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Defining Medicanes: Bridging the Knowledge Gap between Tropical and Extratropical Cyclones in the Mediterranean

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ABSTRACT: The term "Mediterranean tropical-like cyclone" or "medicane" has been used in different ways by different authors. Identification of medicanes has been based on features observed from satellite imagery or on diagnostics applied to numerical weather prediction model outputs. In the absence of an official definition, medicanes are generally considered to be cyclones over the Mediterranean sharing physical processes with tropical cyclones. Nevertheless, recent studies on the dynamics of several systems widely recognized as medicanes show different underlying development mechanisms. A commonly agreed definition is critical and necessary to assess their climatology in past and future climates, as well as to consistently identify such systems in weather forecasts. The scientific community working on Mediterranean cyclones hereby proposes a definition, which is based solely on Earth observations: "A medicane is a mesoscale cyclone that develops over the Mediterranean Sea and displays tropical-like cyclone characteristics: a warm core extending into the upper troposphere, an eye-like feature in its center with spiral cloud bands around, an almost windless center surrounded by nearly-symmetric sea surface wind circulation with maximum wind speed within a few tens of km from the center."

SIGNIFICANCE STATEMENT: Nearly two decades have passed since the term "medicane," short for "Mediterranean hurricane," has become commonly accepted to represent Mediterranean vortices with satellite-observed characteristics typical of tropical cyclones. The absence of an official or commonly accepted definition has created some confusion within the scientific and operational community. To overcome this ambiguity, here, we propose a phenomenological definition that can serve as a reference for future scientific research and operational applications, to be applied to any cyclonic system in the Mediterranean that bears structural similarities to tropical cyclones. This simple definition will assure consistency and, at the same time, can be used with the outputs from numerical models, working as a reference for future scientific research or operational applications.

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1. Introduction

Vortices with satellite-observed characteristics typical of tropical cyclones (TCs), such as cloudless eye-like features surrounded by spiraling clouds and rainbands (Fig. 1), are occasionally observed in the Mediterranean. These storms have been referred to in the past by the terms "hurricane-like cyclone" (Billing et al. 1983; Pytharoulis et al. 1999), "Mediterranean tropical storm" (Ernst and Matson 1983), and "tropical-like cyclone" (TLC; Reale and Atlas 2001). In using these terms, these authors envisioned a specific type of cyclonic vortex over the Mediterranean region that is distinct from the more typical extratropical cyclone (EC) with a comma-shaped cloud system.

Two decades have passed since Emanuel (2005) introduced the term "Mediterranean hurricane," the abbreviation of which, "medicane," has become a commonly accepted term in meteorology, both in the communication to the general public and in the scientific literature. Emanuel (2005) hypothesized that medicanes are maintained by the feedback between surface enthalpy fluxes and wind through the wind-induced surface heat exchange (WISHE) mechanism, similarly to TCs (Emanuel 1986; Rotunno and Emanuel 1987). He applied an axisymmetric, cloud-resolving model to a cyclone case that attained the visual characteristics of a TC within the Ionian Sea in January 1995, to show that the WISHE mechanism yielded a potential maximum intensity comparable to that of an actual TC, supporting the idea that a medicane is analogous to a TC over the Mediterranean.

Emanuel (2005) became the basis for the widely held assumption that medicanes are a separate subgroup of Mediterranean cyclones sharing physical processes with TCs. This assumption was reinforced by several phenomenological similarities between medicanes and TCs: the weakening after landfall (Rasmussen and Zick 1987), the warm-core structure (Lagouvardos et al. 1999), the weak environmental wind shear (Reale and Atlas 2001), and the reduced number of lightning flashes near the center at maturity (Miglietta et al. 2013). Despite these similarities, recent case studies showed that some cyclones widely accepted as medicanes do not only share the same developing mechanisms as TCs but may be also characterized by baroclinic processes, powered by the available potential energy associated with isobaric temperature gradients (e.g., Carrió et al. 2017; Mazza et al. 2017; Fita and Flaounas 2018). Thus, the problem of defining medicanes addresses two main issues for both operational and research purposes: (i) the widely accepted hypothesis that there is a subgroup of Mediterranean cyclones that has unique physical characteristics and should be treated separately from other Mediterranean cyclones for the purposes of operational forecasting and scientific research and (ii) the need to define physical criteria and atmospheric variable thresholds to classify them.

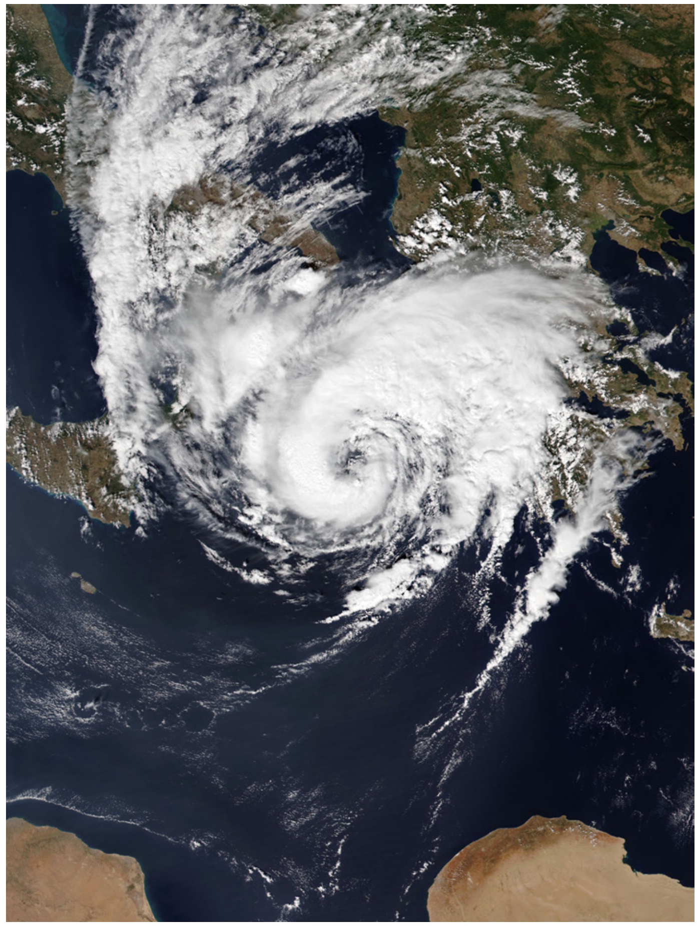

Fig. 1. ***NOAA-20*** **Visible Infrared Imaging Radiometer Suite (VIIRS) corrected reflectance (true color imagery) of Medicane Ianos at 1323 UTC 17 Sep 2020 (credit: https://worldview.earthdata.nasa.gov/).**

