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Discussions

Detection and thermal description of medicanes from numerical simulation

M. A. Picornell[1], J. Campins[1], and A. Jansà[2,*]

[1]Agencia Estatal de Meteorología, Palma de Mallorca, Spain
[2]Universitat de les Illes Balears, Palma de Mallorca, Spain
[*]formerly at: Agencia Estatal de Meteorología, Palma de Mallorca, Spain

Correspondence to: M. A. Picornell (mpicornella@aemet.es)

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Abstract

Tropical-like cyclones rarely affect the Mediterranean region and they can produce strong winds and heavy precipitations. These warm-core cyclones, called MEDICANES (MEDIterranean hurriCANES), are small size, develop over the sea and are infrequent. For these reasons, the detection and forecast of medicanes are a difficult task and many efforts have been devoted to identify them.

The goals of this work are to contribute to a proper description of these structures and to develop some criteria to identify medicanes from numerical weather prediction (NWP) model outputs. To do that, existing methodologies for detecting, characterizating and tracking cyclones have been adapted to small-scale intense cyclonic perturbations. First, a mesocyclone detection and tracking algorithm has been modified to select intense cyclones. Next, the parameters that define the Hart's cyclone phase diagram are tuned and calculated to examine their thermal structure.

Four well-known medicane events have been described from numerical simulation outputs of the ECMWF model. The predicted cyclones and their evolution have been validated against available observational data and numerical analyses from literature.

1 Introduction

In the Mediterranean region intense and small cyclonic storms develop from time to time (Jansà, 2003). Some of them have features of tropical cyclones: they originate and develop over the sea, present a warm-core structure and in most of the cases they have a clear eye surrounded by a convective eye-wall cloud pattern. These quasi-tropical cyclones have been identified as MEDIterranean hurriCANES or MEDICANES, by their common characteristics with hurricanes. They are related to severe weather phenomena as strong winds and heavy precipitations, which can cause damages, especially in maritime navigation or when they make landfall in coastal areas. Heat exchanges, mainly from convective processes and air-sea interaction, play a key role in the for-

mation and maintenance of medicanes. Medicanes usually develop under deep upper tropospheric troughs, in regions of small baroclinity but large air-sea thermodynamic disequilibrium associated with the trough (Emanuel, 2005).

In the last years, much effort has been devoted to investigate different aspects of the medicanes. Some medicane events have been analysed in depth by several authors, in order to document the appearance and evolution of these vortexes from observations and to explore physical mechanisms associated to their formation and maintenance from numerical simulations. At least three medicane events were recorded in the eighties (Ernst and Matson, 1983; Jansà, 1987; Rasmunssen and Zick, 1987), although three more cases during this period are included in recent lists (Tous and Romero, 2011, 2013). In mid January 1995, a well-studied example of medicane occurred in the Ionian Sea. Its evolution and track is described in detail in Lagouvardos et al. (1999) and Pytharoulis et al. (2000). A small quasi-tropical cyclone that affected the Balearic Islands in September 1996 is described in Gili et al. (1997). This event was numerically simulated by Homar et al. (2003). More recently, another well-known medicane occurred on 26 September 2006 and it has been described in several papers (Moscatello et al., 2008; Davolio et al., 2009; Chaboureau et al., 2012, among others). In this last work any possible tropical transition of the cyclone is identified by projecting it into the cyclone phase space and jet crossing is described as a new key mechanism for this transformation.

On the other hand, the atmospheric environments that favour the development and maintenance of medicanes have been studied from different points of view. In Fita et al. (2007) an axisymmetric numerical model was used to do that, complemented with sensitivity analyses with a 3-D model. The characteristics of precursor and non-precursor cyclonic environments for medicane development were studied in Campins et al. (2009). An empirical genesis index, GENPDF, has been also introduced to estimate or forecast the likelihood of medicane genesis (Romero and Emanuel, 2006; Tous and Romero, 2011, 2013). All these papers support the idea that medicanes usually form in areas with a deep, cut-off, cold-core cyclone at upper levels and with strong

convection activity. Surface heat and moisture fluxes play a key role in their development.

