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Geophysical Research Letters

RESEARCH LETTER

10.1029/2023GL106429

A New Refinement of Mediterranean Tropical-Like Cyclones Characteristics

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Key Points:

- A new method to detect cyclones with tropical-like characteristics in the Mediterranean has been developed
- Part of the cyclones with deep warm core developed in low baroclinicity and with intense convective processes, as tropical cyclones
- Some cyclones have weak convective processes and intense vertical wind shear environments, such as warm seclusions or polar lows

Supporting Information:

Supporting Information may be found in the online version of this article.

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Citation:

Gutiérrez-Fernández, J., Miglietta, M. M., González-Alemán, J. J., & Gaertner, M. A. (2024). A new refinement of Mediterranean tropical-like cyclones characteristics. *Geophysical Research Letters*, *51*, e2023GL106429. https://doi.org/10.1029/2023GL106429

Received 3 OCT 2023
Accepted 19 MAR 2024

Abstract

Several warm-core cyclones in the Mediterranean, which were analyzed in the literature, are studied using ERA5 reanalysis, to identify the environment where they develop and distinguish tropical-like cyclones from non-tropical warm-core cyclones. Initially, the cyclone phase space is analyzed to distinguish the cyclones that have a symmetrical deep warm core. Subsequently, the temporal evolution of several parameters is considered, including the distance between the area of maximum tangential wind speed and the cyclone center. Some differences are observed between the cyclones analyzed: one category of cyclones develops in areas of moderate-low baroclinicity and intense convective processes, as occurs in tropical cyclones. Another group of cyclones develops in a strongly baroclinic environment with weak convective processes and intense vertical wind shear, as occurs in warm seclusions. Two cyclones, showing similarities with polar lows, are also identified.

Plain Language Summary

Mediterranean tropical-like cyclones (TLCs) are damaging weather systems, which form over the Mediterranean Sea, resembling tropical cyclones. These cyclones can drive important socio-economic losses in coastal areas. However, due to their small size and the relatively recent investigation of these cyclones, there is currently no robust categorization of which Mediterranean cyclones can be considered TLC. Therefore, in this work, we propose a method to differentiate cyclones that attain actual tropical-like characteristics in part of their lifetime, as they develop a warm core through intense convective processes. The main results of this study show that part of the analyzed cyclones have features similar to tropical cyclones. Another group of cyclones has a behavior closer to extratropical cyclones with weak convective processes in an environment with intense vertical wind shear, as occurs in warm seclusions or polar lows. The results of this study propose a key to identify the Mediterranean cyclones that have tropical-like characteristics.

1. Introduction

The Mediterranean basin is one of the most important cyclogenetic regions of the Northern Hemisphere (Campins et al., 2011). In general, all Mediterranean cyclones have extratropical origin (Trigo et al., 1999); nonetheless, some can develop tropical characteristics in part of their life cycle. These cyclones are frequently called medicanes (MEDIterranean hurriCANES; Emanuel, 2005) or tropical-like cyclones (TLCs). These cyclones are characterized by the presence of deep warm core originated by intense convection in the mature stage (infrared channels and passive microwave sensors; Panegrossi et al., 2023; D'Adderio et al., 2024), and could be detected by satellite images because of their symmetrical structure and the presence of a cloud-free region in their center (visible channels). TLCs can drive important socio-economic losses in coastal areas as a result of intense precipitation, strong winds or storm surges.

The presence of TLCs in the Mediterranean region started to be reported after the advent of satellite imagery, as certain cyclones showed visual similarities with tropical cyclones. However, difficulties were encountered in assessing TLCs from infrared satellite images (Tous & Romero, 2013), as large baroclinic systems that develop symmetrical structures during its occlusion phase could not be clearly differentiated from TLCs. Therefore, their objective characterization has been increasingly performed using numerical data to determine if they achieve a warm core in part of their lifetime. One of the most used methods to identify the different types of cyclones is the Cyclone Phase Space (CPS; Hart, 2003). This tool allows distinguishing cyclones by their thermal structure and symmetry. In this frame, extratropical cyclones are asymmetric cold core cyclones, tropical cyclones are symmetric warm core cyclones, while warm seclusions (the last phase of the evolution of extratropical cyclones in the Shapiro-Keyser conceptual model) and subtropical cyclones generally show a hybrid structure (shallow warm core and cold core in upper levels). The CPS method has been applied to objectively detect Mediterranean TLCs (e.g., Cavicchia et al., 2014; Gaertner et al., 2007; Zhang et al., 2021). However, while in warm seclusions the warm core is frequently limited to the lower troposphere, in some cases it can reach the mid- and upper-troposphere (Maue, 2010). Hence, the CPS method may not be able to distinguish warm seclusions from tropical cyclones, as it does not discriminate the way the warm core is produced. In the case of Mediterranean TLCs, the possibility of confusion between cyclones that develop through the Wind Induced Surface Heat Exchange mechanism (WISHE; Emanuel, 1986), characteristic of tropical cyclones, and warm seclusions has been discussed in Miglietta and Rotunno (2019).