To date, the term medicane has been adopted inconsistently among different studies. The absence of an official or commonly accepted definition has created some confusion within the scientific community. For example, it is not clear whether the term should refer only to WISHE-driven cyclones or should include also warm seclusions[1] (e.g., D'Adderio et al. 2024; Gutiérrez-Fernández et al. 2024). Also, some known "medicanes" do not fit clearly in any of these two categories above, as the cases of Daniel (Argüeso et al. 2024) or that of September 2006 (Moscatello et al. 2008; Chaboureau et al. 2012). Consequently, the results of scientific articles on medicanes' physical development processes or climatological features may not be comparable with each other. Moreover, the lack of a definition inhibits clear communication within communities of atmospheric and climate scientists. Pluralism of criteria to identify medicanes also creates confusion among national weather services for issuing warnings of imminent high-impact weather. This confusion has been exploited by social-media sources, private and governmental weather services, or even individuals who have felt entitled to classify newly formed or forecast cyclones as medicanes (https://en.wikipedia.org/wiki/Mediterranean_tropical-like_cyclone).

[1] A warm seclusion is the end result of an EC evolution in the Shapiro and Keyser (1990) cyclone model.

To overcome this confusion, an initiative to define medicanes has been proposed within the framework of the European Cooperation in Science and Technology (EU COST) Action CA19109 "European Network for Mediterranean Cyclones in Weather and Climate" (MedCyclones, 2020–24; https://medcyclones.eu/). For the last 4 years, MedCyclones has been fostering a community effort to discuss the medicane definition, to review the different criteria and tools used to classify cyclones as medicanes, and to propose a definition that can serve as a reference for future scientific research and operational applications.

This paper aligns with these recent community efforts and aims to

1) summarize the different approaches to identify medicanes in the scientific literature;
2) use atmospheric dynamics to discuss the "problem of defining medicanes"; and
3) reconcile previous, inconsistent criteria to identify medicanes and propose a definition for future considerations in operational forecasting, climate analysis, and scientific research.

This effort will also allow a better understanding of the evolution of different Mediterranean cyclone categories and their related processes in a warming sea and atmosphere. Also, because the International Best Track Archive for Climate Stewardship (IBTrACS) keeps a worldwide database (https://www.ncei.noaa.gov/products/international-best-track-archive) for TC and subtropical cyclone tracks, a definition of medicane would help determine which Mediterranean cyclones may be appropriate for inclusion in this database.

The paper is structured as follows. First, a section on climatology and theory provides an overview of the state of the art in the field, including hypotheses on formation and processes relevant to medicane development. Then, we discuss previous criteria for the identification of medicanes and highlight their differences from the perspective of atmospheric dynamics. A definition of medicanes is then proposed explaining its necessity and demonstrating the application of observational tools to identify recent medicane cases.

2. Previous criteria for the identification of medicanes in the scientific literature

In this section, we provide an overview of the criteria used in the past to identify medicanes as weather systems with tropical-like characteristics. These approaches can be broadly grouped into two categories: phenomenological and structural. Phenomenological approaches are empirical, based on observational data, and are often employed not only for later analysis but also for real-time situations. In contrast, structural approaches are based on diagnostic quantities derived from numerical weather model outputs that identify structural characteristics of the cyclones (symmetry, thermal structure) and are often employed in the postevent analysis by research scientists.

a. Medicane identification based on phenomenological criteria. The interest in TLCs in the Mediterranean began as early as they were identified through satellite images. To our knowledge, Ernst and Matson (1983) and Billing et al. (1983) made the first suggestion of tropical-like cyclones in the Mediterranean, based on visible satellite imagery showing cloud structures similar to those in TCs. Figure 1 shows the notable example of Cyclone Ianos (2020) as a recent cyclone that resembles a TC.

Tous and Romero (2013) were the first to perform a systematic detection of medicanes for the period 1982–2003. They used empirical criteria to discriminate medicanes from other cyclones in infrared satellite imagery. Their criteria were the presence of a continuous cloud cover and symmetric shape, organized around a clear cloudless "eye" that resembles that of TCs, and a diameter smaller than 300 km. This approach resulted in a list of six medicanes, complemented by six additional cases that did not fully comply with the above criteria but that had been "revealed" as medicanes in previous studies. Therefore, Tous and Romero (2013) concluded medicanes to be rather rare events with a frequency of occurrence of the order of very few cases per year.

Tous and Romero (2013) also provided the first systematic effort for a climatological detection of medicanes based on empirical approaches. Their study summarized the highly influential works of the 2000s and early 2010s from the meteorology group of the University of the Balearic Islands (UIB). In this framework, UIB maintained a website that identified

43 Mediterranean cyclones with tropical-like features from 1982 to 2008 (https://meteorologia.uib.eu/medicanes/index.html), setting the standards for the climatological frequency of occurrence of medicanes. Until now, the phenomenological approach has been functioning as the main reference to qualify cyclone cases as medicanes.

No other study provided a consistent climatological identification of medicanes based on satellite imagery. However, within this framework, Nastos et al. (2018) provided a series of 63 case studies that have been identified as medicanes because of their substantial socioeconomic impacts combined with a relatively clear spiral cloud coverage detected in Meteosat images.

Several cyclones have been referred to as medicanes in the past decades by various sources originating from the public media or the scientific community. Although there is no official designation for such storms in the traditional TC naming conventions, a few notable examples of real-time satellite intensity analyses on medicanes have been provided by the National Oceanic and Atmospheric Administration (NOAA). This provides some evidence that automatic intensity estimates provided by NOAA, such as the Dvorak (1984) technique for TC intensity estimation and the Hebert and Poteat (1975) technique for subtropical cyclone intensity estimation, may be applied to track medicanes, suggesting that a procedure similar to the one adopted by the National Hurricane Center could be possible. Nevertheless, the phenomenological approach remains empirical, including systems with different developing mechanisms; hence, it has no physical basis, as discussed in the next sections.

b. Medicane identification based on structural criteria. In contrast to the phenomenological approach, structural criteria have been more recently employed to identify medicanes. The primary tool in this approach has been the cyclone phase space (CPS) diagrams, a diagnostic tool developed by Hart (2003) that applies to model outputs (e.g., renanalysis or forecast simulations). This method requires as input the track of the selected cyclone (i.e., the location of its center in consecutive model outputs) and the geopotential fields at every track point to determine whether the cyclone is axisymmetric (or not) and whether it has a warm or cold core with respect to its environment in the lower and upper troposphere. The appendix provides more details on the diagnostic method of CPS diagrams.