Remote sensing products in general and satellite pictures in particular are valuable instruments to detect these cyclones and to observe their tracks, and appropriate numerical weather prediction (NWP) models are essential to forecast medicanes, as already Mayençon (1984) pointed out. The rarity of these phenomena, their maritime character and their small size make the systematic detection and forecast of medicanes a difficult task. For this reason, studies focused to perform a medicane database systematically and to develop forecasts to alert of these phenomena may prove very helpful.

Recently some criteria had been established by Tous and Romero (2011, 2013) to define a medicane from the Meteosat satellite images. The criteria are based on the structure (the medicane must have a continuous cloud cover and symmetric shape around a clearly visible cyclone eye), size (diameter less than 300 km) and life-time (life-time at least 6 h). In their work, using historical infrared (IR) Meteosat satellite data, lists of medicanes have been created based on aforementioned criteria. The use of satellite images has been recognized as a useful tool to consistently detect storms and, in this case, medicanes Tous and Romero (2011, 2013) but it carries a very laborious task.

Over the last years several methodologies have been developed to follow cyclones from NWP models. One such method for detection and tracking Mediterranean cyclones, including mesocyclones, was developed in the Meteorological Centre of the Balearic Islands (AEMET) and some cyclone databases were obtained from different sets of analysis based on NWP systems (Picornell et al., 2001; Campins et al., 2006). Moreover, Hart (2003) proposes a phase space where the cyclone evolution is represented. Cyclone phase diagrams inform about symmetric/frontal and cold/warm character of the cyclone. The cyclone phase diagrams have been applied to past time and in real time from different numerical models and they are available at http://moe.met.fsu.edu/cyclonephase. Initially, the diagrams have been used for forecasting extra-tropical transition of tropical cyclones and later the diagrams have been

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increasingly used for structural forecasting of subtropical cyclones and cold-core to warm-core evolution (Hart and Evans, 2004).

Recently, progress has been made towards the construction of methods to detect medicanes from numerical models systematically. A method for constructing multidecadal statistics and scenarios of current and possible future medicane activities by means a dynamical downscaling approach had been presented by Cavicchia and von Storch (2012). In their work, several climatic mode simulations, with a high resolution regional atmospheric model and for a number of test cases described in literature, has been performed by employing two horizontal resolutions, one "low" with 0.22° (25 km) grid and one "high", with 0.09° (10 km) in a double nested configuration. In Miglietta et al. (2013) several Mediterranean tropical-like cyclones are analyzed by means of numerical simulations, satellite products and lightning data, in order to achieve a future automatic detection algorithm for discriminating tropical-like cyclones from baroclinic cyclones. Walsh et al. (2013) focus on a subset of all Mediterranean lows, those that have high wind speeds and warm-core, referred to as "warm-core lows" and design a storm detection and tracking algorithm to identify them from the regional climate model RegCM3 running at a horizontal grid spacing of 25 km.

The goals of the present work are to contribute to a proper description of the medicanes and to develop some objective criteria to identify these structures from numerical model outputs in an automatic way. This will favour the systematic detection and prediction of these phenomena, subject to the availability of NWP models with sufficient resolution. This also offers the possibility to build a medicane database from numerical analysis or reanalysis. Besides it can contribute to better forecast medicanes and to develop warnings for these infrequent phenomena. To achieve those goals, aforementioned methodologies for detecting, characterizating and tracking cyclones have been adapted to small-scale intense cyclonic perturbations. Other small and intense cyclones that also affect the region do not have quasi-tropical features, but are also related with severe weather events. These cyclones can also be described by using this

methodology. Their description through the phase diagram may allow the identification of their typology.

