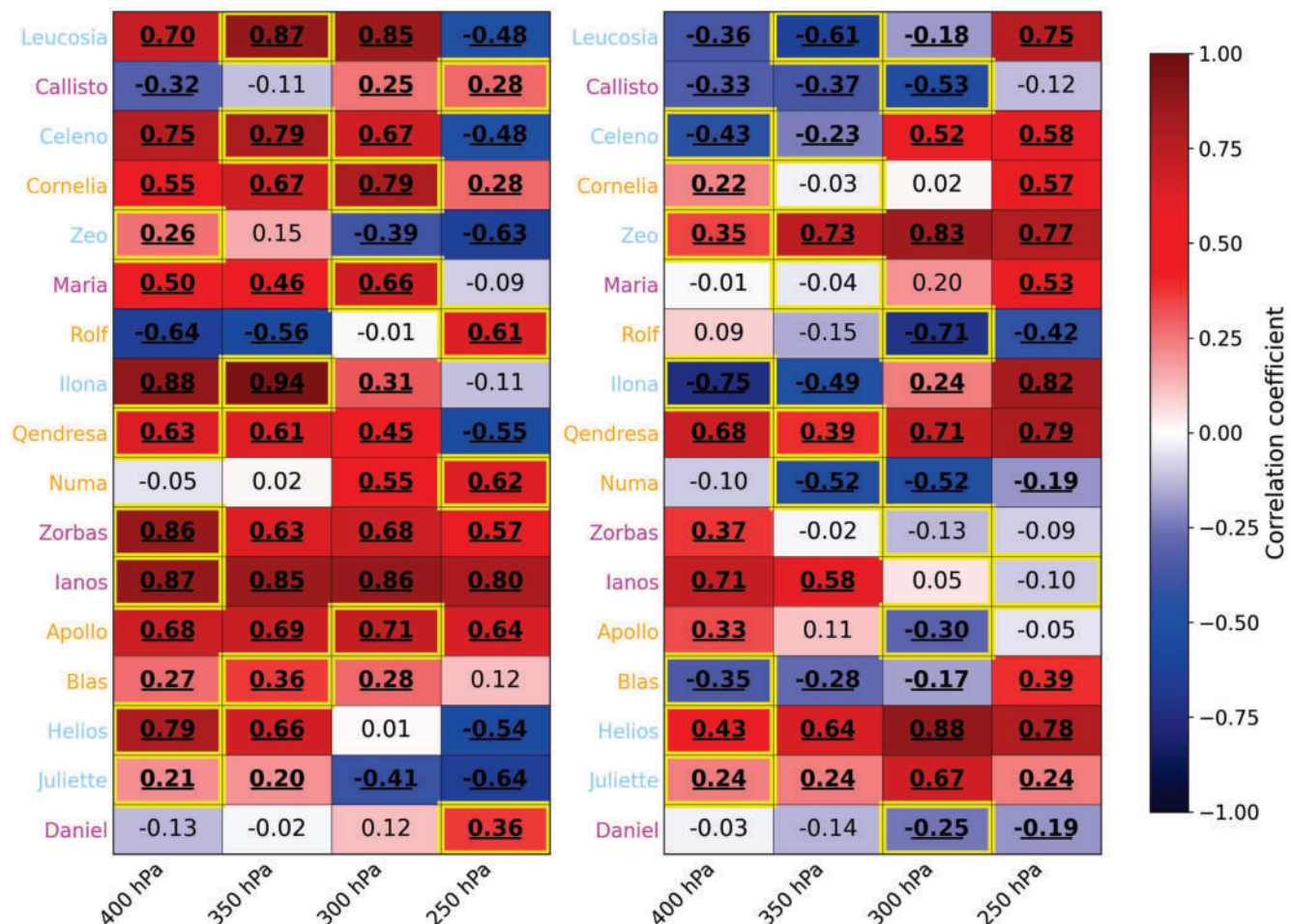


FIGURE 3 Pearson correlation coefficients (a) r_1 and (b) r_2 at 250, 300, 350, 400 hPa for cyclones in Table 1 using ERA5 reanalysis. Cyclones highlighted in magenta, orange, and blue represent September, autumn, and winter cyclones, respectively. Bolded and underlined values indicate statistical significance ($p < 0.05$); non-significant values have $p > 0.05$. Cells highlighted in yellow represent the extreme values among all isobaric levels, that is, the highest value for r_1 and the lowest value for r_2 .

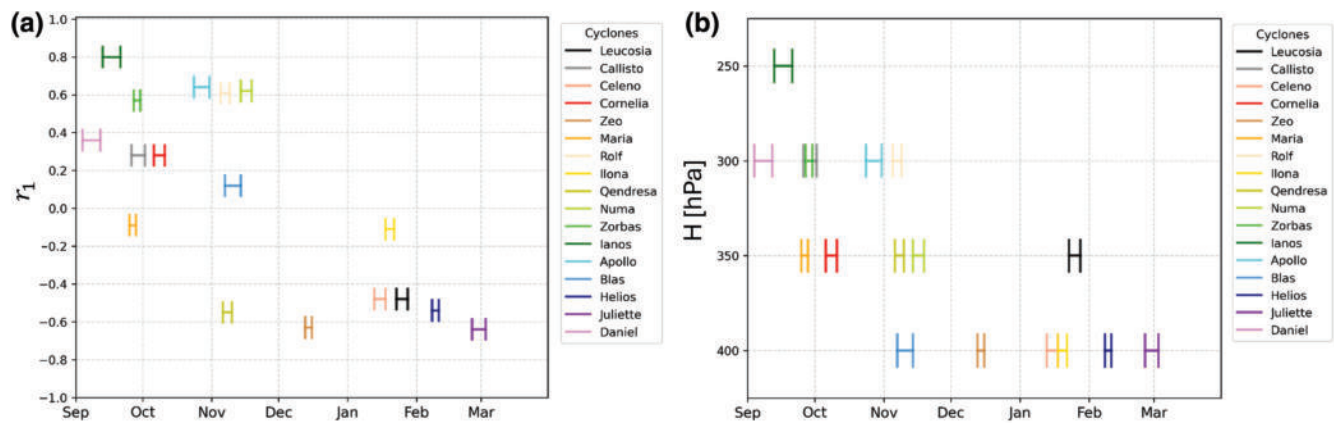


FIGURE 4 Time diagram of (a) r_1 at 250 hPa and (b) H for cyclones in Table 1 obtained using ERA5 reanalysis. Horizontal bars indicate the tracking periods and vertical bars indicate their starting and ending times.

winter the 250-hPa isobaric surface lies above convection more often and is therefore influenced by drier air and subsidence/stratospheric properties rather than convective moistening. The time distribution in Figure 4a confirms this seasonal signal: the largest r_1 values at 250 hPa cluster in the early autumn events, with *Ianos* showing the strongest coupling between deep warm-core development and upper-level moistening. In contrast, at 300–350 hPa r_1 becomes positive for most cases, including several winter cyclones. Taken together, r_1 suggests that the depth of moist convection increases from winter toward early autumn and is generally stronger for the most intense medicanes.

The interpretation of r_2 is less direct, because PV at 250–400 hPa can be shaped by competing processes. On the one hand, latent heating can produce a PV tower from low to upper-tropospheric levels, favouring PV increases ($r_2 > 0$) below the area of most intense heating. On the other hand, diabatic heating can erode an upper-level PV anomaly from below, favouring PV decrease ($r_2 < 0$) at upper levels. Apart from the convective influence, PV may increase again due to the proximity of stratospheric air and radiatively stabilised layers. Consistent with this picture, cyclones exhibit a distinct level where r_2 reaches a minimum (most negative value). We define H as the isobaric level at which r_2 is lowest, interpreting H as the level where diabatic effects are most efficient at weakening the upper-level PV anomaly during warm-core development. Figure 4b shows a clear seasonal signal: H tends to be higher (lower pressure) in September–October cases, while winter cyclones typically have H near 400 hPa. This indicates that the level of maximum PV erosion shifts downward in winter, consistent with shallower convection and a lower tropopause. *Ianos* stands out with the highest H (250 hPa), indicative of exceptionally deep convection

interacting with the upper-level PV structure at unusually high altitude.

To make the physical meaning of these coefficients more tangible, we analyse the time evolution of the Hart parameters together with PV and RH evaluated at H . Figure 5 shows four representative examples (*Celeno*, *Maria*, *Helios*, and *Ianos*), while the complete set of time series for all cyclones is provided in the Supplementary Material (Figure S1). Across most cyclones, the warm-core phase is accompanied by a clear rise in RH at H , consistent with positive r_1 and supporting the interpretation that deep convection moistens the upper troposphere during tropical-like evolution. In contrast, PV exhibits larger case-to-case variability, explaining the spread in r_2 . In the dominant behaviour (e.g., *Leucosia*, *Callisto*, *Celeno*, *Rolf*, *Ilona*, *Numa*, *Zorbas*, *Apollo*), PV at H peaks during the pre-transition stage and then decreases while RH increases as $-V_T^U$ strengthens. This explains the anticorrelation between r_1 and r_2 at the level H shown in Figure 3, consistent with diabatic erosion of the upper-level PV anomaly. A smaller subset (e.g., *Maria*, *Cornelia*, *Qendresa*, *Daniel*) shows a weaker or shorter-lived warm-core phase, with PV remaining quite high near warm-core onset, implying r_2 closer to zero or locally positive despite moistening. Finally, the cases with persistently high PV and limited warm-core development (e.g., *Zeo*, *Helios*, *Juliette*) are consistent with the positive r_2 at all levels identified before.