Therefore, an unambiguous detection method for identifying TLCs in the Mediterranean region is currently missing. Here, we propose a method to differentiate cyclones that attain tropical-like characteristics in part of their lifetime from cyclones that develop a warm core through non-diabatic processes. We will use respectively the term warm core cyclones (WCCs) to refer to all cyclones that reach a deep warm core, independently of the formation process. For some of the most important WCCs considered in the literature, we analyze several environmental parameters, with the final goal of identifying which parameters may be appropriate to detect the cyclones that have tropical-like characteristics (TLCs).

2. Data and Methodology

2.1. Data Used

Fourteen WCCs observed in the last 40 years are analyzed (the list is in Table S1 in Supporting Information S1). The cyclones are identified based on observational evidence and the scientific literature. To characterize these cyclones, we use the ERA-5 reanalysis data, already employed in other works on TLCs, such as Zhang et al., 2021; de la Vara et al., 2021. The focus of these two studies was different to our aim, as they studied respectively the precipitation associated to TLCs (Zhang et al., 2021) and the minimal amount of computational data required to detect TLCs (de la Vara et al., 2021). ERA-5 data have a horizontal spatial resolution of 0.25° and 137 vertical levels from the surface up to a height of 80 km. In our study, ERA-5 reanalysis data are used with a frequency of 6 hr. The variables required for the CPS method are: geopotential height from 300 hPa to 900 hPa, every 50 hPa. For the analysis of other cyclone characteristics, we use: (a) u and v wind-components at 10-m, 700 hPa, and 925 hPa, (b) air temperature at different pressure levels (300, 700, 925, 850 hPa), and (d) specific humidity at 850 hPa. Compared to other data sets, ERA-5 reanalysis data have been selected mainly because of their high resolution appropriate for mesoscale cyclones.

2.2. WCC Tracking and Characterization

The WCC tracks are provided by a composite approach aimed at producing a reference data set for Mediterranean cyclones (Flaounas et al., 2023). This method combines overlapping tracks from different cyclones' detection and tracking methods and produces composite tracks also containing the information about the agreement of the different methods. Compared to individual methods, the composite tracks reproduce more intense and longer-lasting cyclones, with more distinguished early, mature and decay stages.

We analyze the thermal structure of the selected cyclones using the CPS method. This is an objective method to represent the 3-D structure of cyclones and classify them. It is based on three parameters: B, -VTU and -VTL. The B parameter gives an indication of the cyclone symmetry. As in Hart (2003), we assume that values of B above 10 m indicate an asymmetric (frontal) cyclone, whilst values below 10 m correspond to a symmetric (non-frontal) cyclone. -VTL and -VTU represent the lower-troposphere (600–900 hPa) and the upper-troposphere (300–600 hPa) thermal winds, respectively, a measure of the vertical thermal structure. Negative values are indicative of a cold core, whilst positive values indicate a warm core.

Several studies used this method to analyze tropical cyclones in different regions (e.g., Manning & Hart, 2007; Song et al., 2011), as well as TLCs in the Mediterranean (e.g., de la Vara et al., 2021; Miglietta et al., 2011). Due to the smaller size of Mediterranean cyclones, the calculation of the CPS parameters has been applied to a reduced radius of 300 km from the cyclone center (a radius of 150 km was also tested, showing minor changes with respect to the case of 300 km radius), as opposed to 500 km employed for Atlantic cyclones (Hart, 2003). In this study, a cyclone is classified as a WCC if −VTU and −VTL are greater than 0 and B is smaller than 10 m, that is, the cyclone has a Symmetric Deep Warm Core (SDWC) for at least one 6-hourly time step.

2.3. Method for the Detection of Tropical Characteristics

Holland and Merrill (1984) found that, for tropical cyclones, the distance between the maximum tangential wind speed and the cyclone center decreases in the mature stage, when the tropical cyclones become more intense (Chavas et al., 2015). Thus, we expect that for TLCs a similar behavior should be observed when the cyclones reach the SDWC phase. Based on these considerations, we calculate the variation of the distance between the maximum tangential wind speed and the cyclone center for the selected cyclones.

First, we determine the tangential wind speed for each radius around the cyclone center from 31 to 620 km, every 31 km (data grid spacing); then, we calculate the azimuthal mean and identify the radius for which the mean values are the highest for each time step.