This paper is structured as follows. First, in Sect. 2, the aforementioned mesocyclone detection algorithm has been modified in order to select and to characterize intense structures. Furthermore the Hart's cyclone phase diagram has been adapted and tuned to correctly describe the thermal structure of small intense cyclones in general and medicanes in particular. Next, in Sect. 3, the adapted procedure has been applied to the outputs of numerical simulation runs to detect and describe four tropical-like cyclones that affected the Mediterranean region. The predicted cyclones and their evolutions have been validated against available observational data and numerical analyses coming from literature. Finally, in Sect. 4, the results are discussed and the main conclusions are outlined.

2 Methodology

2.1 Intense cyclone detection and tracking

The method for detection and tracking Mediterranean cyclones designed to describe cyclonic perturbations, including mesocyclones, and their characteristics (Picornell et al., 2001; Campins et al., 2006) has been used to obtain some cyclone climatologies from different sets of analyses coming from NWP systems (with moderate resolutions, around 50 km). Typical sizes of detected cyclones are 200–300 km of radius, smaller than the typical extra-tropical cyclones, but clearly larger than the perturbations (like medicanes) that we want to detect and describe now (less than 150 km of radius). The size of the structures that can be properly represented depends on the NWP model resolution. Resolutions of around 25–50 km are probably not enough to correctly describe perturbations of less than 300 km of diameter (like the medicanes). In fact, Walsh et al. (2013) consider that the 25 km horizontal resolution may still not capture highest intensities of the warm-core storms and may not be high enough to effectively cap-

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ture true medicane. In order to check whether a robust operational model, with good physical parametrization and a greater resolution, is able to simulate these small and intense structures, we have selected the European Centre for Medium-Range Weather Forecast (ECMWF) forecasting model outputs, with a horizontal resolution of 15 km.

In the original method, a cyclone is defined as a relative minimum in the mean sea level pressure (MSLP) field, with a mean pressure gradient greater than $\Delta p \geq 0.5\,\mathrm{hPa}\,100\,\mathrm{km}^{-1}$ at least in six of the eight principal directions around the minimum. To avoid excessive noise in some fields (like vorticity, needed for the vortex description) a Cressman filter with an influence radius of 200 km was applied to smooth the analysed fields. The cyclone domain is limited by the zero-vorticity line, searched around the minimum pressure position. The 700 hPa level is considered as the steering level for the cyclone tracking.

Some aspects needed to better describe small-scale intense cyclonic perturbations have been adapted. First of all, to preserve the main features of the small structures the influence radius in Cressman filter has been reduced from 200 km to 50 km. Also a double criterion referred to the pressure gradient is proposed:

– A less demanding criterion to obtain the full life-time of the cyclone, including both previous and later moments of an intense cyclone, $\Delta p \geq 0.5\,\mathrm{hPa}\,100\,\mathrm{km}^{-1}$ at least in six of the eight principal directions around the minimum. This pressure gradient threshold is the same as in previous papers.

– A more restrictive threshold value to select intense cyclones (including possible medicanes), $\Delta p \geq 3.2\,\mathrm{hPa}\,100\,\mathrm{km}^{-1}$ in at least six of the eight directions, which roughly corresponds to a wind speed of about $32\,\mathrm{m\,s}^{-1}$ (hurricane-level intensity).

Other criteria for medicanes will be defined in the next section.

2.2 Thermal structure

The cyclone's life-cycle can be analyzed within the three-dimensional phase space proposed by Hart (2003), providing substantial insight into the cyclone structural evolution.

Each cyclone is characterised by using three fundamental magnitudes of its phase, defined on a circle around the cyclone centre:

1. Parameter B, the storm-motion-relative low troposphere thickness asymmetry inside the cyclone.

2. $-V_T^L$, low tropospheric thermal wind, which measures the cold, neutral, or warm-core structure of the cyclone in the low-middle troposphere.

3. $-V_T^U$, upper-tropospheric thermal wind, which gives the measure of the cyclone phase (cold vs. warm-core) for the upper troposphere and helps to distinguish full-troposphere warm-core cyclones (e.g. tropical cyclones) from shallow warm-core cyclones (warm-seclusions or subtropical cyclones).