Ianos stands out because $H = 250$ hPa and because it exhibits exceptionally strong upper-level moistening concurrent with warm-core growth (very large r_1 at 250 hPa), while the PV–warm-core linkage at the same level is weak (small r_2). This reinforces the interpretation that *Ianos* experienced unusually deep convection but a less clear phase-locking between warm-core evolution and a single

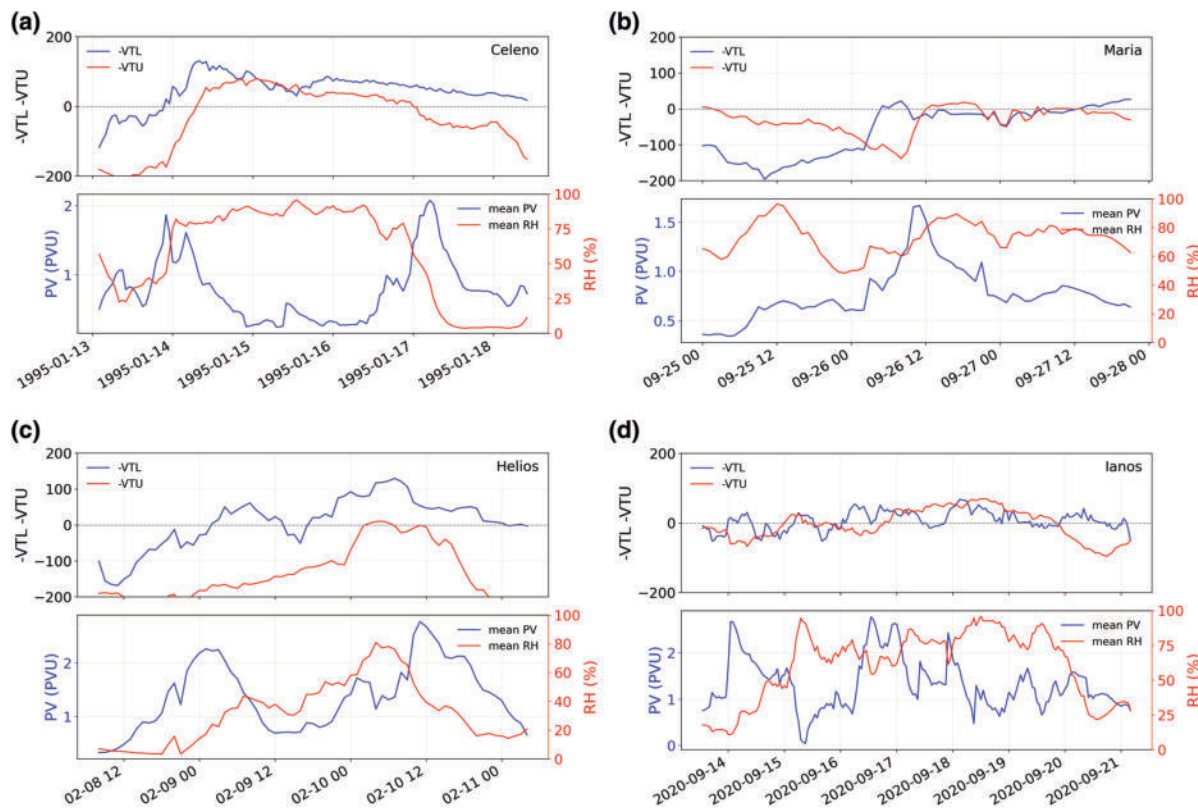


FIGURE 5 $-V_T^L$ and $-V_T^U$ (upper panels) against PV and RH at the level H (lower panels) for cyclones (a) *Celeno*, (b) *Maria*, (c) *Helios*, and (d) *Ianos*.

upper-level PV signal, motivating the dedicated analysis in Section 5.

By combining the sign and vertical structure of r_1 and r_2 with the time series of PV and RH at level H , we identify three recurring behaviours.

Type-1 cyclones (*Leucosia*, *Callisto*, *Celeno*, *Rolf*, *Ilona*, *Numa*, *Zorbas*, and *Apollo*) share a coherent evolution in which an upper-level PV anomaly is followed by a marked increase in RH and a rapid growth of the deep warm core. In these cases, r_1 is positive and r_2 tends to be negative at H , supporting the interpretation that warm-core intensification occurs as convection moistens the upper troposphere while diabatic heating reduces PV near or just below the cloud top. A representative example is *Celeno* (Figure 5a). In type-2 cyclones (*Maria*, *Cornelia*, *Qendresa*, and *Daniel*), PV increases while $-V_T^U$ rises, yielding weaker anticorrelation or even positive r_2 at some levels. A clear example is *Maria* (Figure 5b), where a PV increase briefly anticipates a short-lived warm-core phase, suggesting a more direct role of upper-level forcing during the warm-core stage itself (Moscatello *et al.*, 2008a). Type-3 cyclones (*Zeo*, *Helios*, and *Juliette*) exhibit positive r_2 at all levels, with persistently high PV during much of their lifetimes and warm-core signals that are weak or intermittent. This behaviour suggests that these systems

remain strongly controlled by upper-level PV anomalies. A representative example (*Helios*) is shown in Figure 5c.

Two cases deserve separate mention. *Blas* shows a more complex, multi-phase evolution, while *Ianos* has the strongest upper-level moist-convection signature (largest r_1 at 250 hPa and highest H , i.e., 250 hPa), yet r_2 at 250 hPa is only weakly negative.

Finally, this grouping provides a direct bridge to Section 4: PV streamers are frequently associated with descending, low- θ_e air, so types 1–2 should preferentially exhibit identifiable dry-intrusion signals near cyclogenesis and/or during warm-core formation, while *Ianos* should be comparatively less affected by dry intrusions. This expectation is tested explicitly using back-trajectories in the next section.

4 | DIAGNOSING DRY INTRUSIONS USING BACK-TRAJECTORIES

Section 3 suggests that the large-scale environment modulates medicane evolution through the joint behaviour of upper-tropospheric humidity and PV streamers. In particular, type-1 cyclones tend to exhibit an increase of PV

prior to warm-core onset, followed by a PV decrease during the warm-core phase, consistent with an upper-level PV anomaly preceding warm-core onset and its subsequent diabatic erosion. Conversely, type-2 cyclones show PV increases at the beginning of the mature phase, while type-3 cyclones maintain persistently high PV throughout their evolution. Because PV streamers and cut-offs are typically accompanied by descending, dry, high-PV air, we test this interpretation with a Lagrangian diagnostic based on back-trajectories. In addition, to connect the Lagrangian perspective to an Eulerian thermodynamic signature, we also analyse 700-hPa equivalent potential temperature (θ_e) at the same times used for the trajectory composites (see [Supporting Information Figures S3 and S4](#)).

Back-trajectories are computed with HYSPLIT every 3 hours, as described in Section 2.2. We consider two time windows: a cyclogenesis window (± 6 h around the genesis time in Table 1) and a warm-core onset window (± 6 h around the time when the main deep warm core forms, here defined by $-V_T^U > 0$). Importantly, the second window is designed to capture the timing of the structural transition toward a deep warm core rather than the time of maximum deepening, which may occur earlier or later depending on the specific case.

Following the Lagrangian definition of Raveh-Rubin (2017), a “classical” dry intrusion is identified using a descent threshold of 400 hPa in 48 h. In our sample, this strict threshold captures only the strongest descending airstreams (see [Supporting Information Figure S2](#)); therefore, we also consider lower thresholds of 350 and 300 hPa in 48 h, which capture weaker, but still dynamically relevant, descent better near Mediterranean cyclones.

4.1 | Early-stage dry intrusions

Back-trajectories in the cyclogenesis window, using a descending threshold of 300 hPa in 48 hours (Figure 6), show that most cyclones are associated with a nearby descending airstream consistent with an upper-level PV streamer/cut-off configuration. Several cases show a well-defined, long-range descending airstream directed toward the Mediterranean basin (e.g., *Callisto*, *Celino*, *Cornelia*, *Zeo*, *Rolf*, *Ilona*, *Qendresa*, *Numa*, *Zorbas*, *Blas*, *Helios*, *Juliette*). In these events, the dry intrusion arrives close to the storm environment already near the genesis time, supporting the interpretation from Section 3 that an upper-level PV anomaly is part of the environmental preconditioning. For other cyclones (e.g., *Zeo*, *Numa*, *Blas*, *Juliette*), the descending trajectories are organised around a broader cyclonic circulation rather than a narrow streamer filament, indicating that the PV anomaly is already evolving toward a closed structure. Finally, in some

cases, descent is present but displaced far from the cyclone centre (notably *Leucosia* and, more clearly, *Daniel*), consistent with a separation between the intrusion and the incipient low-level vortex at the selected time.

The θ_e maps (see Supplementary Material Figure S3) provide a coherent thermodynamic counterpart to these patterns. In the early-stage window, most cyclones exhibit a filament or tongue of relatively low θ_e approaching the basin from the upstream side of the large-scale flow and intersecting the developing low-level vortex (Miglietta *et al.*, 2021). This low- θ_e feature is the expected dry-intrusion footprint: it marks the arrival of comparatively dry/low-entropy mid-tropospheric air into the baroclinic environment surrounding the cyclone. Conversely, *Ianos* stands out because the cyclogenesis window does not display a clear, organised dry intrusion approaching the storm (Figure 6). However, a weak low- θ_e filament still interacts with the incipient vortex (Figure S3), suggesting that a more detailed analysis is required for this cyclone.

4.2 | Warm-core onset dry intrusions

During the warm-core onset window (Figure 7), descending airstreams often become dynamically coupled to the cyclone circulation and the geometry of the intrusion provides additional information. A first subset (e.g., *Callisto*, *Celino*, *Qendresa*, *Zorbas*, *Helios*) exhibits a dry intrusion that wraps around the cyclone during the transition (similar to Miglietta *et al.*, 2017), consistent with PV advection around the vortex and subsequent tightening of the circulation. A second subset (e.g., *Leucosia*, *Ilona*) features an intrusion approaching from the south-southwestern flank, more suggestive of a baroclinic frontal environment where dry-air advection and moisture gradients coexist near the cyclone. A third subset (e.g., *Cornelia*, *Zeo*, *Numa*, *Blas*, *Juliette*) is characterised by a broad descending signal persisting from the previous stage. *Maria* and *Daniel* exhibit comparatively weaker or more intermittent descending signals near the core, consistent with their classification in Section 3 as cases where a narrow PV streamer contributes to the warm-core formation during the mature phase. Finally, *Ianos* again stands out: trajectories satisfying the descent criteria remain sparse in the warm-core onset window, indicating that the formation of a deep warm core in *Ianos* is not associated with a classical dry-intrusion pathway detectable with our thresholds.