The study by Gaertner et al. (2007) was the first to employ CPS diagrams to analyze Mediterranean cyclones with tropical characteristics, in the context of climate change simulations. Cavicchia et al. (2014) extended the use of CPS diagnostics to analyze medicanes in a climatology. They also identified the most affected areas and the large-scale conditions favorable for their development. Because the relatively coarse resolution of the reanalysis does not represent smaller-scale cyclones properly, Cavicchia et al. (2014) used a regional climate model to downscale the NCEP reanalysis to 10-km horizontal grid spacing in the period 1948–2011. They found that the frequency of medicane occurrences was about 1.5 cases per year, similar to the number of TLCs in the UIB website identified through a phenomenological approach. Similar structural approaches have been more recently employed by Gaertner et al. (2018), Ragone et al. (2018), Zhang et al. (2021), and de la Vara et al. (2021). In all these studies, cyclone intensity criteria were used in addition to CPS diagnostics to discriminate medicanes as the strongest systems among the ones diagnosed as deep warm-core, axisymmetric cyclones. In fact, the additional criteria on cyclone intensities tune the number of medicanes (Cavicchia et al. 2014; Ragone et al. 2018) to match the rarity of medicane occurrences in the UIB website (i.e., 0–5 cases per year).

Finally, the aforementioned studies used different modeling approaches and applied different criteria and configuration thresholds (e.g., in terms of cyclone tracking methods, CPS diagram parameters, pressure gradient, maximum wind intensity and duration, warm anomaly intensity). Therefore, the application of such criteria led to inconsistent lists of medicanes.

This implies a certain weakness of the diagnostic methods to match cyclones identified phenomenologically as medicanes, which also suggests a high sensitivity of the physical structure and of the intensity of resolved Mediterranean cyclones to the selected criteria.

3. Past identification of medicanes under the prism of governing atmospheric processes

In this section, we discuss, in conjunction with the phenomenological and structural approaches, the main atmospheric processes that have been suggested to govern the development of cyclones identified as medicanes. Thus, our aim is to provide physical context to the problem of defining medicanes rather than making a relevant overview of scientific literature. A more detailed description of the state of the art on the processes of Mediterranean cyclones, including medicanes, has been recently provided in the review article by Flaounas et al. (2022).

a. On the applicability of tropical cyclone dynamics to medicanes. Both phenomenological and structural approaches consider medicanes as cyclones sharing similar—if not the same—development mechanisms with actual TCs. Therefore, medicanes have been traditionally expected to comply with the dynamics of TCs rather than the dynamics of ECs. In this framework, the similarity of some medicanes to the weak Atlantic baroclinically induced TCs that experience tropical transition[2] (Davis and Bosart 2004) was discussed in Dafis et al. (2020).

Most of our knowledge on medicane dynamics stems from past cyclone cases, several of them analyzed in many scientific articles, mainly through limited-area model simulations. Emanuel (2005) and Fita et al. (2007) used idealized simulations of an axisymmetric model that resolves TC dynamics according to the WISHE mechanism, in which an initial deep, cold cutoff low over the relatively warm Mediterranean—generally associated with the southern intrusion of the polar jet (Miglietta et al. 2017)—works as an ideal embryo for incubating these tropical-like cyclones. The interpretation of medicanes as actual TCs depends upon the direct applicability of the WISHE mechanism.

Fita et al. (2007) focused on seven cyclone cases, which have been phenomenologically identified as medicanes. All seven cases have been shown to attain a theoretical maximum wind speed (calculated as the potential intensity for TCs; Bister and Emanuel 1998) comparable to the one of TCs. Nevertheless, Fita et al. (2007) highlighted the limitations of the axisymmetric model to realistically reproduce medicanes. For instance, they found remarkably inconsistent development time scales between the observations and the axisymmetric model.

In the WISHE mechanism, the vertical thermal gradient between the sea surface temperature (SST) and the upper troposphere is critical for the development of TCs. According to their own phenomenological and physical criteria, Tous and Romero (2013) and Cavicchia et al. (2014) found no significant anomalies in SST prior to or during the development of the identified medicanes. Indeed, most of the identified medicane cases have formed over SSTs well below 26.5°C (Miglietta et al. 2013) because cold-air intrusions in the extratropics may increase the temperature difference between the sea surface and the tropopause, thus increase the conversion efficiency of thermal energy into mechanical energy (Palmén 1948), making possible the development of medicanes even in January. This is consistent with TCs that develop at relatively high latitudes in the subtropics from a baroclinic precursor under conditions of strong tropical transitions, where the SST threshold for tropical cyclogenesis is reduced to 24.3°C (McTaggart-Cowan et al. 2015). Still though, such a threshold value is rarely met homogeneously in large maritime areas in the Mediterranean Sea, especially in seasons other than late summer/fall when most medicanes develop.

[2] With tropical transition, we refer to cyclones where "a fundamental dynamic and thermodynamic transformation of an extratropical precursor (of baroclinic origin and initially considered a cold-core system) is required to create a warm-core TC" (Davis and Bosart 2004).

The hypothesis of medicanes developing according to the WISHE mechanism has been discussed in several papers (e.g., Lagouvardos et al. 1999; Moscatello et al. 2008; Tous et al. 2013; Argüeso et al. 2024) and recently tested by Miglietta and Rotunno (2019). The authors performed numerical sensitivity tests for two prominent case studies of Mediterranean cyclones, both identified phenomenologically as medicanes by Tous and Romero (2013), both diagnosed as deep, symmetric warm-core cyclones in CPS diagrams, and both simulated by the axisymmetric TC model in Fita et al. (2007). Numerical sensitivity tests were performed by turning off the surface heat fluxes (i.e., negating cyclone development according to the WISHE mechanism). Results showed that one of the cases developed due to baroclinic processes regardless of turning off the surface heat fluxes, whereas intensification was strongly inhibited in the other case. Consequently, the WISHE mechanism may not apply to all cyclones that present phenomenological resemblances to TCs or attain warm-core structures.

b. Role of extratropical cyclone dynamics in medicane development. The hypothesized direct relevance of TC-like dynamics to medicanes has obscured the important role of baroclinic forcing in Mediterranean cyclogenesis. In fact, almost all cases identified as medicanes in the scientific literature have been initiated by baroclinic processes (Flaounas et al. 2022), typically retaining the presence of a cutoff low or an upper-tropospheric system close to their center, in some cases even around the stage of maturity (i.e., stage of maximum intensity). For instance, Fita and Flaounas (2018) and, more recently, Emanuel et al. (2025) focused on the similarities of some medicanes with subtropical cyclones; Emanuel (2005) and Fita et al. (2007) stressed the importance of upper-tropospheric systems for the potential intensity of medicanes. Fita et al. (2007) concluded that "tropical-like Mediterranean storms grow and evolve from a combination of deep convection and typical midlatitude baroclinic processes," suggesting the importance of large-scale forcing together with a "SST-controlled boundary layer."