Hence, we calculate the temporal variation of the distance (x) between the azimuthally-averaged maximum tangential wind and the cyclone center in the 24 hr period before the cyclone gains a SDWC (from t_0–4 to t_0):

$$\text{Trend}_{\text{distance}} = \frac{x_{t_0} - x_{t_0-4}}{t_0 - t_{0-4}} \tag{1}$$

Also, we consider additional parameters providing indications about the tropical or non-tropical nature of the cyclones. The Coupling Index (CI) is a measure of the bulk tropospheric stability (Bosart & Lackmann, 1995), defined as the difference between the potential temperature at the dynamic tropopause (approximated here as its value at 300 hPa: $\theta_{300\text{ hPa}}$ and the 850 hPa equivalent potential temperature ($\theta_{e,850\text{ hPa}}$)

$$\text{CI} = \theta_{300\text{ hPa}} - \theta_{e,850\text{ hPa}} \tag{2}$$

McTaggart-Cowan et al. (2015) found that almost all tropical cyclones develop with CI smaller than 22.5°C.

The Baroclinicity Index (BC) or Eady Growth Rate is an environmental parameter that provides an accurate estimate of the maximum growth rate for baroclinic cyclones (Hoskins & Valdes, 1990), and is defined as

$$BC = 0.31 f V_Z N^{-1} \tag{3}$$

where f is the Coriolis parameter, V_Z is the vertical gradient of horizontal wind, and N is Brunt–Väisälä frequency. The baroclinicity index is defined at 850-hPa, in which the vertical differences in V_Z and N are calculated using the 925 and 700 hPa levels. Yanase et al. (2014) showed that in extratropical cyclones the values of BC are higher (close to 1 day^{-1}) than in tropical cyclones (around 0 day^{-1}).

The effect of vertical wind shear has been widely discussed in the tropical cyclone literature. According to the theory of Davis and Bosart (2003), in a baroclinic environment strong convection processes are necessary to reduce the vertical wind shear and make the environment favorable to the possible development of tropical cyclones. In our work, we defined the wind shear (WS) as

$$\text{WS} = \sqrt{(u_U - u_L)^2 + (v_U - v_L)^2} \tag{4}$$

where the subscript L (lower) corresponds to 925 hPa and U (upper) to 200 hPa. This equation was used in Evans and Guishard (2009).

Finally, we have used the Convective Available Potential Energy (CAPE) data directly downloaded from ERA-5.

To study the statistical significance of the differences between the different cyclone types, we use the p-values of the two-sided Wilcoxon rank sum test (Wilks, 2006). This calculation tests the null hypothesis that data in x and y are samples from continuous distributions with equal medians, against the alternative that they are not. This test assumes that the data samples are independent.

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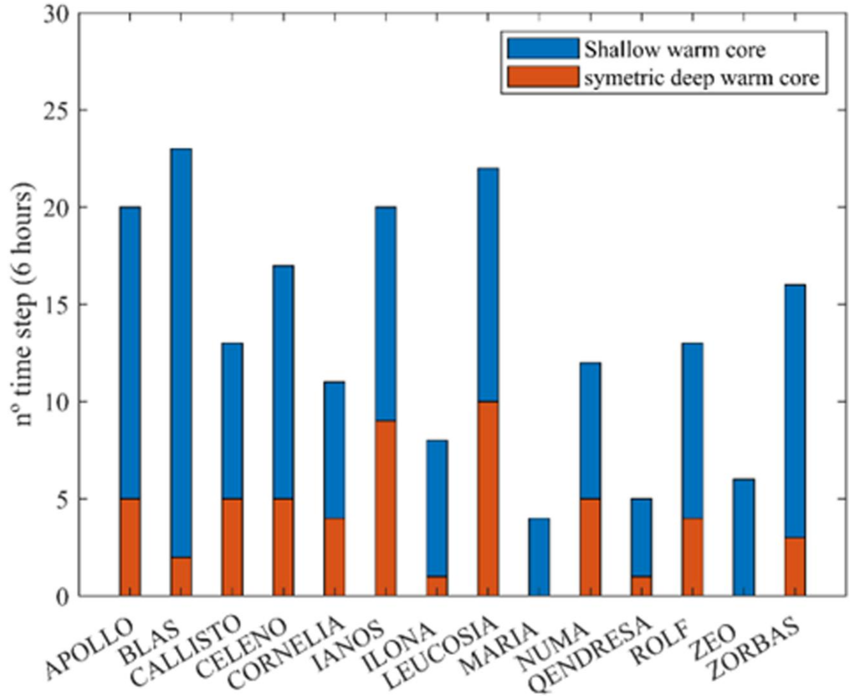

Figure 1. Number of 6-hr time steps in which the selected cyclones show a shallow warm core (blue bar) and SDWC (orange bar).