The θ_e fields (see Supplementary Material Figure S4) clarify two robust features of the mature-stage thermodynamic structure. First, when a dry intrusion is present near the cyclone, it corresponds to a low- θ_e filament that wraps cyclonically around the MSLP minimum. Second,

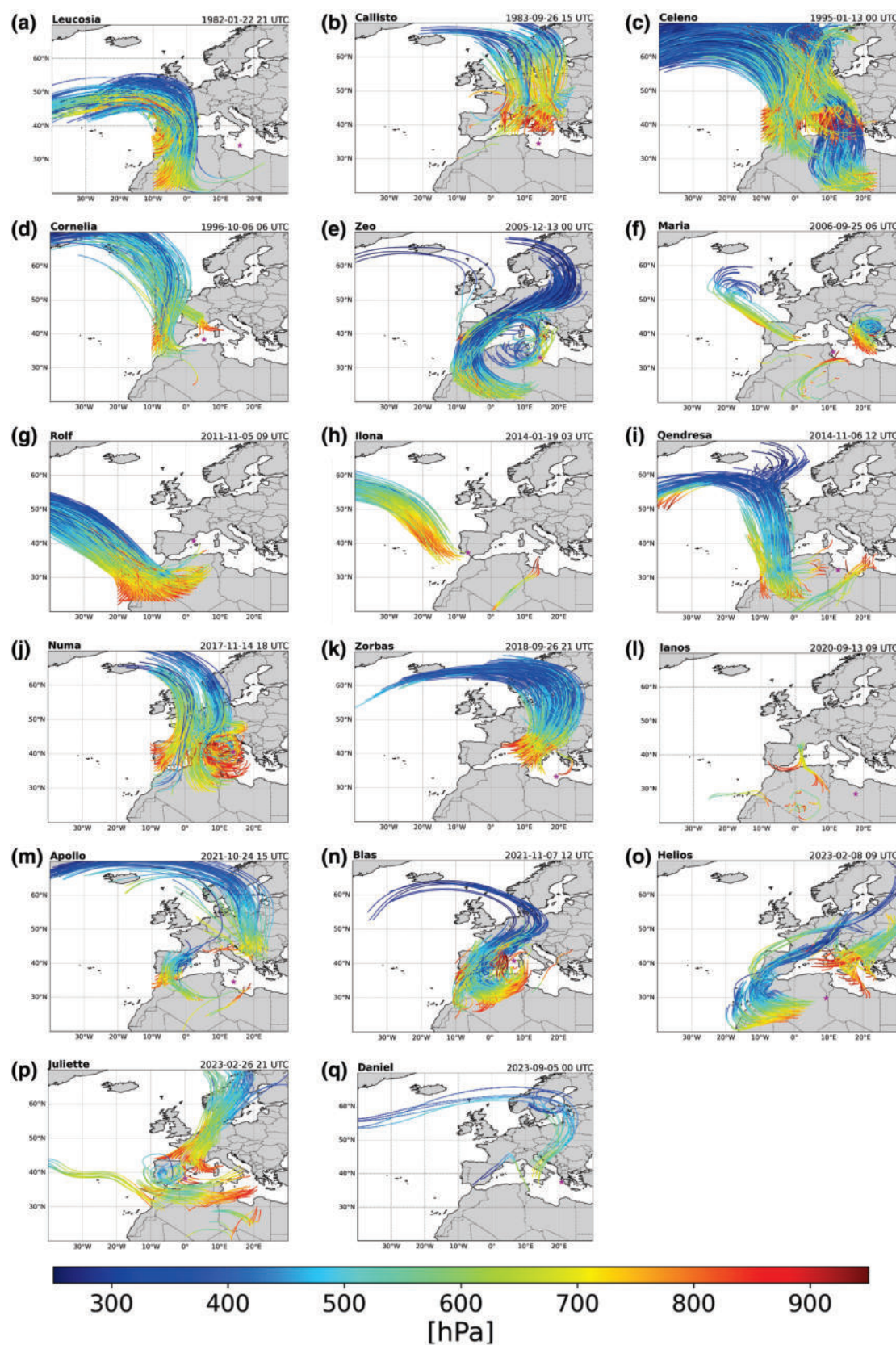


FIGURE 6 48-h back-trajectories in the early stages of cyclone lifetime computed with HYSPLIT with a minimum descent of 300 hPa/48 h: (a) *Leucosia*; (b) *Callisto*; (c) *Celeno*; (d) *Cornelia*; (e) *Zeo*; (f) *Maria*; (g) *Rolf*; (h) *Ilona*; (i) *Qendresa*; (j) *Numa*; (k) *Zorbas*; (l) *Ianos*; (m) *Apollo*; (n) *Blas*; (o) *Helios*; (p) *Juliette*; (q) *Daniel*. Magenta stars represent the position of the cyclone at the starting time defined in Table 1 ± 6 hours.

and importantly for the interpretation of warm-core development, the θ_e maps at 700 hPa show a warm-seclusion signature in all cyclones: during (or shortly after) the warm-core onset, a pocket of relatively higher θ_e becomes increasingly isolated near the cyclone centre as lower θ_e air wraps around it. In cases with strong and well-coupled intrusions, this seclusion appears sharper and forms earlier, consistent with a faster structural transition. In *Ianos*, a warm-seclusion-like θ_e pattern is still evident near the cyclone centre despite the absence of a strong low- θ_e intrusion.

4.3 | Quantifying dry intrusion strength

Figure 8 provides a compact metric of the dry-intrusion signal near the storm core (within 5° of the cyclone centre) and helps connect trajectories to the correlation-based grouping. Two cases stand out for the strongest early dry-intrusion signal: *Celso* and *Zorbas*, which show the largest number of descending trajectories (100+) near the cyclone centre in the early stage. In Section 3, it was shown that type-1 events, like these two cyclones, typically show a sharp warm-core onset and a PV evolution consistent with an initial PV increase followed by erosion during the mature phase; the strong and early descent signal in Figure 8 supports the interpretation that a more intense dry intrusion may favour a faster warm-core transition, even if it is probably not the only controlling factor. More generally, most type-1 cyclones display a detectable early-stage dry-intrusion signal near the core (*Callisto*, *Celso*, *Rolf*, *Ilona*, *Numa*, *Zorbas*), consistent with their opposite r_1/r_2 behaviour at level H . Type-2 cyclones tend to show a comparatively more relevant intrusion signal later in their life cycles, consistent with PV increases occurring near maturity. Type-3 cyclones (*Zeo*, *Helios*, *Juliette*) show more persistent dry-intrusion activity throughout their evolution, coherent with their persistently high PV signal inferred from the correlation analysis.

It is instructive to focus on September events (*Callisto*, *Maria*, *Zorbas*, *Ianos*, and *Daniel*), because these cyclones develop in a warmer and moister background environment and, as shown in Section 3, tend to exhibit higher H and stronger upper-level moistening during warm-core growth.

Zorbas and, to a lesser extent, *Callisto*, display a pronounced intrusion approaching and/or wrapping around the vortex during the pre-transition and warm-core onset windows (Figures 6 and 7), together with the largest descent counts within 5° in Figure 8. Consistently, the Hart parameters show a rapid increase in $-V_T^U$ (up to 200 units in 24 hours), indicating a fast warm-core development. Correspondingly, the θ_e fields reveal a marked low- θ_e

intrusion signal interacting with the cyclone environment and a rapid transition toward a warm-seclusion-like structure near the MSLP minimum. In contrast, *Maria* and *Daniel* exhibit smaller descent counts, in line with their less persistent or less pronounced warm-core evolution and their stronger upper-level PV influence. In particular, a spike in $-V_T^U$ is observed in the mature phases of *Maria* on September 26 (Figure 5b), coinciding with the arrival of a narrow but intense dry intrusion (Figure 7f). Intensification due to a PV streamer was discussed for *Maria* in Moscatello *et al.* (2008a) and Chaboureau *et al.* (2012). For *Daniel*, a jump in $-V_T^U$ is observed on September 10, coinciding with a weak dry intrusion (~ 300 hPa in 48 h, shown in Figure 7q), which is associated with a narrow PV streamer (Emanuel *et al.*, 2024; Hewson *et al.*, 2024). Finally, September cyclones also demonstrate that high intensity can be reached without a strong classical dry intrusion: *Ianos* develops an exceptionally deep warm core and strong upper-level moistening despite weak descent counts in both the genesis and warm-core onset windows and the absence of an organised intrusion pattern in the trajectory maps. Nonetheless, the θ_e fields still show a warm-seclusion-like pattern near the cyclone centre. This contrast suggests that, while dry intrusions may accelerate warm-core formation by enhancing upper-level forcing and organising convection, other processes can dominate in early autumn.

In light of the peculiar characteristics of *Ianos* identified through the correlation and back-trajectory analyses, this cyclone is investigated in greater detail in the following section.

5 | IANOS

Sections 3 and 4 represent how upper-level PV structure, upper-tropospheric moistening, and dry intrusions co-evolve during the transition toward a deep warm core. In that framework, *Ianos* stands out for the following reasons: (i) it exhibits the largest r_1 at 250 hPa and the highest level H (250 hPa), indicating exceptionally deep convection and strong upper-level moistening during warm-core growth; (ii) r_2 at the same level is close to zero, suggesting that the warm-core evolution is not tightly phase-locked to a single upper-level PV signal; and (iii) the back-trajectory analysis detects no pronounced dry intrusion near cyclogenesis or warm-core onset using the thresholds adopted for the multi-case comparison. These combined diagnostics motivate a focused analysis of *Ianos* as a case study in which a very intense and deep warm core develops despite a weak Lagrangian dry-intrusion fingerprint.

Figure 9 shows the time evolution of the minimum RH of *Ianos* obtained from ERA5 within a radius