Three-dimensional cyclone phase space is presented using two cross sections, the phase diagrams, which facilitate an objective classification of cyclones from the analysis of their life-cycle in the phase space.

In the present paper some parameters have been modified to take into account the small dimensions of the cyclones we are dealing with (particularly medicanes). The exploration radius of 500 km, proposed by Hart, can smooth out their warm-core structure, as pointed out by Chaboureau et al. (2012), who used a radius of 200 km, obtaining near-zero values of B to indicate symmetry of the supposed medicane. Cavicchia (2013), after considering several possible radii, obtained the best results using a radius of 100 km. Miglietta et al. (2013) incorporate a variable radius, as suggested Hart (2003), considering the extension of the warm-core anomaly at 600 hPa. In the present work, after several attempts and in order to use a storm-size-dependent circle of exploration, the mean radius of the warm-core anomaly is used to estimate the three phase parameters. This radius is calculated from the line of zero-temperature-Laplacian around the temperature maximum at 700 hPa closest to cyclonic centre. If no temperature maximum is located, taking into account the results of previous works, a radius of 90 km is used.

Moreover, two layers, 925–700 hPa and 700–400 hPa, slightly lower than those of Hart have been explored. Therefore:

$$B = \overline{(Z_{700} - Z_{925})}|_L - \overline{(Z_{700} - Z_{925})}|_R$$

where R indicates right of current storm motion, L indicates left of storm motion and
the overbar indicates the areal mean over a semicircle of exploration.

In this work, the thermal structure of the selected mesocyclones is scrutinized by means of the two phase diagrams. The criteria proposed by Hart to define tropical cyclones are imposed to qualify a mesocyclone as a medicane:

– The cyclone is thermally symmetric, with $B < 10$ m.

– A warm-core structure of the cyclone must be present in the low-middle and in the upper troposphere, that is, $-V_T^L > 0$ and $-V_T^U > 0$.

2.3 Numerical simulations of test cases

In order to test the suitability of the aforementioned criteria to define an intense cyclone and to discriminate mainly between medicanes and other small intense cyclones, pre-vious methodology has been applied to four well-known medicane events occurred be-tween 1982 and 1996. Two of them occurred in the Western Mediterranean in late sum-mer and two have been identified in Central-Eastern Mediterranean in winter. Three of them have been selected from the aforementioned satellite-derived data base (Tous and Romero, 2013).

The ECMWF T1279L91Cy36r1 forecast model (hereafter ECT1279), which corre-sponds to a horizontal resolution of 15 km (detailed documentation is available at http://www.ecmwf.int/research/ifsdocs/CY36r1), has been run for the selected cases. For each event, four runs have been performed, with initialization times separated 24 h, starting at 12:00 UTC of the day before the first appearance of the cyclone, with lead times from 06 to 72 h every 6 h. The analysis comes from the ERA-40 fields, interpo-

lated to the model resolution. For each event, the best simulation has been selected and the results are presented in the following section.

The predicted cyclones and their evolution have been validated against available observational data and numerical analyses from literature. According to this, the four selected cases correspond to tropical-like structures, including compact spiral cloud vortexes, although the name medicane is not always used. We must also take into account that, usually, a medicane is clearly identified when it reaches its mature stage, but in most of the cases it is difficult to identify its initial or final stages. This hampers the validation of the numerical simulations and prevents finding an exact correspondence between the two descriptions. In spite of this, these papers are a good reference to validate our procedure.