The important role of large-scale circulation in the development of cases recognized as medicanes has been stressed in several case studies. For instance, the interaction of a jet streak with the cyclone may favor its rapid or even explosive intensification, either induced by barotropic processes (Reale and Atlas 2001) or by convection on the favorable left-exit side of the jet (Chaboureau et al. 2012). The case of Ianos (2020), which has been considered a TC in terms of intensity and dynamics (Lagouvardos et al. 2022), has been reproduced by atmospheric models only when the jet streak was accurately located with respect to the cyclone center (Sánchez et al. 2024; Pantillon et al. 2024). Potential vorticity (PV) streamers (i.e., narrow, elongated filaments of high-PV air near the tropopause, direct result of preceding Rossby wave breaking, that correspond to southern deviations of the polar jet; Raveh-Rubin and Flaounas 2017) control the coupling with the low levels and determine the exact location and intensity of the cyclones (Cioni et al. 2016; Kouroutzoglou et al. 2021), affecting the medium-range predictability. For example, short-wave perturbations on the North Atlantic waveguide 3–7 days before the development of intense medicanes dramatically affected their subsequent evolution (Pantillon et al. 2013; Di Muzio et al. 2019; Portmann et al. 2020).

Only recently, PV diagnostics were employed to quantify the relative contributions of diabatic and baroclinic processes to the development of several cases of medicanes. Carrió et al. (2017), Flaounas et al. (2021), and Givon et al. (2024) found that a combination of diabatic and baroclinic forcing was relevant to the development of several renowned medicane cases (identified as such in several past studies through phenomenological or structural approaches).

c. On the limitations of CPS diagrams to attribute unique development mechanisms to medicanes. The use of CPS diagrams has provided a straightforward diagnostic tool to characterize medicanes as deep warm-core systems with the axisymmetric structure, hence as a direct equivalent to TCs. As discussed in the previous section, medicanes are expected to initially develop through baroclinic processes. For example, Zhang et al. (2021, their Fig. 2a) showed that the medicanes identified according to CPS diagnostics develop within a baroclinic environment and later through the synergy between baroclinic and diabatic processes. Consequently, CPS diagrams diagnose medicanes showing a gradual change from cold-core to deep warm-core systems. This has been regarded in several studies as an indication of tropical transition (e.g., Chaboureau et al. 2012).

However, some studies question the adequacy of CPS diagrams to diagnose cyclone development mechanisms. A notable example of CPS limitations resides in the diagnosis of warm seclusions as actual axisymmetric, warm-core systems. Mazza et al. (2017) and Fita and Flaounas (2018) analyzed the dynamics of two cases that have been widely renowned as medicanes according to phenomenological criteria, showing that the diagnosis of a warm core through CPS diagrams was due to a warm seclusion. Therefore, CPS diagrams are unable to distinguish the processes leading to different physical characteristics of cyclones and thus to identify whether the warm core is due to diabatic forcing associated with deep convection or is associated with the last phase of the life cycle of an EC.

For medicanes, traditionally considered to be of smaller size than TCs or ECs, several studies proposed to change the CPS diagnostics accordingly, thereby using shallower vertical layers (e.g., Picornell et al. 2014), and a diagnostic radius smaller than 500 km, as originally used by Hart (2003). For instance, Miglietta et al. (2011) used a radius of 100 km, and Fita and Flaounas (2018) used a radius of 250 km. Such radii are smaller than the characteristic length scale of frontal structures and upper-tropospheric systems. Therefore, the diagnostic parameters B (the storm-motion relative 900–600-hPa thickness asymmetry) and $-V_T^U$ (the thermal-wind magnitude in the upper troposphere; see the appendix) may be misleading for the diagnosis of symmetric or upper warm-core structures. These considerations need to be taken into account in future studies. Nevertheless, CPS diagrams have benefitted the field of Mediterranean cyclones by providing a link with other communities working on tropical transitions, they have assured continuity between different studies on medicanes, and they have given a more objective context with respect to the phenomenological identification of medicanes that largely resides on arbitrary and empirical approaches.

4. Reconciling past approaches to the identification of medicanes and proposing a definition

One major challenge in reaching a definition of medicane is the reconciliation of the phenomenological and structural approaches to medicanes. The first is arbitrary and solely based on Earth observations, appropriate for forecasters that need real-time information for warning and tracking; the second is model dependent and largely based on CPS diagrams and is more suitable for researchers. Both approaches have served the cause of setting foundations for the development in the field. In parallel, the combined use of these two approaches poses limitations to further advancements, due to studies often reaching inconsistent results and to the impossibility of compiling a definite list of well-established cases. This makes it challenging to understand their long-term behavior and trends. In our opinion, a medicane definition is necessary that needs to fulfill two criteria.

- Be solely based on Earth observations. This will grant consistency in the identification of cyclones as medicanes and assure reproducibility by models. Therefore, a definition will favor exchanges between weather services about issuing warnings. In addition, Earth observations will assure equal accessibility to the means that define medicanes.
- The term medicane has become commonly accepted in meteorology, both in communication to the general public and in scientific literature and is associated with an event

characterized by strong intensity and impact. Considering that it may not be easy to discriminate the development mechanisms of different cyclones in real time from a phenomenological or a structural perspective, a definition that includes a wider number of cyclones could be useful to generate attention from public authorities responsible for civil protection actions and from the general public in potentially dangerous cases, going in the direction of an impact-based forecasting approach encouraged by the World Meteorological Organization (WMO).

Such a definition will be accommodating to previous, most renowned studies that defined medicanes either using phenomenological or structural criteria. Otherwise, a definition would have to challenge the validity of previous results, which will still be used as a basis in forthcoming or future studies. Most importantly, an accommodating definition will assure continuity in the field of research on medicanes.