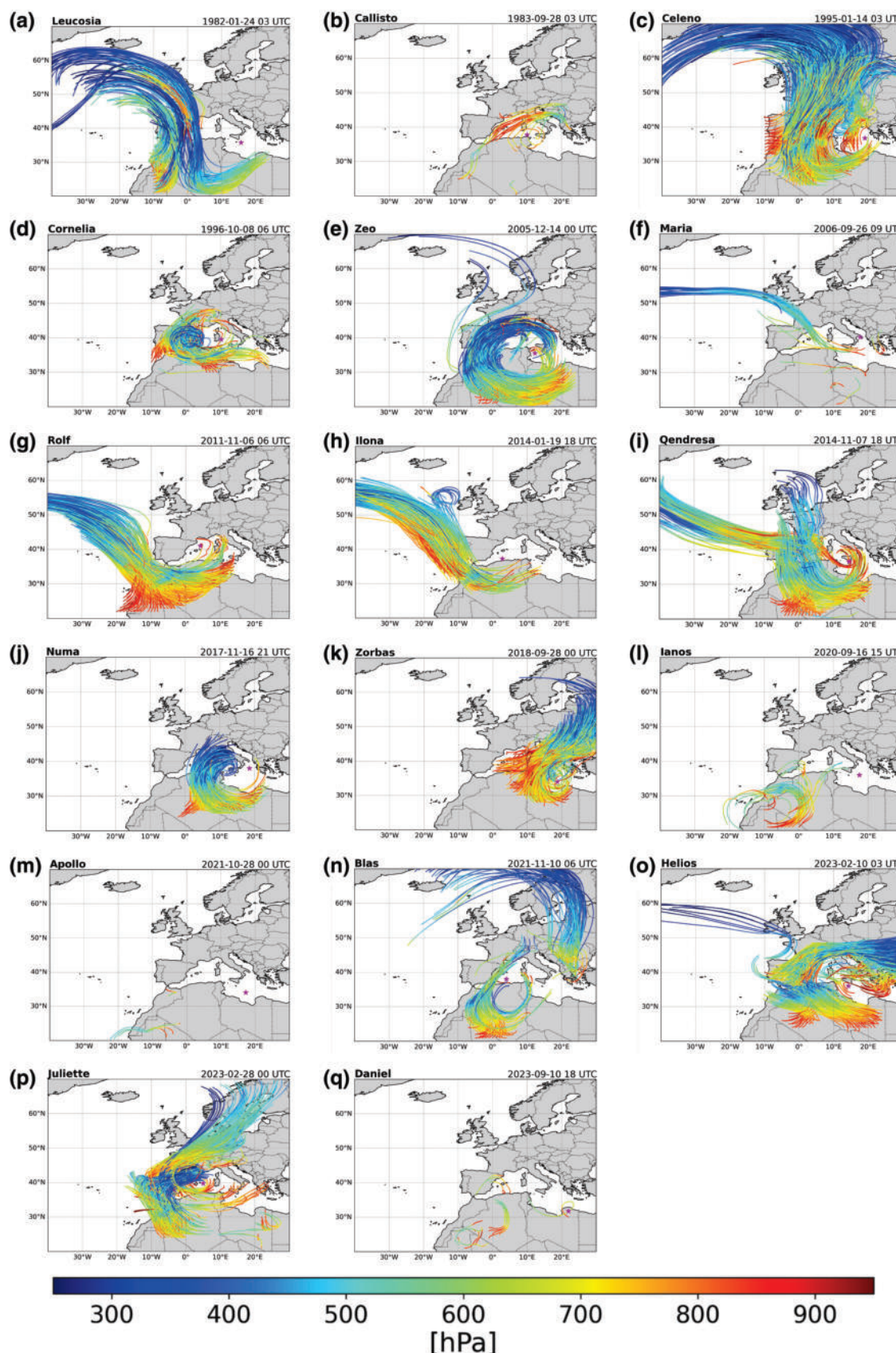


FIGURE 7 As in Figure 6, but for the warm-core formation period ± 6 hours: (a) *Leucosia*; (b) *Callisto*; (c) *Celeno*; (d) *Cornelia*; (e) *Zeo*; (f) *Maria*; (g) *Rolf*; (h) *Ilona*; (i) *Qendresa*; (j) *Numa*; (k) *Zorbas*; (l) *Ianos*; (m) *Apollo*; (n) *Blas*; (o) *Helios*; (p) *Juliette*; (q) *Daniel*.

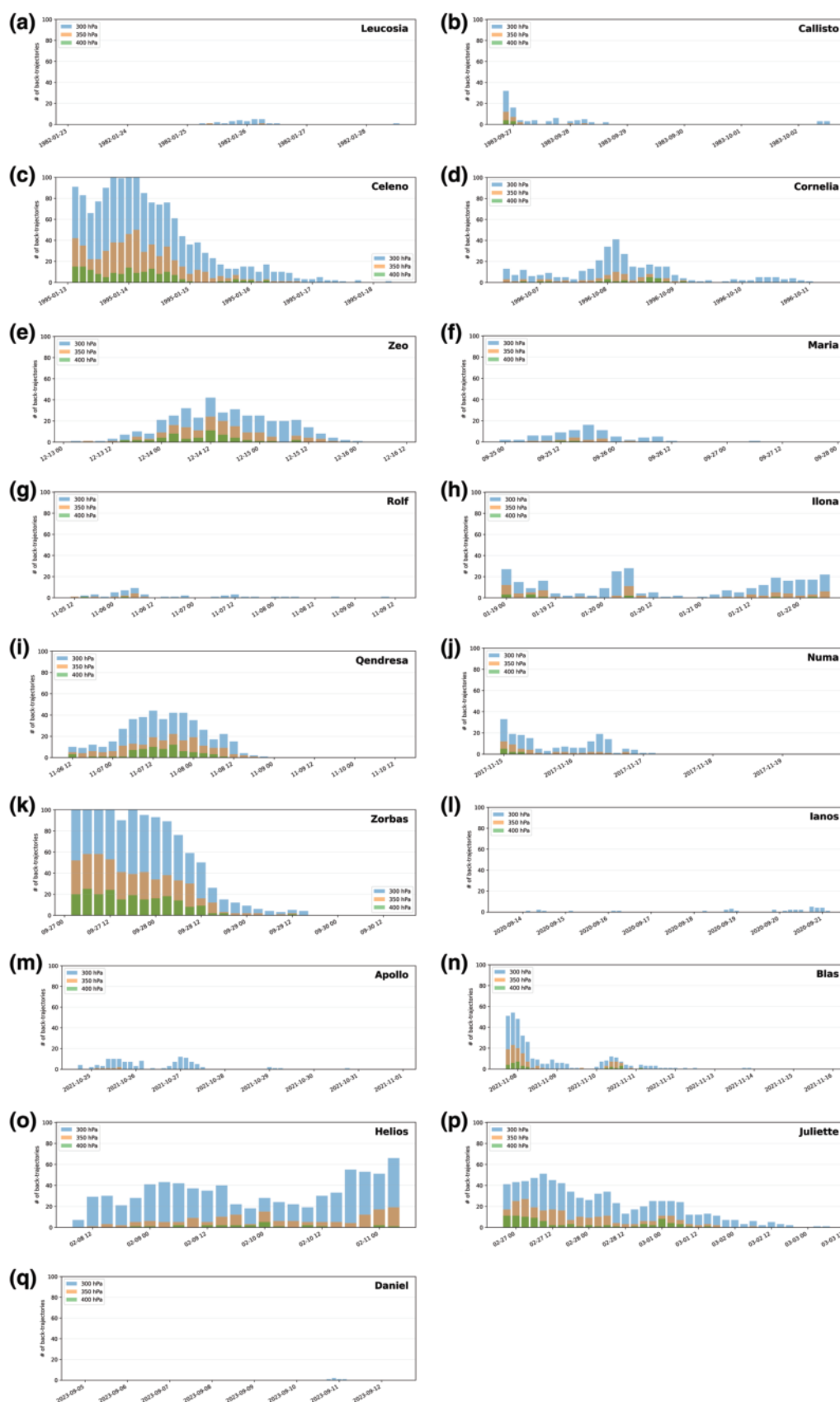


FIGURE 8 Number of back-trajectories within 5° from the cyclone centre using descending thresholds of 400, 350, and 300 hPa: (a) *Leucosia*; (b) *Callisto*; (c) *Celeno*; (d) *Cornelia*; (e) *Zeo*; (f) *Maria*; (g) *Rolf*; (h) *Ilona*; (i) *Qendresa*; (j) *Numa*; (k) *Zorbas*; (l) *Ianos*; (m) *Apollo*; (n) *Blas*; (o) *Helios*; (p) *Juliette*; (q) *Daniel*. Counts are cumulative across thresholds. Back-trajectories were computed every 3 hours.

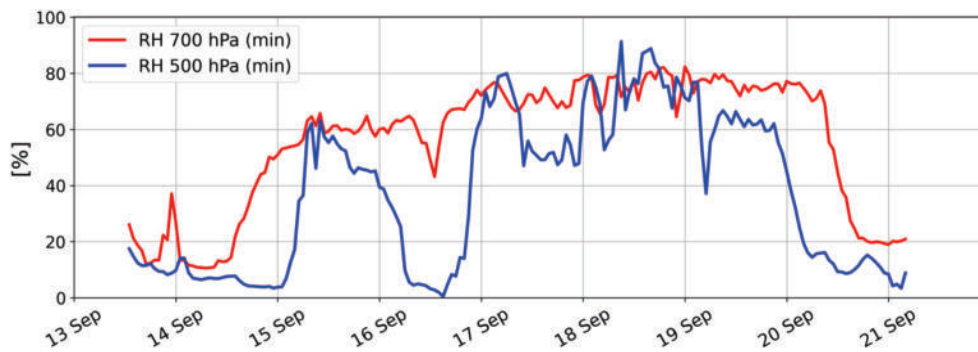


FIGURE 9 Time evolution of minimum RH from ERA5 at 500 and 700 hPa within a radius of 1.0° from the cyclone centre for *Ianos*.

around the cyclone centre. A comparison with Figure 5d reveals two tropical-like phases: an early short episode on September 15 and a longer and more intense phase from the evening of September 16–19. Both phases are preceded by very low mid-tropospheric humidity, with minimum RH values dropping below 20% at 500 hPa (and also reduced at 700 hPa). This raises the question of whether a dry intrusion is effectively present. A physically consistent explanation is that PV streamers and tropopause folds can advect stratospheric dry air into the Mediterranean and over/around the cyclone, while only a subset of parcels undergoes sufficient descent to satisfy a strict dry-intrusion definition. In other words, a trajectory threshold based on large descent preferentially captures the deepest descending branch, but may sample the broader PV streamer only partially (as also illustrated by the limited subset of qualifying trajectories within the streamer geometry in Fita & Flaounas, 2018).

To address this question, we combine a synoptic analysis of PV structure, baroclinicity, and moisture transport with a trajectory analysis using a weaker descent threshold and a convection-permitting WRF simulation that resolves the mesoscale convective dynamics and enables an analysis of the terms in the PTE, thereby providing a more robust assessment of the processes driving cyclone intensification.

5.1 | Synoptic analysis

Here we analyse the synoptic conditions in which *Ianos* formed and evolved using ERA5 reanalysis, supplemented by a detailed back-trajectory analysis with HYSPLIT. The objective is to clarify the role of upper-level dynamics during both the early and mature stages of the cyclone. Several meteorological fields are considered, including geopotential height at 500 hPa, dynamic tropopause, and wind at 300 hPa (Figure 10), as well as the Eady growth rate or baroclinicity (BC)

[day^{-1}], integrated water vapour (IWV) [$\text{kg} \cdot \text{m}^{-2}$], and integrated vapour transport IVT [$\text{kg} \cdot \text{m}^{-1} \cdot \text{s}^{-1}$] (Figure 11) at six different time steps. Regarding the diagnostic variables, the dynamic tropopause height is defined as the highest isobaric level where PV exceeds 1.5 PVU. BC, here computed at 850 hPa, is an index of baroclinicity calculated following (Yanase *et al.*, 2014):

$$\text{BC} = 0.31fV_zN^{-1}, \quad (2)$$

where f is the Coriolis parameter, V_z is the vertical gradient of the horizontal wind (computed between 925 and 700 hPa), and N is the Brunt-Väisälä frequency. BC is an Eady-type measure of baroclinic growth potential, with larger values indicating a more baroclinically favourable environment (stronger low-level shear and/or weaker static stability) and smaller values indicating weak near-core baroclinic control and a reduced frontal imprint at the cyclone centre. Finally, IWV and IVT are defined as in Ralph *et al.* (2017):