3 Results

3.1 January 1982 event

The overview of this case is based on Ernst and Matson (1983) and Reed et al. (2001). On 23rd January 1982 a storm formed over the warm waters between Sicily and Libya, meanwhile at 500 hPa a cut-off was observed over Tunisia. The storm evolved in two phases. During the first phase of its development, the low deepened nearly 20 hPa in 48 h as it moved north-westward. It achieved its maximum depth when it arrived to the southeast of the Sicilian coast. At this stage the system was relatively large and possessed an extensive region of convective cloud bands. The presence of smaller-scale hook-shaped band is an indicator of a vortex embedded within the larger scale cyclonic circulation. The system described a small loop south of Sicily (Reed et al., 2001, Fig. 1). During the second phase, from 26 at 00:00 UTC onwards, the system shrank in size, taking the appearance of a tropical-like storm in IR satellite imagery, with a well organized convective cloud band spiralling into an eye-like centre. Subsequently the system made a second small loop before accelerating eastward (Reed

et al., 2001, Fig. 1). The warm ocean and intense convection probably played a major role in generating and maintaining this small warm-core cyclone.

When this event has been simulated by the ECT1279 model, the best forecast of this medicane is from run 24 January at 12:00 UTC. Along 72 h of simulation, a cyclone is detected and the model is able to reproduce the complicated path and to forecast the abrupt changes of direction after the loops (see Fig. 1). At upper levels a cut-off is located over Tunisia on 26 at 12:00 UTC, as in Reed et al. (2001). From 25 at 00:00 UTC to 27 at 06:00 UTC the mean pressure gradient overcomes the more restrictive threshold value and thereby the cyclone is classified as intense. During the first part of the life-cycle, when cyclone spins around the first loop, the central pressure decreases to its minimum value (see Fig. 2a), although not to the observed values, while the vorticity reaches a relative maximum (see Fig. 2b). The system is very symmetric and its positions in the phase diagram I are very close among them (see Fig. 3a). Along the second stage of cyclone-life the central pressure increases, disagreeing the pressure evolution described in literature. However, the model itself is able to predict the observed contraction in scale of the system and the radius decreases, reaching a radius of about 150 km 26 at 12:00 UTC, meanwhile the vorticity achieves the highest value (see Fig. 2b). Along this stage the cyclone is also described as symmetric and at low level becomes warmer regarding to the previous stage (see Fig. 3a). The warm-core is about 130 km radius (see Fig. 2b), except at the beginning, when the cyclone is extensive. As phase diagram II shows (see Fig. 3b), a deep warm-core structure is present throughout all life-time and the upper thermal wind reaches two differentiated maxima, one in each of the two stages of cyclone-life. The cyclone presents characteristics of medicane for about 60 h.

In this simulation the system evolves in agreement with the evolution described by Reed et al. (2001). The cyclone is described as intense and symmetric throughout most of its life and with a deep warm-core, therefore the system is identified as a medicane for much of simulated path.

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3.2 September 1983 event

On 27 September 1983 a sub-synoptic vortex-like disturbance was formed in the central part of a low of modest intensity, between Sicily and Tunisia. After its formation, the vortex moved in a large circle in about 4 days and it was best developed over the sea
⁵ west of Sardinia and Corsica (see Fig. 1). Finally it vanished after having made landfall close to its place of origin, as it is described in Rasmunssen and Zick (1987). The major tools for the study were Meteosat images, from IR and visible (VIS) spectrum, and wind data from low and high levels, obtained by tracking cloud elements from these images. As described by the authors, the upper air synoptic situation in the region was domi-
¹⁰ nated by a deep and cold cut-off over the Western Mediterranean, centred in northern Tunisia. At 12:00 UTC on 27 the Meteosat IR image exhibited a large scale cloud spiral and deep convection. Three hours later, the formation of the sub-synoptic vortex was indicated by strong pressure falls and a low-level secondary centre of positive relative vorticity in the region. On 28, VIS image showed the dissolving large scale cloud spiral,
¹⁵ with the sub-synoptic vortex in its centre (see Fig. 5 in Rasmunssen and Zick, 1987). The cyclonic activity was contracted into the central part of the low and a cloud-free spot, similar to an "eye", was shown. On 29 September a tight and almost circular mesoscale cloud vortex was observed and around noon the vortex was characterized by a warm-core structure. Later the vortex started to weaken, when it moved into a re-
²⁰ gion with decreasing sea surface temperature. During the second landfall at Corsica at 30 September the vortex intensified.