3. Results

3.1. Analysis of CPS Parameters

We analyze the thermal structure of the selected WCCs with the CPS method, to check if they attain a SDWC. Figure 1 shows the number of time steps in which the cyclones have a SDWC (red columns) and a shallow warm core ($-VTL > 0$ and $-VTU < 0$ values; blue column). Twelve of the fourteen cyclones studied here show a SDWC structure for at least one time step in the ERA-5 data, and all show a shallow warm core at least for a few time steps. The average duration of the SWDC phases is around 24 hr, in agreement with Cavicchia & von Storch, 2012. The presence of a shallow warm core is observed on average for about 60 hr.

Maria and Zeo are the only cyclones that do not show deep warm core features ($-VTL > 0$, but $-VTU < 0$), and they are discarded in the following analysis. However, previous studies based on numerical simulations (Fita & Flaounas, 2018; Miglietta et al., 2011) show that both cyclones reveal a SDWC structure for a few hours. A deeper investigation of the ERA-5 fields was performed for these two cyclones, showing that a SDWC structure emerges for Maria considering hourly resolution data: this suggests that, for short-duration, fast-evolving cyclones, 6 hr time resolution is not fine enough to reproduce their evolution properly. Also, for both Zeo and Maria the values of -VTU are very close to 0, and become clearly positive when a smaller radius is considered in the calculation of the CPS parameters (150 km): thus, a reduced radius may be better suited for the smallest vortices.

As indicated before, the existence of a SDWC phase does not necessarily correspond to tropical characteristics, as some warm seclusions can show a similar behavior. Additional diagnostics are calculated to determine which of these phases actually correspond to tropical characteristics.

3.2. Study of the Distance Between the Maximum Tangential Wind Speed and the Cyclone Center

As mentioned above, the distance D between the azimuthally averaged maximum tangential wind and the cyclone center is expected to decrease as a tropical cyclone reaches its mature stage (Mallen et al., 2005; Zhang et al., 2011). If such a scale reduction is found for some of the WCCs but not for others, this behavior could be used to filter out TLCs from the rest of the WCCs.