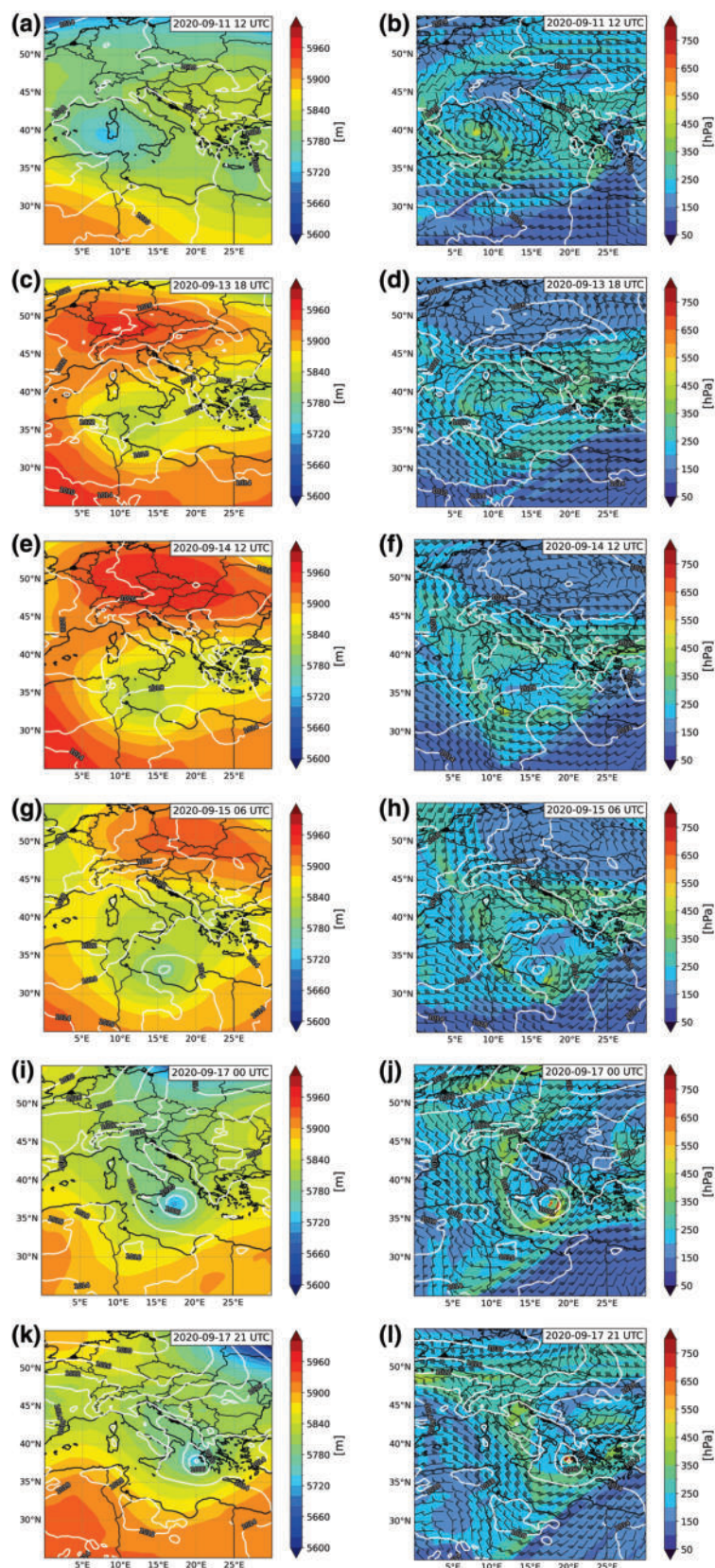
$$\text{IWV} = \frac{1}{g} \int_{p_{\text{sfc}}}^{p_{\text{top}}} q \, dp, \quad (3)$$

$$\text{IVT} = \frac{1}{g} \int_{p_{\text{sfc}}}^{p_{\text{top}}} qV \, dp, \quad (4)$$

where g is the gravitational acceleration, q is the specific humidity, V is the wind velocity, and p_{sfc} and p_{top} are the pressure at the surface and at the highest level considered, respectively.

Prior to cyclogenesis (September 11, 1200 UTC; first row in Figures 10–11), a cut-off low over the western Mediterranean is associated with a lowered dynamic tropopause and a hook-shaped PV streamer (Couto *et al.*, 2024). Convection occurs over the central Mediterranean and the moisture field shows a developing moist reservoir (IWV locally $\sim 40\text{--}45 \text{ kg} \cdot \text{m}^{-2}$). This early convective activity is important, as it preconditions the basin for subsequent deep convection and can modify the

FIGURE 10 ERA5-based maps obtained for (a,b) September 11, 1200 UTC; (c,d) September 13, 1800 UTC; (e,f) September 14, 1200 UTC; (g,h) September 15, 0600 UTC; (i,j) September 17, 0000 UTC; and (k,l) September 17, 2100 UTC. Contours represent mean sea-level pressure; shading represents geopotential height at 500 hPa (left) and dynamic tropopause height with wind barbs (half barbs and full barbs correspond respectively to 5 and 10 knots, the flag corresponds to 50 knots) at 300 hPa (right).



upper-level PV environment through outflow and diabatic effects, in line with the pathway discussed by Sánchez *et al.* (2024).

During cyclogenesis (September 13, 1800 UTC; second row in Figures 10–11), the cut-off shifts toward the Strait of Sicily, while the surface cyclone forms over

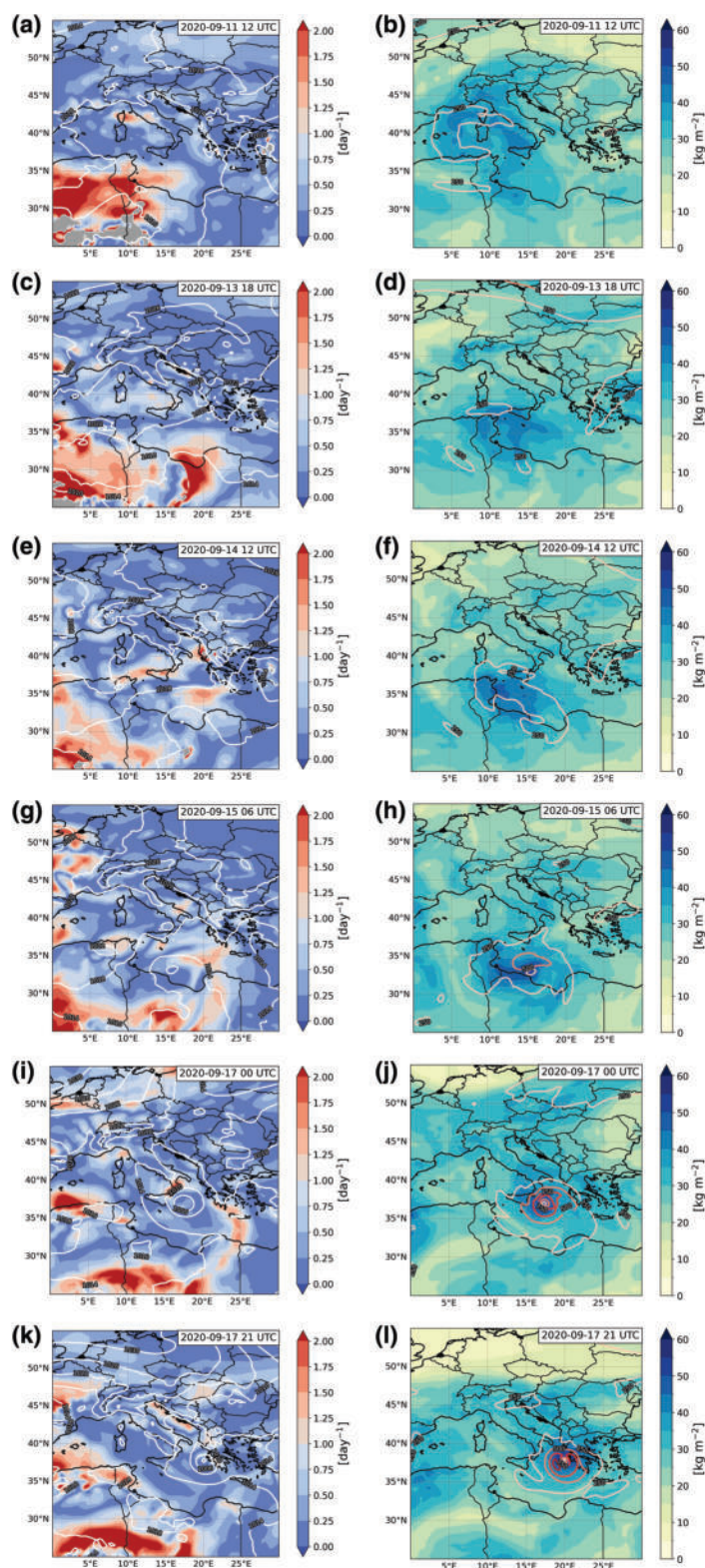


FIGURE 11 ERA5-based maps obtained for: (a,b) September 11, 1200 UTC; (c,d) September 13, 1800 UTC; (e,f) September 14, 1200 UTC; (g,h) September 15, 0600 UTC; (i,j) September 17, 0000 UTC; and (k,l) September 17, 2100 UTC. Contours and shading represent respectively mean sea-level pressure and Eady growth rate (left) and IVT (contours) and IWV (shading) (right).

northern Libya on the lee side of the Atlas Mountains (as suggested for *Maria* by Moscatello *et al.*, 2008a, 2008b). The 500-hPa flow shows marked diffuence, while a weak northwesterly jet streak approaches the Gulf of Sidra. In the same region, BC exhibits a sharp gradient and the dynamic tropopause lowers, consistent with upper-level

forcing coexisting with a developing low-level baroclinic zone. IWV increases to $\sim 45\text{--}50 \text{ kg} \cdot \text{m}^{-2}$, supporting the development of mesoscale convective systems.

On September 14, 1200 UTC (third row in Figures 10–11), the surface low is located over very warm waters in the Gulf of Sidra ($\text{SST} > 28^\circ\text{C}$; Varlas *et al.*, 2023),

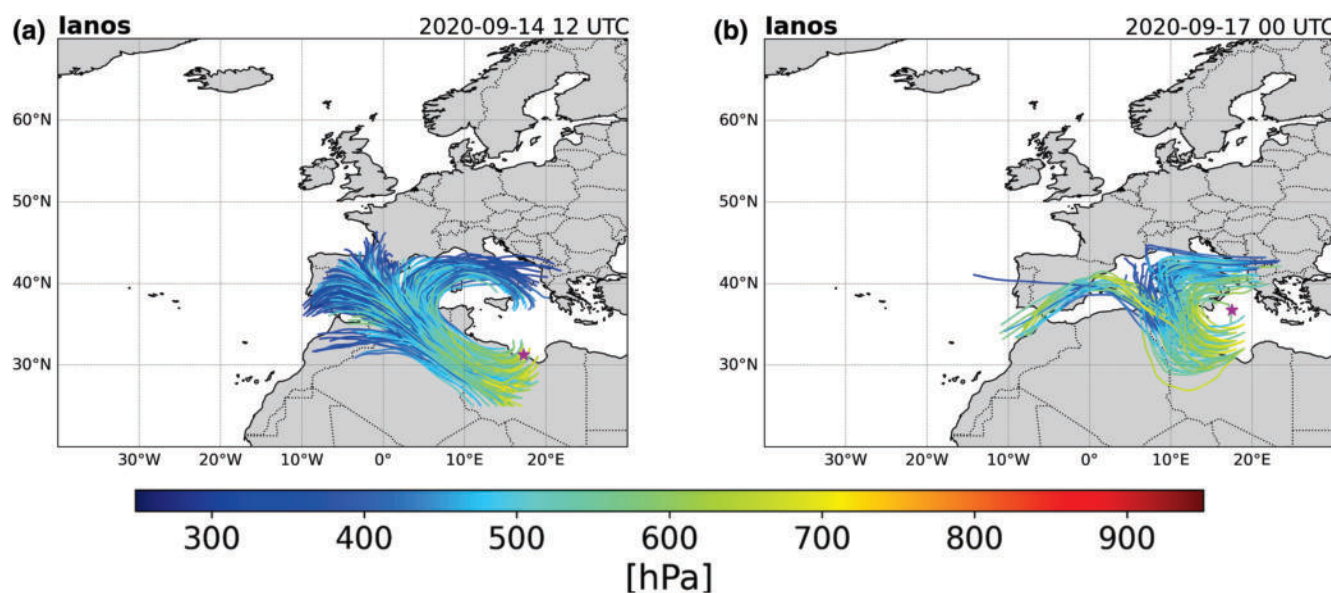


FIGURE 12 Back-trajectories computed with HYSPLIT using a descending threshold of 150 hPa/60 h, (a) starting on September 14, 1200 UTC and ending on September 11, 0000 UTC and (b) starting on September 17, 0000 UTC and ending on September 14, 1200 UTC. The magenta star represents the position of the cyclone at the starting time. Results have been obtained from ERA5 reanalysis.