This case is poorly forecasted by ECT1279 model. The best run, day 27 at 12:00 UTC, forecasts a moderate cyclone along 72 h of simulation. According to the analysis, on 27 at 12:00 UTC at high levels a cut-off is centred between Tunisia and
²⁵ Sardinia and an extensive surface cyclone appears west of Sicily. Six hours later and agreeing with the observation described above, the system size shrunk and geostrophic vorticity increases (see Fig. 4b). On 28 at 00:00 UTC the central pressure is the lowest (see Fig. 4a) and low level thermal wind reaches its maximum and positive

value, revealing the presence of a warm-core. In the phase diagrams (see Fig. 5) the cyclone is classified as symmetric cyclone with shallow warm-core. Later, the cyclone moves eastwards and when it tracks over the island of Corsica the pressure increases suddenly and the air at low levels cools. Since 29 at 00:00 UTC, the pressure falls and the system remains symmetric, a weak low level warm-core appears but the system evolves into a deep cold-core cyclone, increasing in size (see Fig. 4b). The system is symmetric along all its life-time but the pressure gradient does not overcome the threshold value (see Fig. 4a). Upper level thermal wind values indicate that a cold-core is present at that levels during the entire simulation, although it weakens from day 28 at 18:00 UTC (see Fig. 5).

According to these results, we can state that both the forecast and the methodology are able to detect and track the cyclone, although thermal features are not well represented. Cyclone strength is underestimated during the forecast period and the model is not able to forecast the warm-core structure, i.e. the cyclone is not well simulated and therefore not classified as medicane.

3.3 January 1995 event

During the period 14–18 January 1995 a sub-synoptic vortex with characteristics of a tropical storm developed between Italy and Greece. Satellite imagery revealed that this vortex was associated with a clearly defined "eye" surrounded by cloud bands, a warm-core, small dimension and rather long life-time, as it is explained in Lagouvardos et al. (1999) and in Pytharoulis et al. (2000). This vortex formed behind a pre-existing low centre, which progressed towards the east, while the new vortex moved independently southwards (see transcribed path in Fig. 1). As it is described in detail on the previous studies, from satellite imagery a cut-off low was observed over Sicily at 12:00 UTC on 14 January. A surface low pressure system (called parent low) was evident over the sea west of Greece in MSLP maps, with winds of 22 and 29 m s^{-1} and a pressure of 992.5 hPa reported by ships. Sensible and latent heat fluxes played a significant role in the deepening of the parent low. Twenty-four hours later, at 12:00 UTC

on 15 January, a secondary low was created, it became independent of the parent low and it followed a southward path. The Meteosat satellite images showed spiral cloud bands around a clearly defined "eye". By 06:00 UTC on 16 January deep convection clouds were spirally distributed at a radius of 150 km, while lower clouds were evident at a radius of 200 km around the vortex centre. A 23 m s^{-1} surface wind and a relative maximum of air temperature were reported by a ship. The storm dissipated when it reached the northern African coast, on 18 January.

The analysis on 14 at 12:00 UTC, when simulation starts, shows that an extensive and deep cyclone is located in the Ionian Sea. Six hours later, the large cyclone splits into two smaller cyclones. One of them intensifies and becomes symmetric with a deep warm-core structure. Its evolution may be analysed from the phase diagrams (see Fig. 7) and from the track chart (see Fig. 1). In the phase diagram I the cyclone is classified as symmetric along its full life and an structure of deep warm-core is identified from 14 at 18:00 UTC onwards. Warm-core radius varies from about 100 km during the most intense period up to around of 140 km. Minimum central pressure value is reached on 14 at 12:00 UTC, agreeing with observed strong wind but with a higher value than the observed pressure. At 12:00 UTC on 15 January the medicane is very small, with maximum values of the geostrophic vorticity and of the low level thermal wind (see Fig. 6 and 7). On 16 January the central pressure continues rising (see Fig. 6a), according with the evolution described in the literature, and the mean pressure gradient decreases. As a result the cyclone is identified as a medicane until 16 January, with a life-time of 24 h. Along the entire simulation cyclone follows a track close to the observed one, travelling towards the Libyan coast.