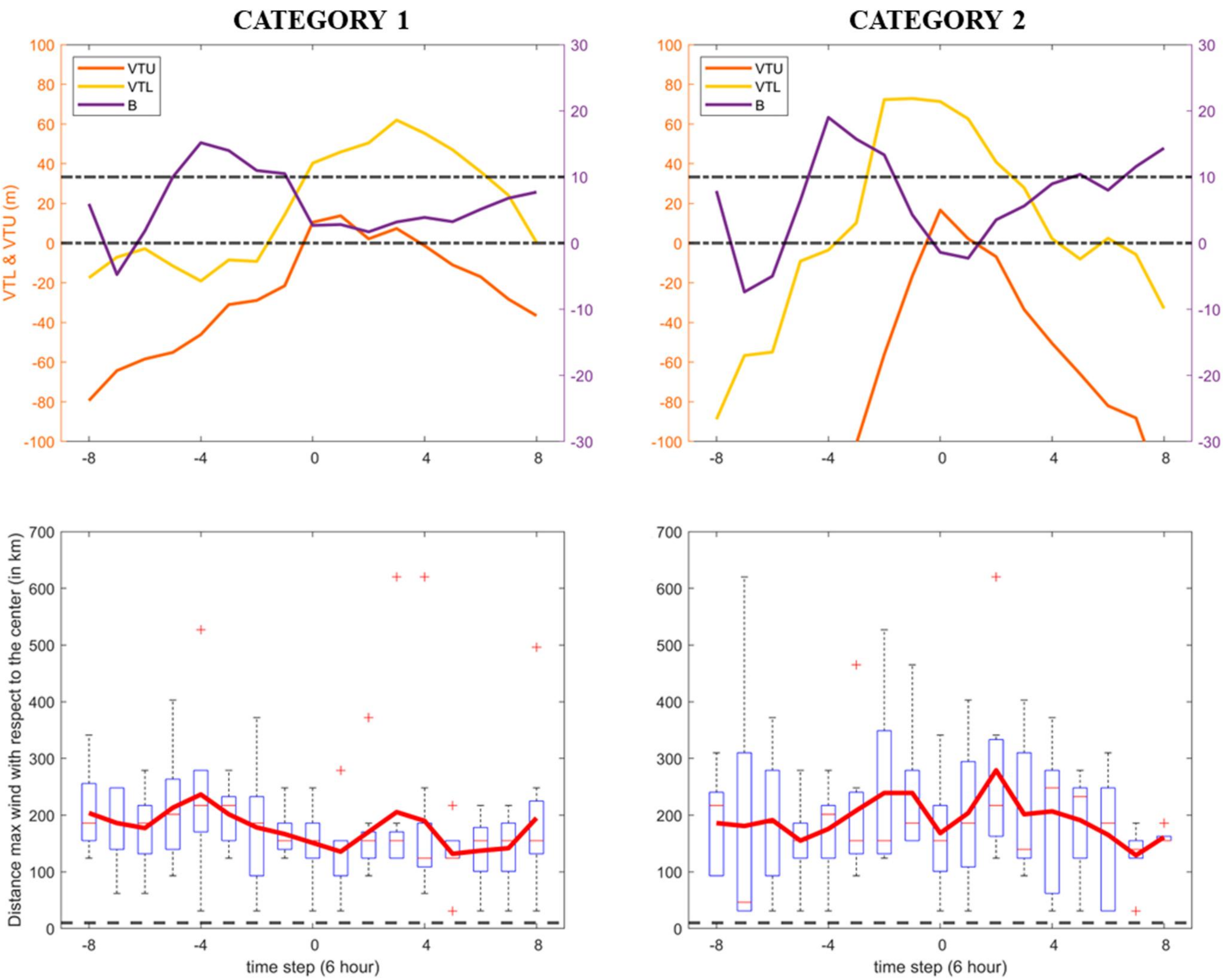

Figure 2. (a) Mean CPS parameters (−VTU, −VTL, and B) of WCCs within category 1 from 8 time steps before to 8 after the time t_0 when the cyclone enters the SDWC phase; (b) is the same as (a) but for WCCs in category 2. (c) Box-and-whiskers plot and mean values (red line) of the distance between the maximum azimuthally-averaged tangential wind and the cyclone center for the WCCss within category 1; the red crosses represent values above the 95th percentile or below the 5th percentile; (d) is the same as (c) but for WCCss within category 2.

The twelve analyzed cyclones show two different behaviors in terms of change of D in the 24 hr period before the cyclones acquire a SDWC structure. Considering that three cyclones have two different SDWC phases, a total of sixteen phases are examined. We found a decrease in D with time, similar to tropical cyclones, in 10 cases, which will be assigned to category 1, while stationary or increasing D is identified in 5 cases, which will be assigned to category 2. In Leucosia, Callisto and Zorbas, showing two different SDWC periods, an increase of D is observed in the first phase, and a decrease of D in the second; in Ianos a decrease of D is observed in both SDWC periods.

Figure 2 shows the mean values of the different CPS parameters (top panels) and the variation of D with time (bottom panels) separately for the two categories. Regarding the change of D with time, in category 1 an anti-correlation is generally observed between the temporal variation of D and -VTU (−0.68); conversely, the correlation is positive in category 2 (0.4). In fact, in category 1 the maximum D is reached at t_0-4 and the minimum at $t_0 + 1$, while in category 2 nearly the opposite situation occurs, as the minimum D is at t_0-4 and the maximum at $t_0 + 2$. The time evolution of the mean D generally reflects the evolution of the individual cyclones in each category (apart from Celeno and Leucosia in Category 1, characterized by an increase of D around t_0). The average values of D are greater than those typically expected in mature tropical cyclones (a few tens of km; Mallen et al., 2005); however, we should consider that D is evaluated based on the azimuthal average and not on