Taking into account the above criteria, we propose the following definition:

A medicane is a mesoscale cyclone that develops over the Mediterranean Sea and displays tropical-like cyclone characteristics: a warm core extending into the upper troposphere, an eye-like feature in its center with spiral cloud bands around, an almost windless center surrounded by nearly-symmetric sea-surface wind circulation with maximum wind speed within a few tens of km from the center.

Hence, the terms medicane and Mediterranean tropical-like cyclone should be considered equivalent. This definition has several benefits over the older approaches.

- It recognizes the existence of a deep warm core regardless of the generation process, following the indications from early studies (e.g., Fita et al. 2007) that WISHE is not expected to exclusively contribute to the development of a medicane (as discussed in section 4.2 in Flaounas et al. 2022).
- It assumes that medicanes do not correspond to systems of homogeneous physical characteristics and do not develop according to a unique physical mechanism. In fact, this definition includes warm-core cyclones that are structurally similar to TCs in several ways such as tropical transitions, subtropical cyclones, and warm seclusions; the climatological identification of different subcategories of medicanes requires dedicated climate studies that should be among the main research perspectives in the field.
- Consequently, our definition is accommodating different subcategories of medicanes, as suggested by Miglietta and Rotunno (2019), and is not excluding CPS diagrams as useful numerical tools for the diagnosis of medicanes in climatological model datasets or case studies.

From genesis to cyclolysis, a hypothetical trajectory in CPS space can be identified that depicts the relative contribution of baroclinic forcings to sustain the cyclonic circulation in the different stages of development. Belonging to this continuum, medicanes should be expected to follow a trajectory that gradually places a cyclone from a stage of a baroclinically driven cyclone (as EC) to either a mostly, if not entirely, surface-flux-driven cyclone or a warm seclusion. However, diabatic and baroclinic processes may contribute differently to the development of medicanes depending on the case (e.g., Flaounas et al. 2021; Givon et al. 2024).

Note that this definition does not include all intense Mediterranean cyclones. Storm "Vaia" (Davolio et al. 2020) is an example of an extratropical cyclone of significant intensity and impact (with maximum precipitation, during the 3 days of the event, reaching almost 900 mm in the eastern Alps and wind gusts exceeding 200 km h^{-1}, responsible for extensive damage to forests over an area of 41 000 ha), which did not meet any criteria in the definition of medicane, since it does not show a warm core, an eye-like feature at its center, an almost windless center surrounded by a nearly symmetric sea surface wind circulation.

5. Examples of diagnosis of medicanes using Earth observations

Polar-orbiting satellite measurements can be used to identify the key features of medicanes such as the occurrence, extent, and distribution of the warm core (Panegrossi et al. 2023; D'Adderio et al. 2024) and of the surface wind field (Tiesi et al. 2021). Although these techniques open new perspectives on the analysis of the cyclone properties, they are limited by the discontinuous spatial and temporal coverage of polar-orbiting satellites. In the following, we rely on previous studies to highlight examples of medicane identification using Earth observations.

a. Diagnosis of warm-core structure. Recently, Panegrossi et al. (2023) and D'Adderio et al. (2024) applied a well-established methodology to Mediterranean cyclones widely recognized as medicanes, aiming to diagnose their warm-core structure. The applied method has been originally developed for TCs (Brueske and Velden 2003) and is based on brightness temperature (BT) anomalies in temperature sounding channels in the oxygen absorption band from 50 to 60 GHz. Among the analyzed cyclones, medicanes Zorbas (2018) and Ianos (2020) showed persistent, deep warm-core structures in their mature stages, associated with the latent heat release due to deep convection. Figure 2 (left) shows the deep warm-core structure in the mature stage of Ianos as a distinct warm BT anomaly at three levels of the

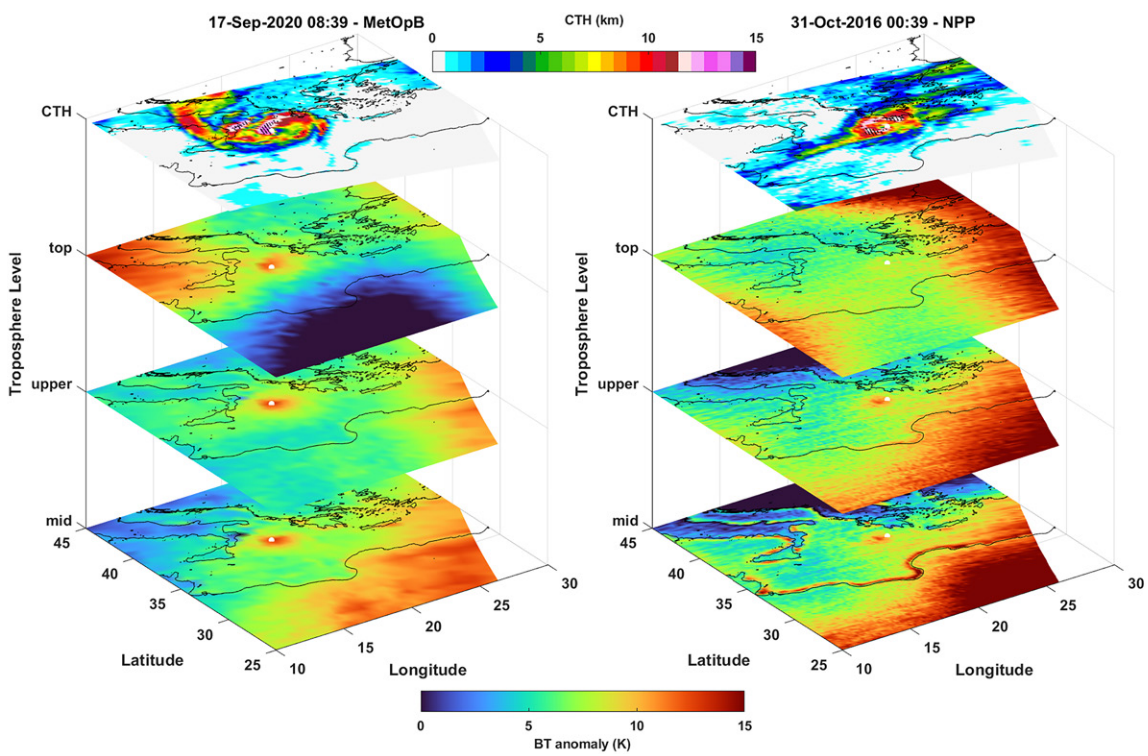

Fig. 2. BT anomalies, CTH, and deep-convection occurrences (black dots) derived from microwave humidity sounder high-frequency channels [see Panegrossi et al. (2023) for details] for (left) Ianos and (right) Trixie. Mature phases are shown for each medicane (for Ianos, AMSU-A pass at 0839 UTC 17 Sep 2020 and for Trixie, Advanced Technology Microwave Sounder (ATMS)–SNPP pass at 0039 UTC 31 Oct 2016). The white dot shows the position of the ERA5 mean sea level pressure minimum. The mid, upper, and top levels correspond to the peak of the weighting function (which indicates the height providing maximum contribution to the microwave radiation measured by the radiometer) for the different channels, which are approximately at 450–400, 350–300, and 250–200 hPa.