As mentioned before, on 14 at 18:00 UTC the large cyclone splits into two smaller cyclones. The weakest one, an orographic cyclone, is located downwind of the Peloponnesus peninsula. In this case, in the phase diagrams (see Fig. 8) it is initially classified as an asymmetric warm-core, becoming symmetric as moves south-eastwards. But this cyclone is not intense along the lifecycle and the warm-core structure is reduced to low troposphere. In this case the system is classified as a small cyclone with

a shallow warm-core structure, as befits an orographic cyclone, and not as medicane, unlike the other cyclone.

As noted by Pytharoulis et al. (2000), the ECMWF T213/L31 version (62 km horizontal resolution), operational at 1995, predicted the translation of the low centre towards the east, but the forecast of the secondary vortex formation failed, because it was too small for this model. The version ECT1279 (15 km horizontal resolution) is capable to simulate two smaller cyclonic centres, one of them with features of quasi-tropical cyclone. The later version of the model represents an improvement in the description of these structures.

3.4 September 1996 event

On 12 of September 1996 a small quasi-tropical cyclone formed in the gulf of Valencia and later affected the Balearic Islands. From the radar images an eye of clear air surrounded by a circular wall of cumulonimbus was observed at 04:50 UTC (see Fig. 11 in Gili et al., 1997). The cyclone crossed the island of Majorca with an intense fall of pressure between 12:00 UTC and 13:00 UTC in the pressure record from the observatory in Palma (see Fig. 8 in Gili et al., 1997), reaching a value less than 993 hPa. Strong winds were recorded on the Island and a warm-core was identified. At 17:00 UTC the intensity of the cyclone decreased. The cyclone moved towards North-East and it arrived to Sardinia at 21:00 UTC (see transcribed path in Fig. 1, from Gili et al., 1997). The system was identified as a quasi-tropical cyclone at least between 04:00 UTC and 21:00 UTC, along 17 h approximately.

In this case the best simulation started on 11 of September at 12:00 UTC, when an extended low pressure centre (300 km of radius) is localized in front of the Algerian coast. Six hours later a secondary centre is detected off-shore Spanish, over the sea. During the following hours, the extensive low moves towards North-East, weakening. A secondary low intensifies and six hours later, at 00:00 UTC on 12, it is detected as an intense and symmetric cyclone but with cold-core structure at low levels. At 06:00 UTC on 12, the minimum central pressure value is reached although far from

the observed value (see Fig. 9a), and begins to form a deep warm-core, but the small cyclone is slightly asymmetric (see Fig. 10). During the following hours, the vortex moves north-eastwards and becomes symmetric and, according to their position in the phase diagrams, it is classified as a medicane. At 18:00 UTC on 12 it is located at South-West of Majorca, with a delay of 6 h compared to the observed track (see Fig. 1). At this moment the geostrophic vorticity reaches its maximum value, the medicane is very symmetric and small and a pronounced deep warm-core is present (see Fig. 10). Six hours later the medicane weakens. Along the whole life-time the cyclone is small, with a 100–140 km radius (see Fig. 9b).

The cyclone is classified by the procedure as a medicane during 18 h. From the comparison of the forecast cyclone track against the track from observations it can be established that the medicane evolution is delayed 6 h. The forecast pressure values are higher than the observed ones. In this case the cyclone has been poorly simulated; probably a higher resolution model would be needed to represent it correctly.