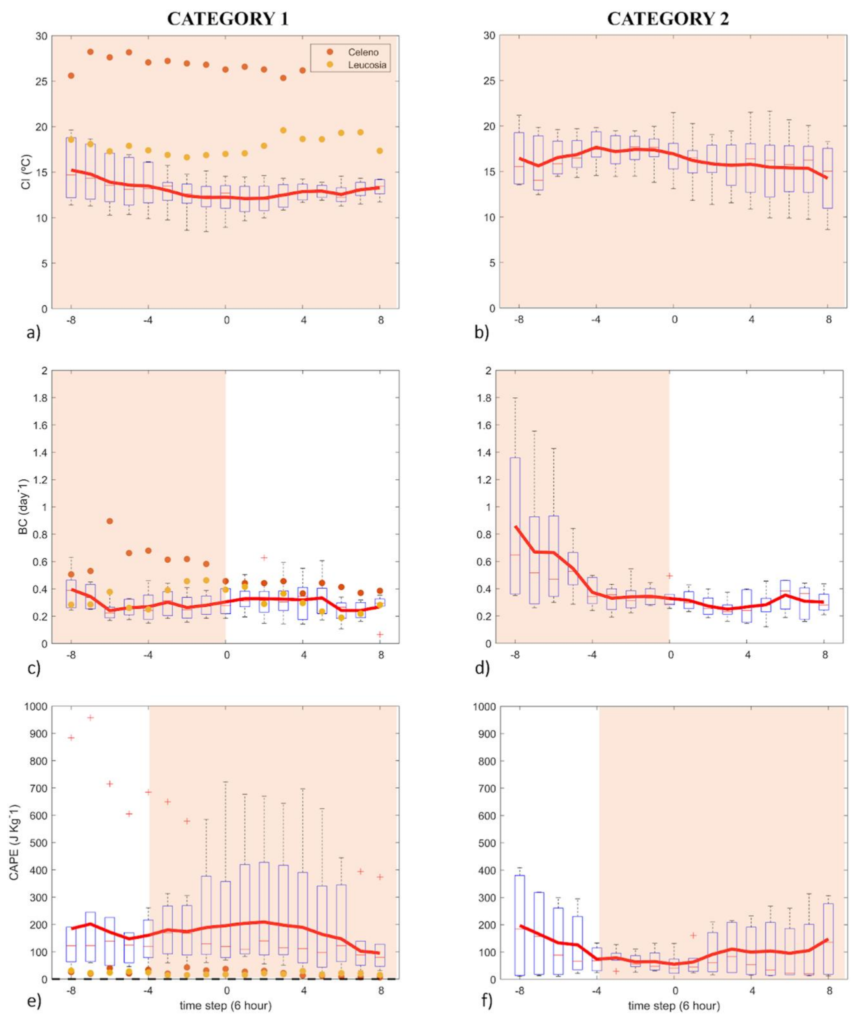

Figure 3. (a) Boxplot and mean values (red line) of CI (a), BC (c), CAPE (e) for WCCs within category 1 from 8-time steps before to 8 after the time t_0 cyclones acquire a SDWC; (b), (d), (f) are the same as (a), (c), (e) but for category 2. The red crosses represent values that are above the 95th percentile or below the 5th percentile. The orange shading indicates whether the variables are statistically different in a confidence interval greater than 95% between the two cyclone categories (Wilcoxon statistical test). Celeno (red points) and Leucosia (orange points) cyclones are not included in the statistical analysis.

the individual maxima. Also, the relatively coarse resolution of ERA-5 somewhat limits the accuracy in the evaluation of D since it smooths out the wind field.

Lastly, the figure shows that the cyclones within category 1 have a longer lasting and more intense warm core in the upper levels (−VTU) as well as in the low levels (−VTL) than those in category 2. This different evolution may be attributed to the longer phase with intense sea surface fluxes in category 1 (see also Miglietta & Rotunno, 2019). Also, the appearance of a warm core in the low levels anticipates the presence of an upper-level warm core by 42 hr in Category 1, but only by 18 hr in Category 2.

3.3. CI and BC

Here, we investigate whether the two categories identified above, characterized by a different evolution of D with time, also differ regarding other physical properties. In other terms, we analyze whether the time evolution of D around t_0 is effective for discriminating cyclones with different characteristics, that is, TLCs from non-tropical warm-core cyclones. In this effort, Figure 3 shows the time variation of CI (top), BC (middle), averaged over a 1,000 km radius, and of convective available potential energy (CAPE; bottom), averaged over a 300 km radius around the cyclone center, separately for the two categories. The cyclones in category 1 show lower values of CI over the whole lifetime, close to those observed in North Atlantic tropical transitions (Calvo-Sancho et al., 2022). In category 1, the average CI decreases from about 15°C at t_0-8 to about 12°C at t_0-4, and then remains nearly constant until $t_0 + 8$; conversely, in category 2, CI slightly increases to about 18°C from t_0-8 to t_0-4, then slowly decreases to 15°C until $t_0 + 8$. The application of a Wilcoxon statistical test to each cyclone at 24 hr-long intervals reveals that the differences in the distributions of CI for the two categories are statistically significant in all periods analyzed.

Regarding BC, the main differences between the two categories occur before t_0. From t_0-8 to t_0-4, the average values in category 2 decrease from about 1 day^{-1}, a typical value for baroclinic cyclones, to about 0.3 day^{-1}. Conversely, in category 1 they decrease from 0.4 to 0.2 day^{-1}, closer to the values characteristic of tropical cyclones (Yanase et al., 2014). Such a difference is associated with the persistence of a jet stream close to the cyclone center for a longer period in cyclones of category 2 (not shown). The Wilcoxon statistical test shows that the differences in the distributions of BC between the two categories are statistically significant from t_0-8 to t_0.

About CAPE, the values obtained in category 1 are higher mostly from t_0-4 onward. In fact, for cyclones in category 1 a slight increase in mean CAPE is observed around t_0-4 up to about 200 J kg^{-1}. Conversely, in category 2, CAPE values are close to 200 J kg^{-1} at t_0-8 but rapidly decrease to about 50 J kg^{-1} at t_0. The Wilcoxon statistical test shows that the differences in the distributions of CAPE between the two categories are statistically significant from t_0-4 onward.