upper troposphere (see Panegrossi et al. 2023 for details). The figure also shows the cloud-top height (CTH) (Rysman et al. 2022) and deep-convection pixels (black dots; Hong et al. 2005) derived from passive microwave humidity sounder channels, suggesting the key role of diabatic forcing in the formation of the warm core. Other medicanes showed a shallower warm core and a reduced occurrence of deep convection (as in subtropical cyclones and warm seclusions, respectively): Fig. 2 (right) illustrates that the latter is the case for the mature stage of Cyclone Trixie.

b. Diagnosis of symmetric wind field. Here, we show evidence of a symmetric wind field around Ianos. Figure 3a shows Ianos near-surface wind fields as retrieved from ASCAT over the Ionian Sea just before landfall over Greece (i.e., when the cyclone is in its mature stage on the evening of 17 September 2020, about 12 h later, the warm-core detection in the left panel of Fig. 2). The wind field shows a nearly symmetric distribution with maximum wind close to the cyclone center. However, the relatively coarse resolution and the limitation of the retrieval algorithm at high wind speed may underestimate the maximum wind speed, and the cyclone's proximity to land may affect the diagnosis of wind speed symmetry. An assessment of the case of Trixie suggests that the wind is less axisymmetric at the time shown in Fig. 3 (right), due to a much stronger wind maximum on the west side [a similar asymmetry is observed at other times in the synthetic aperture radar (SAR) retrievals from Avenas et al. (2025, manuscript submitted to *Quart. J. Roy. Meteor. Soc.*)]. Therefore, Trixie satisfies all the requisites for the definition of medicane, except for the nearly symmetric sea surface wind circulation. This stresses that a clear identification is not always straightforward. Application of our definition may still classify cyclones within a "gray zone," revealing a continuum of cases between "ordinary" Mediterranean cyclones and medicanes.

Additionally, wind speed in medicanes, as well as the location of atmospheric fronts evidenced by rain signatures (Colin and Husson 2024) and by discontinuous wind speed or direction, can be derived from SAR. Although *Sentinel-1* satellites acquire data over European waters, the limited area scanned by these polar-orbiting satellites, as well as the small extent of medicanes, make it difficult to acquire frequent retrievals useful for the detection of wind structures as in TCs. Yet, five Mediterranean warm-core cyclones (Trixie, Helios, Numa, Apollo, Blas) have been collocated with 17 *Sentinel-1* acquisitions to date, allowing observations of their wind field and orientation of wind streaks (i.e., the sea surface imprints of atmospheric boundary layer rolls approximately aligned with the mean wind direction). Despite the discontinuities in wind direction or frontal structures observed in several SAR

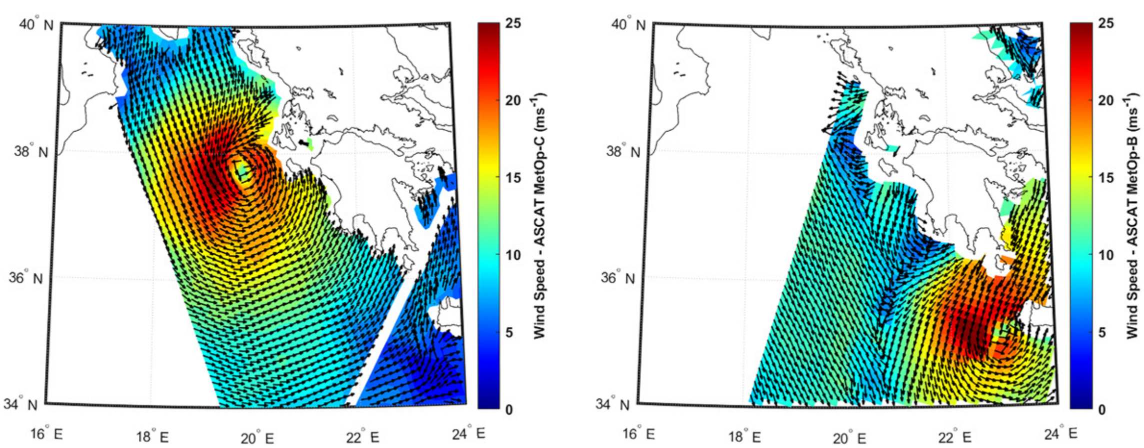

Fig. 3. Surface wind speed retrieved from *METOP-C* ASCAT (12.5-km grid spacing) images centered (left) at 2057 UTC 17 Sep 2020 (during the most intense phase of Ianos) and (right) at 0919 UTC 30 Oct 2016 (in the mature stage of Trixie) (source: OSI SAF). Wind direction is obtained from the ERA5 reanalysis (arrows are not scaled with wind speed).

images, sometimes detached from the cyclone center as in the case of warm seclusions, these cyclones are still considered as fulfilling the medicane definition.

For instance, Fig. 4 shows Cyclone Blas during its mature stage, approaching Elba Island and the Tyrrhenian coast of central Italy on 15 November 2021. The cyclone center south of the Elba Island shows weaker wind speeds. A clear wind direction discontinuity can be identified around it in the northwestern quadrant, which differentiates this circulation from the circularly symmetric flow generally observed for mature TCs.

The SAR image on 26 October 2021 of the mature stage of Cyclone Apollo near Sicily (Fig. 4b) shows a closed-shaped storm center, a frontal structure on the eastern side, and heavy rain signatures along the boundary—revealed by bright and/or dark patches—resulting from different contributions of the sea surface roughness (i.e., increased or decreased surface scattering) or the atmosphere (volume scattering or attenuation by hydrometeors). One may expect that tropical transitions, such as Zorbas and Ianos, should show a stronger similarity to the circularly symmetric circulation typical of a TC; unfortunately, SAR images were not available for these two cyclones. In conclusion, SAR images can be helpful to identify the detailed wind pattern and differentiate among the different categories of medicanes, especially when they will assure a more frequent spatial and temporal coverage.