favouring strong surface fluxes and convective intensification (Miglietta *et al.*, 2011; Pytharoulis, 2018). At this stage, the surface cyclone is still partly decoupled from the upper-level low. Importantly, when trajectories are filtered with a weaker descent criterion, a shallow descending branch becomes detectable (Figure 12a). This highlights directly the limits of the strict dry-intrusion definition: the synoptic PV streamer is present and dry air is advected into the region, but only a limited portion of parcels undergo strong descent into the mid-troposphere, so the dry-intrusion definition used for the multi-case comparison underestimates streamer-related dry-air influence for *Ianos*.

At the onset of the first tropical-like phase (September 15, 0600 UTC; fourth row in Figures 10 and 11), the surface and upper-level circulations become more vertically aligned and the cyclone lies near the tip of the hook-shaped PV streamer. Moisture content increases ($IWV \sim 50\text{--}55 \text{ kg} \cdot \text{m}^{-2}$), while IVT intensifies and wraps around the cyclone, indicating that convection is being sustained by both the developing circulation and an ample moisture supply. Notably, BC is small near the cyclone centre, consistent with a transition away from near-core baroclinic control once vertical alignment is established.

During the main tropical-like phase (September 17, 0000 UTC; fifth row in Figures 10 and 11), the cyclone deepens and remains vertically aligned. The upper-level configuration places *Ianos* near the left-exit region of a jet streak, favouring upper-level divergence and ascent. At the same time, the trajectory analysis again indicates a modest

descending signal ($\sim 200 \text{ hPa}$ in 60 h) wrapping around the cyclone (Figure 12b), consistent with dry upper-level air being present in the broader PV streamer environment even if strong mid-level descent remains limited. Moisture is extreme (IWV peaks near $\sim 60 \text{ kg} \cdot \text{m}^{-2}$, IVT exceeds $1000 \text{ kg} \cdot \text{m}^{-1} \cdot \text{s}^{-1}$), implying that the dynamical setting is conducive to organised deep convection. This combination (strong moisture supply, deep convection, and only shallow or limited descent) provides the synoptic explanation for the low RH values observed in Figure 9: very low RH values can occur near the system due to the proximity of upper-level dry air and modest streamer descent, without a classical deep dry intrusion reaching lower levels. This is also illustrated by the 3D representation in Figure 13, which shows the points with $PV > 1.5 \text{ PVU}$ and differentiates between dry air ($RH < 50\%$, in yellow), linked to the dry intrusion, and moist air ($RH > 50\%$, in red), associated with the PV tower. The figure also reveals a PV deficit and enhanced moistening in the upper part of the cyclone, consistent with the moistening and convective erosion of the PV cut-off described by the correlation coefficients in Section 3.

On September 17, 2100 UTC (sixth row in Figures 10 and 11), *Ianos* is located over the Ionian Sea and approaches western Greece, maintaining a coherent warm-core structure. In the lower troposphere, the BC field shows an enhanced along-coast baroclinic zone ($> 1 \text{ day}^{-1}$) near Greece, consistent with strong land–sea contrasts and coastal/orographic effects that locally sharpen horizontal temperature gradients and vertical shear. This

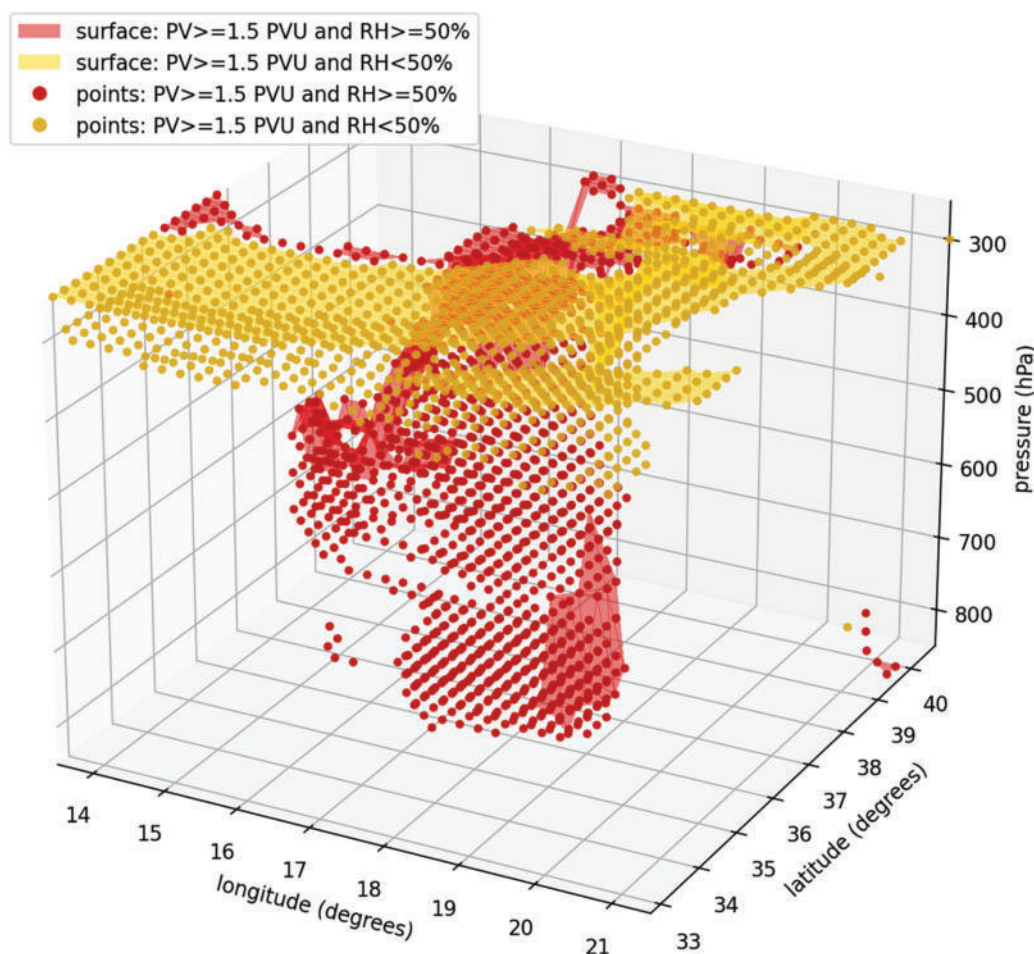


FIGURE 13 Three-dimensional representation of air parcels with $PV > 1.5$ PVU for *Ianos* at 0000 UTC on September 17. Red points denote moist air ($RH > 50\%$), while yellow points denote dry air ($RH < 50\%$).

coastal baroclinicity does not appear to control the warm-core transition at the cyclone centre, but it likely contributes to the asymmetric near-surface structure and intensity of the wind field as the cyclone approaches the coast, by reinforcing the low-level pressure gradient.

Overall, the ERA5 analysis depicts *Ianos* as a cyclone that forms in a synoptically active environment with PV streamer/cut-off structures, but where the deep descending branch of the streamer is weak or only partially sampled by a strict Lagrangian intrusion definition. At the same time, abundant moisture and early convective preconditioning, highlighted by Sánchez *et al.* (2024), support exceptionally deep convection and a strong warm-core transition, consistent with the extreme H values identified in Section 3.

5.2 | WRF simulation

ERA5 underestimates *Ianos* intensity (minimum MSLP ~ 1000 hPa) and cannot resolve key mesoscale convective structures; therefore, to overcome these limitations, we

analyse a 3-km WRF simulation initialised on September 15 at 0000 UTC (Section 2.3).

5.2.1 | Comparison with ERA5

Figure 14 compares some cyclone features derived from ERA5 and the WRF simulation. The WRF track closely follows ERA5 during the first two simulation days, with a southward deviation developing from the evening of September 16 (Figure 14a), consistent with similar deviations reported in Pantillon *et al.* (2024). The major difference lies in intensity: WRF deepens the cyclone substantially more than ERA5, capturing a rapid pressure fall (~ 9 hPa in 3 h) on the afternoon of September 16 and reaching a minimum pressure (989.7 hPa) much closer to observations (984.7 hPa in Palliki; Lagouvardos *et al.*, 2022, Figure 14b). The warm-core signal is also stronger in WRF: $-V_T^U$ increases sharply during the intensification episode and remains elevated afterward (Figure 14c), while maximum wind speed exceeds $140 \text{ km} \cdot \text{h}^{-1}$ during