The time evolution of BC, CAPE and CI for the individual cyclones is similar to that of the mean in each category, apart from Celeno and Leucosia in category 1 (Figures 3a, 3c, and 3e). For the latter two cyclones, high values of CI (above 18°C) and of BC (up to 0.9 day^{-1} in Celeno), and low CAPE (25 J kg^{-1}) occur at early stages, and stand out from the other cyclones in category 1 throughout most of their life cycle. Therefore, the environment has singular characteristics compared to the other cyclones in category 1, although they have a similar reduction in D. Their characteristics are also different from those of cyclones in category 2. Therefore, these two cyclones are kept separated from both categories in the following analysis.

3.4. Analysis of Composite Maps

In this section, composite maps (Figure 4) have been analyzed to further investigate differences between the characteristics of the environment in which the cyclones of the different categories develop (see also Figure S2 in Supporting Information S1). To this aim, we calculated the spatial distribution of CI, CAPE, and WS surrounding the cyclone, averaged in the 24 hr period before the cyclones acquire a SDWC.

Lower values of CI are identified in cyclones of category 1 (Figure 4a), not only near the cyclone center (values in the range 5–10°C cover an extensive region), in agreement with the spatial distribution for cyclones experimenting tropical transitions, as reported in Calvo-Sancho et al. (2022). Conversely, in category 2 (Figure 4b), and even more in Celeno and Leucosia (Figure 4c), low values (below 10°C) are confined only near the cyclone center, while much higher values (up to 30°C for category 2, 40°C for Celeno and Leucosia) are observed in the surrounding environment, suggesting very different environmental conditions between the two categories, and also the peculiarity of Celeno and Leucosia.

Strong differences are also apparent in CAPE (Figures 4d–4f). In category 1, higher values can be observed from north-west to south-east across the cyclone center (about 500 J kg^{-1} near the center), with peaks of about 1000 J kg^{-1} in the south-eastern region. In category 2, the values are much lower around the cyclone center (about 100–200 J kg^{-1}); the highest values are again observed in the southeastern region, but much smaller than in category 1 (about 500 J kg^{-1}). Lastly, in Celeno and Leucosia, the CAPE is negligible everywhere.

Finally, the WS field is shown in Figures 4g–4i. In category 1 (Figure 4g), the WS values are below 10 m s^{-1} in a radius of 200 km around the cyclone center, while in Category 2 WS values are higher (20–30 m s^{-1}), and even greater in Celeno and Leucosia (above 40 m s^{-1}), especially in the southeastern side. Such strong differences in CI, WS, and CAPE indicate that the environment in cyclones of category 1 is much more favorable to the development of deep convection, and is more similar to that observed in tropical cyclones, while cyclones in category 2 have features closer to baroclinic cyclones.