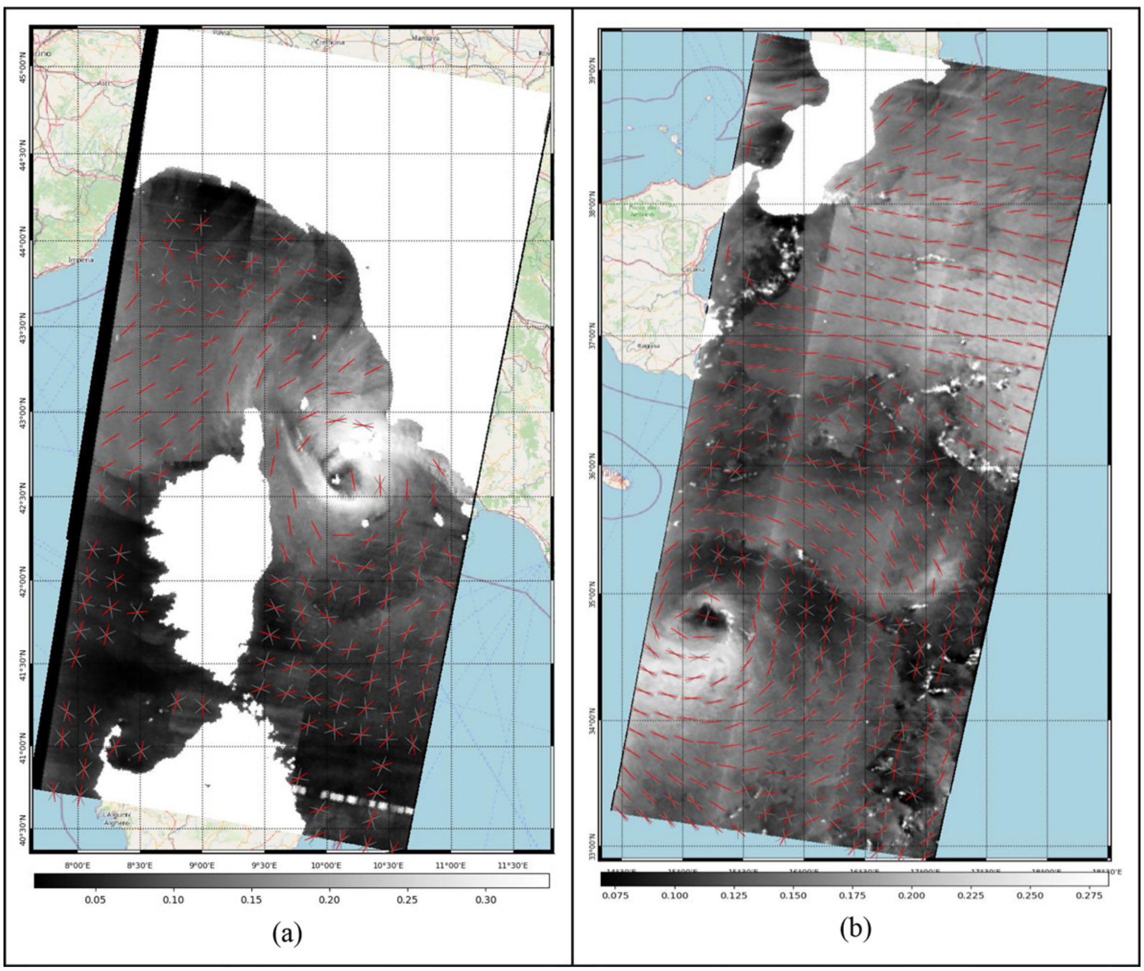

Fig. 4. ***Sentinel-1*** **acquisition of (left) Blas (near Corsica) at 0527 UTC 15 Nov 2021 and (right) Apollo (south of Sicily) at 1647 UTC 26 Oct 2021. The grayscale image shows the detrended sea surface roughness (dimensionless) for the VH polarization, while the red bars indicate the wind streaks orientation derived from the SAR image texture. Two gray bars are added around each red bar to form a cone which corresponds to the standard deviation error associated with the estimation of the orientation (Husson et al. 2021). Maximum sustained wind speed measured from SAR reaches 29 m s^{-1} for (left) Blas and 23 m s^{-1} for (right) Apollo, respectively. These wind speeds are estimated from the SAR data based on a dual-polarization wind inversion, well suited for high wind regimes (Mouche et al. 2019).**

6. Conclusions

This paper addresses the growing interest in quantifying the gray zones between different categories of Mediterranean cyclones. Recognizing that the term medicane has been widely used in the past to represent cyclones with diverse development mechanisms, here, we propose the term "medicane" to be used for the characterization of any cyclonic system in the Mediterranean that bears structural similarities to TCs. As such, medicane refers to systems driven by different development mechanisms. Therefore, this definition includes systems that develop deep warm cores and symmetric wind fields due to both diabatic and baroclinic forcing, in other words, a sole or combined outcome of the WISHE mechanism and baroclinic processes [broad categorization and example cases of physical mechanisms are provided in Miglietta and Rotunno (2019)]. Thus, a medicane is a warm-core cyclone that might have phenomenological, structural, or physical characteristics similar to polar lows, warm seclusions, subtropical cyclones, or even tropical cyclones.

Thus, the definition we provide is purely based on a phenomenological approach. Conversely, from the perspective of the development mechanism, some medicanes have been recently proposed to belong to the category of "cyclones from locally originating potential intensity" (CYCLOPs; Emanuel et al. 2025), including also polar lows, subtropical cyclones, Kona storms, and some Australian east coast cyclones. CYCLOPs are cyclones partially or fully driven by surface enthalpy fluxes, as TCs, but the potential intensity supporting their development is not present in the prestorm environment, as it is the case of TCs, but rather generated locally during their development. It should be clear that our definition of medicane encompasses cyclones developing in very different environmental conditions, as discussed in Gutiérrez-Fernández et al. (2024), including Mediterranean cyclones with different development processes, among which CYCLOPs.