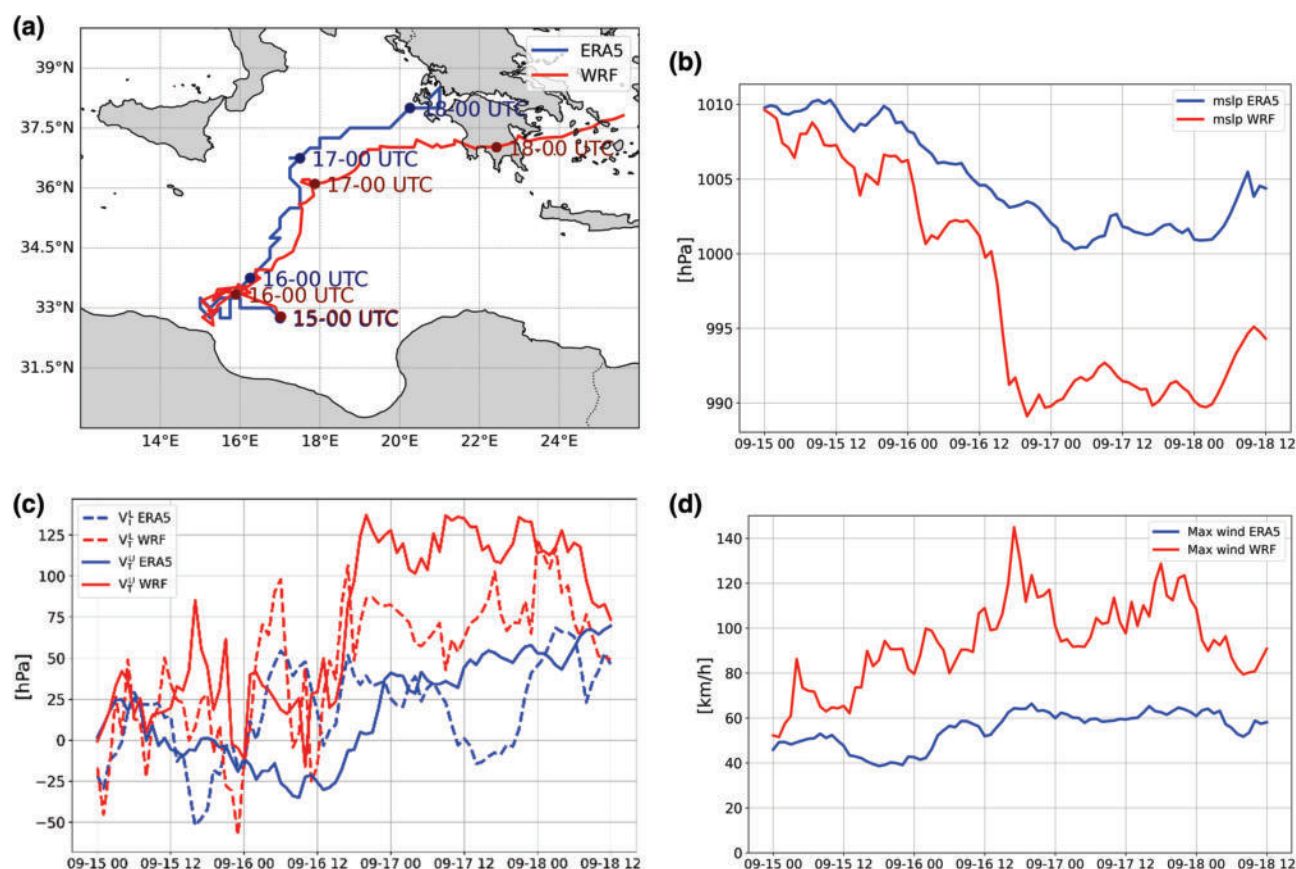


FIGURE 14 Comparison of the evolution of *Ianos* between ERA5 and WRF: (a) trajectory; (b) mean sea-level pressure minimum; (c) Hart parameters computed within 2° from the cyclone centre; and (d) maximum wind speed.

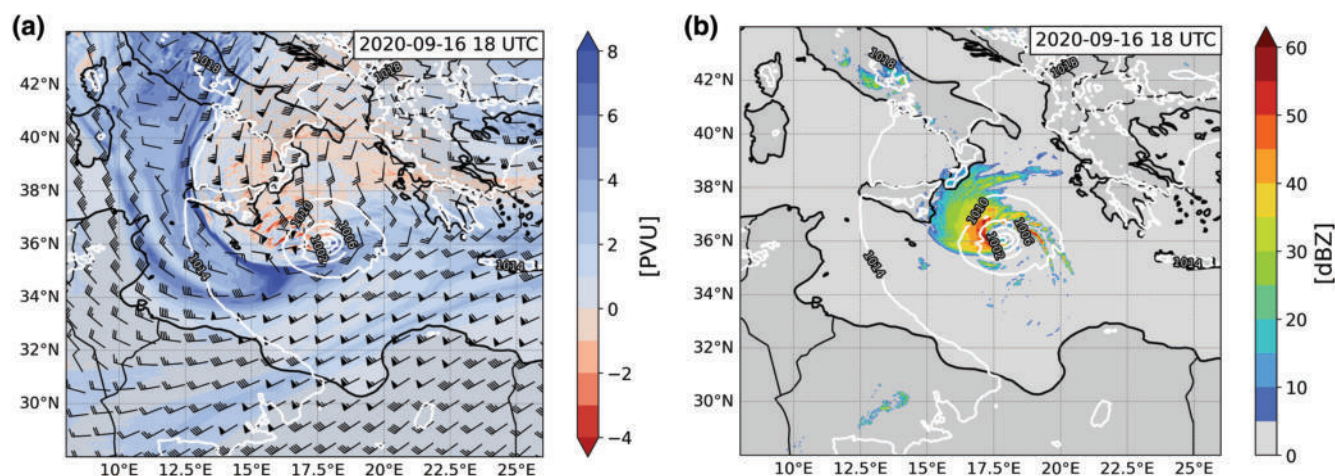


FIGURE 15 Maps from the WRF simulation on September 16, 1800 UTC. White contours represent mean sea-level pressure (MSLP); shading represents (a) 250-hPa PV with wind barbs (half barbs and full barbs correspond to 5 and 10 knots, respectively; the flag corresponds to 50 knots) and (b) maximum reflectivity (right).

the main intensification, with another peak in proximity of landfall due to the along-coast baroclinicity described above (Figure 14d). Together, these results confirm that a high-resolution model is needed to reproduce the rapid

intensification and the associated warm-core deepening of *Ianos* correctly.

To link this intensification to the synoptic setting, Figure 15a (September 16, 1800 UTC) shows that a PV

streamer is located west of the cyclone at 250 hPa, while a broad low-PV region extends to the north. Following Sánchez *et al.* (2024), this low-PV environment can be interpreted as the combined outcome of earlier convective activity over the central Mediterranean and the outflow produced by *Ianos* itself (see also Pantillon *et al.*, 2024). The resulting PV gradient and jet structure create a dynamically favourable configuration: the PV streamer reaches the southern side of the cyclone while *Ianos* is positioned near the left exit region of the jet streak, coincident with the sharp pressure fall and rapid growth of $-V_T^U$. At the same time, maximum reflectivity (Figure 15b), computed using WRF-Python, indicates organised convection near the cyclone, while convection is suppressed beneath the high-PV/dry upper-level air, illustrating the dual role of upper-level PV structures in supporting large-scale ascent but ventilating/suppressing convection locally.

5.2.2 | Pressure tendency equation (PTE) diagnostic

We quantify the drivers of intensification using the PTE (appendix of Fink *et al.*, 2012), computed from the WRF simulation within a radius of 100 km around the cyclone centre (Figure 16). To the best of our knowledge, this diagnostic tool has been applied to Mediterranean cyclones only in Fita and Flaounas (2018), Dafis (2020), and Miglietta *et al.* (2023). Despite a non-negligible residual that limits strict closure at convection-permitting resolution, the qualitative signal is robust.

The surface pressure tendency is predominantly negative during the first two days, with the strongest deepening occurring on September 16 afternoon (Figure 16a). This deepening is associated primarily with negative contributions from EP (evaporation–precipitation term) and

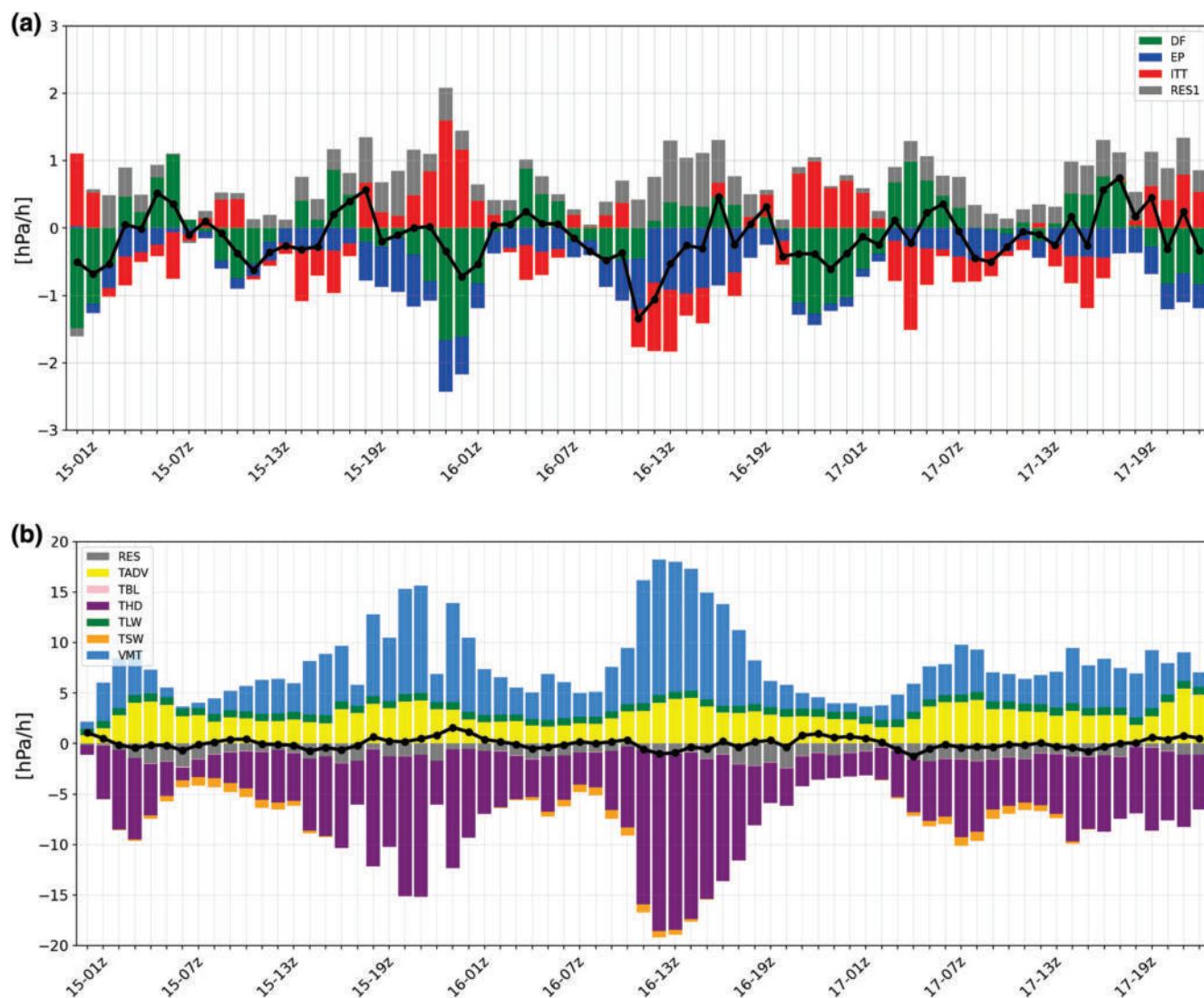


FIGURE 16 PTE analysis of *Ianos* computed within a radius of 50 km. (a) Surface pressure tendency (black line), which is decomposed into DF, ITT, EP, and RES (bars). (b) ITT (black line) decomposed into TADV, VMT, TBL, THD, TLW, TSW, and RES (bars). For an explanation of the terms see the Appendix.