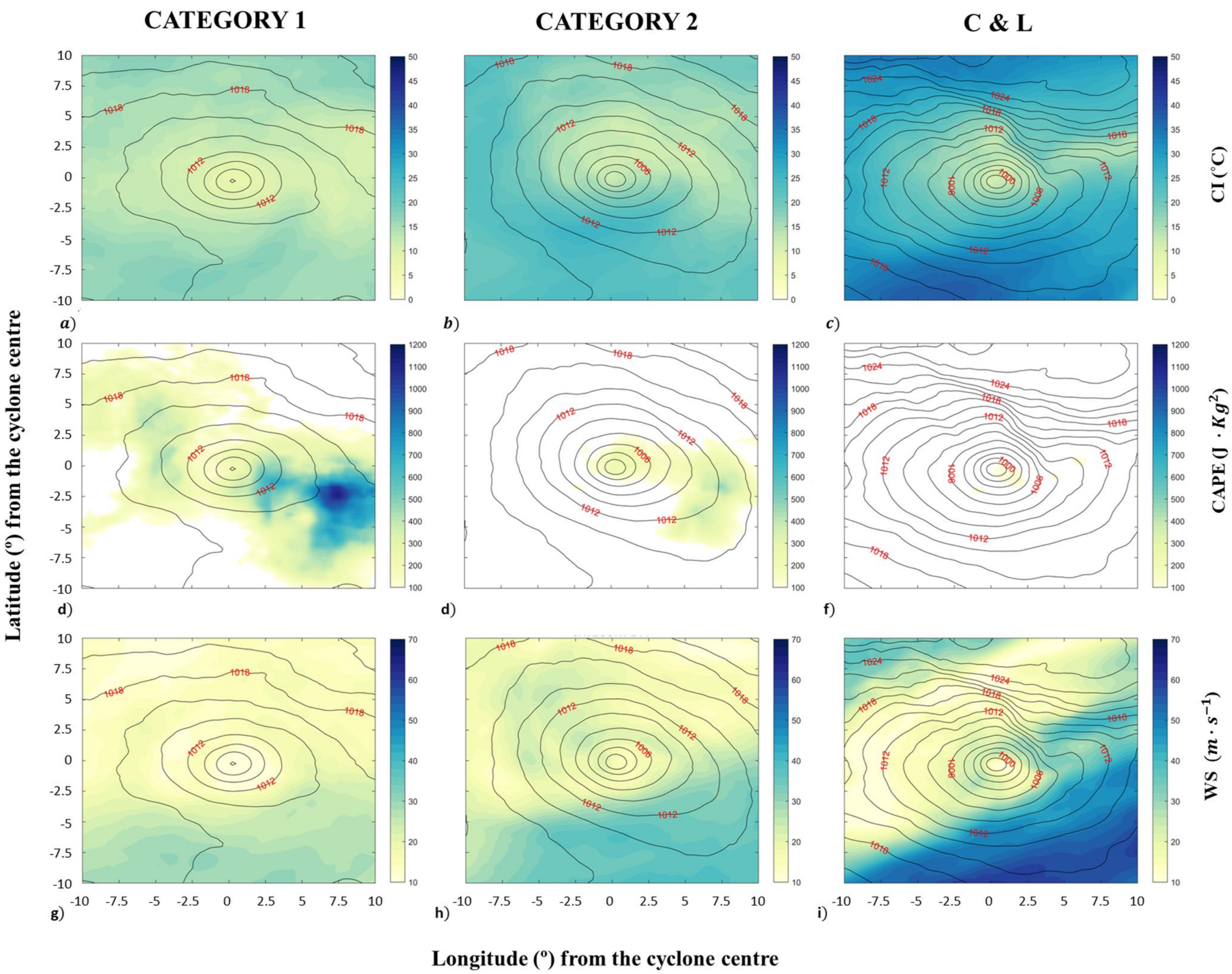

Figure 4. (a) Composite maps of CI (shading; °C) and sea level pressure (contours, hPa) for category 1; d) the same as a) but for CAPE (J kg^{-1}); (g) the same as (a) but for WS (m s^{-1}); the second (third) column shows the same field but for category 2 (Celeno and Leucosia). The composites are calculated over the 24 hr before the cyclones acquire a SDWC.

Celeno and Leucosia have different characteristics from the other categories, considering the very low CAPE, the high baroclinicity and coupling index. Their small size in the mature stage and the intense surface sensible heat fluxes (Figure S1 in Supporting Information S1), possibly due to the occurrence of the two events in January, indicate some similarities of these two cyclones with polar lows (Føre et al., 2012).

4. Conclusions

We used the ERA5 reanalysis to analyze some of the most intense Mediterranean WCCs in the last 40 years to determine the ones showing actual tropical characteristics. In previous works on Mediterranean tropical-like cyclones using the CPS method, all cyclones that acquired a symmetric deep warm core were considered as cyclones with tropical features; however, warm seclusions can also reach a deep warm core (Maue, 2010) and cannot be distinguished using this method. Therefore, here we analyzed several parameters to distinguish the cyclones belonging to the two categories: Tropical-like Cyclones (TLCs) and non-tropical warm-core cyclones.

The main results are:

- The different time evolution of the radius of maximum wind was used to discriminate TLCs from non-tropical warm-core cyclones, since a reduction of the distance occurs in the former category but not in the latter (Table S1 in Supporting Information S1);

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- The classification above is effective in identifying cyclones with different environmental characteristics: TLCs (category 1) have a weaker coupling index, develop in less baroclinic and more unstable environments.
- Two cyclones (Celeno and Leucosia) show a reduction in the radius of maximum wind as they acquire a deep warm core, but other properties are different from Category 1. The stronger sensible heat fluxes and the different values of the environmental parameters (very low CAPE, high baroclinicity) indicate that these cyclones, which developed in January, have peculiar characteristics.

Therefore, these results confirm that not all the cyclones with a deep warm core in the Mediterranean area are cyclones with actual tropical features (Dafis et al., 2020; Miglietta & Rotunno, 2019). We hope that these results will contribute to the ongoing effort of clarifying the definition of "medicanes," which is one of the initiatives of the COST Action on Mediterranean cyclones (https://www.cost.eu/actions/CA19109/).

Data Availability Statement

In this work, all data come from previously published sources. The cyclone tracking is available through Flaounas et al. (2023) and all data for the cyclone characterization have been obtained through Hersbach et al., 2023a; Hersbach et al., 2023b.

Acknowledgments
This work has been funded by the University of Castilla La-Mancha and the European Regional Development Fund, through Grants [2019/5964] and [2021/12543]. The present activity has been developed in the framework of the COST Action 19019 "MEDCYCLONES".

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