Being based on Earth observations, the simple definition proposed here will assure consistency while, at the same time, the cyclone structure may be diagnosed by numerical models, since it is independent of the specific development process. Also, this definition accommodates the classification of some cyclones as medicanes in previous studies, assuring continuity in the field of research. Thus, we expect that this definition will solve the confusion within the scientific community and operational weather services, working as a reference for future scientific research or operational applications.

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Data availability statement. This study contains modified Copernicus *Sentinel-1* data; *Sentinel-1* is part of the European space component of the Copernicus European program (https://www.copernicus.eu). The SAR images/products were obtained from Collecte Localisation Satellite (CLS) company and produced with SAR wind processor codeveloped by CLS and IFREMER from the level 1 GRD products freely downloaded from the Copernicus Open Access Hub (https://scihub.copernicus.eu/). ECMWF is gratefully acknowledged for the analyses that served to produce Figs. 2–4 and A1.

APPENDIX

Cyclone Phase Space Diagram

The cyclone phase space (CPS) diagram is a tool useful to represent the evolution of the cyclone characteristics (Hart 2003). The diagram is based on three parameters (B, $-V_T^L$, and $-V_T^U$) evaluated in a radius of 500 km around the cyclone center. The term B represents the storm-motion relative 900–600-hPa thickness asymmetry across the cyclone and determines whether the cyclone structure is asymmetric (EC) or symmetric (TC). A threshold of $B = 10$ m has been identified for the distinction between the two categories. The other two parameters

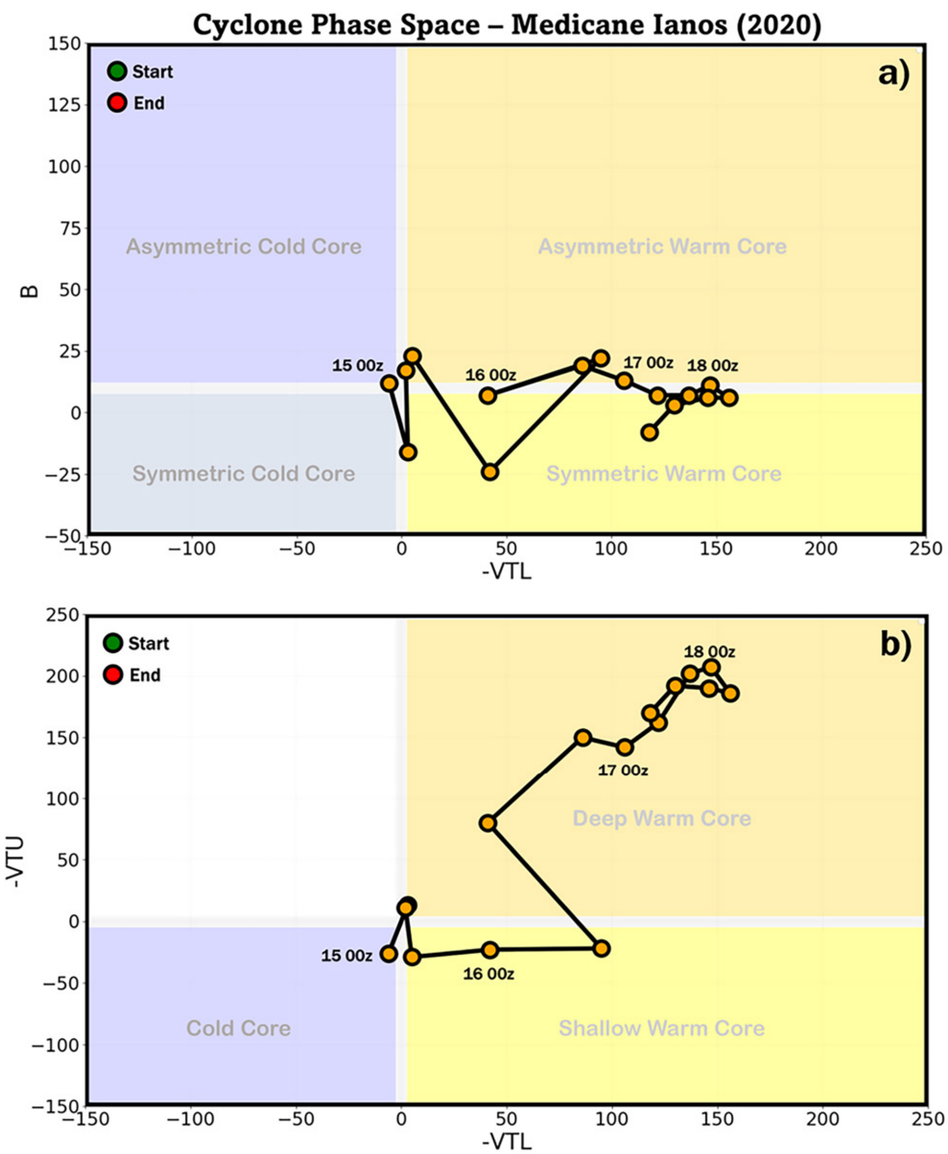

Fig. A1. CPS diagrams for Medicane Ianos: (a) B (900–600 hPa) vs. $-V_T^L$ (900–600 hPa) and (b) $-V_T^U$ (600–300 hPa) vs. $-V_T^L$ (900–600 hPa). Here, the values are calculated within a 150-km radius around the minimum mean sea level pressure in the operational 6-h ECMWF analyses from 0600 UTC 15 Sep to 0000 UTC 20 Sep 2020. The labels DD HHz indicate the date (DD) and hour (HH; UTC).

evaluate the thermal-wind magnitude in the lower (900–600 hPa) and upper (600–300 hPa) troposphere ($-V_T^L$ and $-V_T^U$, respectively). These parameters identify if the gradient of geopotential anomalies increases or decreases with height. Therefore, the identification of cold-core (EC) and warm-core (TC) structures in the lower and upper troposphere is based on thermal-wind balance.

The phase space is usually represented using two diagrams: $-V_T^L$ versus B and $-V_T^L$ versus $-V_T^U$. The full life cycle of a cyclone is defined through the trajectory in these phase diagrams. A TC is a thermally symmetric, deep warm-core cyclone (i.e., $-V_T^L$ and $-V_T^U$ greater than 0), thus belonging to the lower-right side of the first diagram and to the upper-right quadrant of the second diagram (Fig. A1).

For mesoscale cyclones such as medicanes, a smaller radius is usually employed to compute the parameters; also, some minor adaptations to the vertical layers where the parameters are calculated were proposed in Picornell et al. (2014).

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