ITT (vertically integrated temperature tendency), indicating that phase changes of water and column warming are central to the rapid pressure fall.

The ITT decomposition (Figure 16b) shows that the intensification is dominated by diabatic heating (THD), which remains strongly negative and peaks during the rapid deepening phase, consistent with latent heat release in organised convection. In contrast, temperature advection (TADV) is persistently positive (cold-air advection) and therefore opposes the deepening, while vertical motion (VMT) is also positive, indicating that adiabatic cooling associated with ascent partially compensates for diabatic warming. Radiative and boundary-layer contributions are comparatively small. This behaviour differs from the PTE balance documented in other Mediterranean cyclones, such as *Zeo* (Fita & Flaounas, 2018) and the Adriatic meso-beta cyclone analysed by Miglietta *et al.* (2023), where warm-air advection plays a clearer intensifying role. For *Ianos*, the PTE therefore supports a narrative in which the timing and organisation of intensification are modulated by the upper-level PV/jet configuration, but the dominant deepening mechanism is diabatic heating associated with intense convection, consistent with the large r_1 diagnosed in Section 3 and the weak classical dry-intrusion signal in Section 4.

6 | DISCUSSION AND CONCLUSIONS

In this study, we analysed 17 Mediterranean tropical-like cyclones (medicanes) using ERA5 reanalysis, with the goal of linking upper-level dynamics to the onset and evolution of the warm core and clarifying the role of dry-air intrusions. We combined correlation-based diagnostics designed to summarise compactly the joint evolution of convection, humidity, and PV, a Lagrangian dry-intrusion analysis based on HYSPLIT back-trajectories, and a convection-permitting WRF simulation and PTE analysis for the outlier case of *Ianos*.

The correlation diagnostics provide a simple way to screen cyclone-to-cyclone variability and connect it to physical mechanisms. The coefficient r_1 highlights the tight relationship between deep convection and upper-tropospheric moistening, which is strongest in early autumn, when the background environment is warm and moist. The coefficient r_2 , evaluated across multiple pressure levels, helps identify the height at which PV and the deep warm core tend to decouple, consistent with the idea that diabatic heating can erode PV near or just below cloud top, while PV above is influenced by stratospheric intrusions and radiative effects. This framework leads to the phenomenological grouping introduced in

Section 3: type-1 cyclones show a PV-preconditioned evolution followed by diabatic maturation, type-2 cyclones show warm-core pulses that remain more directly tied to upper-level PV forcing, and type-3 systems retain persistently high PV and weaker or less persistent tropical-like characteristics, in agreement with the classification in Miglietta and Rotunno (2019).

From the back-trajectory analysis, interpreted together with the correlation diagnostics, the results suggest the following synthesis: type-1 and (partly) type-2 cyclones frequently exhibit identifiable descending intrusions near the developing vortex, consistent with the r_1/r_2 signatures that imply moistening and diabatic PV modification during the transition; type-3 cyclones show more persistent intrusion activity, consistent with their high-PV behaviour. The θ_e fields clarify the dynamical meaning of these intrusions further: when a dry intrusion approaches the cyclone, it tends to be embedded in low- θ_e air that wraps cyclonically toward the centre, sharpening the baroclinic structure and helping organise convection. At the same time, the θ_e maps show that a warm-seclusion-like structure is visible in all cases: the mature phase is characterised by a high- θ_e core near the MSLP minimum, surrounded by lower- θ_e air. This recurrent warm-seclusion signal emphasises that, even when a cyclone becomes symmetric and develops a warm core, its evolution often retains an extratropical seclusion imprint, and the deep warm core can emerge from different combinations of seclusion dynamics and diabatic heating.

Focusing on September medicanes (*Callisto*, *Maria*, *Zorbas*, *Ianos*, and *Daniel*) is particularly informative because these storms occur in an environment that favours deep convection and strong moistening aloft. Within this subset, stronger and more coherent dry-intrusion signatures during the early stages are generally associated with a faster development of the deep warm core (e.g., *Callisto* and *Zorbas*), consistent with the idea that descending low- θ_e , high-PV air can promote a more rapid structural transition by sharpening upper-level forcing and organising convection. However, some medicanes can become intense even without a strong, classical dry intrusion, most notably *Ianos*, and weaker or less organised intrusions (e.g., *Maria* and *Daniel*) can still be followed by warm-core growth, sometimes aided by interaction with upper-level PV streamers. This indicates that, in early autumn, additional pathways, such as stronger air-sea fluxes, persistent moist inflow, and sustained diabatic heating, can compensate for, or even dominate over, the dynamical role typically attributed to strong descending intrusions.

Ianos is the key outlier that motivates the concluding high-resolution analysis. Despite being among the most intense medicanes on record (highest wind speed ever recorded), it shows no clear signal of a strong dry intrusion

even under the relaxed descent criterion, while exhibiting one of the deepest warm-core signatures. The WRF simulation represents the sharp deepening and rapid growth of the warm core better compared with ERA5, and it highlights that the most pronounced intensification coincides with the interaction between *Ianos* and an upper-level PV streamer, occurring within a broader low-PV environment influenced also by earlier convective activity and by cyclone outflow (as discussed in Sánchez *et al.*, 2024; see also Pantillon *et al.*, 2024). The PTE analysis applied to WRF output confirms that the intensification is driven predominantly by diabatic processes (dominant warming contribution in ITT) and evaporation–precipitation effects. Moreover, cold advection is detected, contrasting with cases such as *Zeo*, where warm-air advection plays a more important role together with diabatic heating. Finally, the simulation also suggests that mesoscale baroclinicity and coastal pressure-gradient enhancement near southern Italy and Greece can contribute to the damaging wind footprint at landfall, pointing to impacts that may be underestimated in coarser reanalyses.

Overall, the combined evidence supports a unified view, in which dry intrusions are common features of Mediterranean cyclone evolution and can accelerate warm-core transition by sharpening baroclinic structure and modulating convection. However, they are not a necessary condition for strong medicane intensification, particularly in early autumn. The correlation diagnostics provide a compact screening tool to identify when warm-core evolution is driven more strongly by humidity or diabatic effects rather than tightly coupled to upper-level PV, with the trajectory and θ_e analyses providing the physical interpretation. Future work should pursue back-trajectories and PV and θ_e diagnostics using convection-permitting simulations to reduce the sensitivity to descent thresholds and capture PV streamer structure better, and process-oriented intercomparisons across cases to quantify when warm-seclusion dynamics versus diabatic amplification dominates warm-core formation.

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DATA AVAILABILITY STATEMENT

The ERA5 reanalysis data were downloaded from the Copernicus CDS (Climate Data Store) website (<https://cds.climate.copernicus.eu/datasets/>). ECMWF operational analysis and forecast data used to initialise the WRF simulation were downloaded from the MARS catalogue (<https://www.ecmwf.int/en/forecasts/dataset/operational-archive>). Other data are available upon request.

ORCID

Daniele Nigro  <https://orcid.org/0009-0001-6406-114X>

Lorenzo Giovannini  <https://orcid.org/0000-0003-1650-0344>

Simona Bordoni  <https://orcid.org/0000-0003-4771-3350>

Stavros Dafis  <https://orcid.org/0000-0002-1513-1930>

Mario Marcello Miglietta  <https://orcid.org/0000-0003-2898-1595>

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SUPPORTING INFORMATION

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APPENDIX A

The pressure tendency equation (PTE), introduced by Fink *et al.* (2012), provides a diagnostic framework to assess the contribution of different physical processes to the intensification of cyclones. The equation considers an atmospheric vertical column extending from the surface to an upper-boundary pressure level p_2 . The equation is given as

$$\underbrace{\frac{\partial p_{\text{sfc}}}{\partial t}}_{Dp} = \underbrace{\rho_{\text{sfc}} \frac{\partial \phi_{p_2}}{\partial t}}_{D\phi} + \underbrace{\rho_{\text{sfc}} R_d \int_{\text{sfc}}^{p_2} \frac{\partial T_v}{\partial t} d \ln p}_{\text{ITT}} + \underbrace{g(E - P)}_{\text{EP}} + \text{RES}_{\text{PTE}}, \quad (\text{A1})$$

where p_{sfc} is the surface pressure, ρ_{sfc} is the density of surface air, $\phi(p_2)$ is the geopotential at pressure p_2 , R_d is the gas constant for dry air, T_v is the virtual temperature, g is the gravitational acceleration, E represents surface evaporation, and P is surface precipitation. The various terms, from left to right, represent respectively the surface pressure tendency Dp [hPa/h], the change of geopotential height at the upper boundary $D\phi$, the vertical integrated temperature tendency ITT, the mass change by evaporation and precipitation EP, and the residual term due to discretisation RES_{PTE} needed to close the equation.

In physical terms, if all other terms are zero, a lowering of the upper boundary would cause a decrease in surface pressure, associated with mass evacuation by divergent winds. Conversely, if the height of the column is constant, a warming causes a horizontal expansion and thus a loss of mass in the column, again associated with a decrease in surface pressure. The term ITT can be decomposed further into four different terms:

$$\underbrace{\frac{\partial p_{\text{sfc}}}{\partial t}}_{Dp} = \underbrace{\rho_{\text{sfc}} \frac{\partial \phi_{p_2}}{\partial t}}_{D\phi} + \underbrace{\rho_{\text{sfc}} R_d \int_{\text{sfc}}^{p_2} \frac{\partial T_v}{\partial t} d \ln p}_{\text{ITT}} + \underbrace{g(E - P)}_{\text{EP}} + \text{RES}_{\text{PTE}}, \quad (\text{A2})$$

where $\mathbf{v}$ and ω are the horizontal and vertical wind components, T is the temperature, c_p is the specific heat at constant pressure, and $\dot{Q}$ is the diabatic heating rate. From left to right, the terms represent the horizontal temperature advection TADV, the vertical motion VMT, the change of temperature due to diabatic processes DIAB, such as radiative warming/cooling, latent heat release, diffusion and dissipation, and the residual due to discretisation in

time and space RES_{ITT} necessary to close the equation. Lastly, the term DIAB can be decomposed as follows:

$$\text{DIAB} = \text{TBL} + \text{THD} + \text{TLW} + \text{TSW}, \quad (\text{A3})$$

where the terms on the right-hand side represent the rate of change of temperature due to diabatic processes calculated in the WRF physical parameterisations, which

are the planetary-boundary-layer-related processes (TBL), microphysics and convective processes including latent heat release (THD), longwave radiation (TLW), and shortwave radiation (TSW). In this work, all these quantities are averaged over a radius of 100 km around the cyclone centre. The top boundary is set at 50 hPa. A three-time-step smoothing has been applied to reduce the noise in the results.