4   Summary and discussion

A method to detect and describe small and intense cyclonic structures, in particular medicanes, from NWP model outputs is presented. This method has been developed from existing methodologies to identify cyclones and to study their life-cycle in the cyclone phase space that have adapted to the characteristics of the medicanes, in an attempt to contribute to the development and complementing methodologies that have been developed in the last years by different authors. Medicanes are small and intense cyclonic structures with strong pressure gradient, related to the presence of very strong winds and a thermal structure characterized by the presence of a warm-core, in which development and maintenance the heat flows from the land-sea interaction and the convective heat release play a key role. The medicanes develop mainly on the sea, so in areas where observations are scarce, which can make difficult to track them accurately and sometimes can make unnoticed these phenomena, especially in cases

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in which land areas are not affected. Therefore, the systematic and automatic detection of these phenomena from the outputs of NWP models is presented as a good choice to obtain climatology of these phenomena and to improve the prediction of severe phenomena accompanying the medicanes.

⁵ Previously to test the procedure, and in order to check briefly the performance of the operational model to represent these small and intense structures, four well-known medicane events have been explored and four simulations have been done for each one of them. Results show that the ECT1279 forecast model represents two of these phenomena, 1982 and 1995 medicanes, acceptably and approaches the 1996 case.

¹⁰ The 1983 event is the worst simulated one. The cyclone, described in the literature as quasi-tropical cyclone, is forecasted as not enough strength one to be considered as a medicane and the model is not able to forecast the deep warm-core structure. In general the pressure value in the cyclone centre is higher than observed, although the model simulates very well the intensification and variations in the size of these cy-

¹⁵ clones. Forecast chain runs from ERA-40 analyses, with too low resolution to describe small cyclones, therefore small cyclones can be properly characterized from H +06, when the ECT1279 model has already been able to simulate the deepening of the cyclone.

In order to adapt the method to the characteristics of medicanes and to establish

²⁰ selection criteria to discriminate different typologies of small intense cyclones, the existing procedures have been modified in two main ways: a more restrictive selection criteria has been introduced to select small intense cyclones and thermal parameters have been calculated by using a storm-size-dependent circle around the cyclone centre. In summary, three criteria to identify a cyclone as a medicane, according with their

²⁵ strength and their thermal structure, has been established: the cyclone must be intense, $\Delta p \geq 3.2\,\mathrm{hPa}\,100\,\mathrm{km}^{-1}$, thermally symmetric, $B < 10\,\mathrm{m}$, and a warm-core structure must be present in the low-middle and in the upper troposphere, that is, $-V_T^L > 0$ and $-V_T^U > 0$. For the 1982 and 1995 events the detected cyclone is identified as a medicane according to the proposed criteria along much of the simulation. For the 1996

event the cyclone is initially symmetric, but with cold-core structure, and becomes medicane only twelve hours after its formation. In the phase diagrams the systems are classified as symmetric deep warm-core. Besides, for the 1995 event a weak orographic cyclone has been detected and it has been successfully differentiated from the medicanes by using the phase diagrams. In all four cases the simulated cyclone tracks are close to the corresponding observed paths, although from the 1996 medicane the evolution is delayed 6 h regarding the observation.

We can summarize that in three of four cases an intense small cyclone is forecasted with appropriate thermal structure, that is, it is symmetric and with a deep warm-core. Warm-core radii vary from about 100 km during the most intense period up to around of 140 km. Cyclone radii range from values higher than 300 km, corresponding to parent lows, to 150 km, at the time when medicane is shrunk.

Thereby, in all three cases a medicane is simulated. The ECT1279 forecast model allows describing medicanes, at least the larger ones, although with some limitations and an objective description of medicanes can be obtained by means the automatic procedure.

Although the model here used presents some limitations, the obtained results are acceptable. The model here used is capable of simulating intense storms and, therefore, is adequate to validate the adapted procedure and to establish the criteria that define a medicane. However, scarcity of observations over the sea is a major drawback in the forecast of medicanes. The improvement of initials conditions, e.g. by means of remote sensing data, will lead to a better prediction of these phenomena. Besides, improvements can be achieved increasing the model resolution and especially by means of high resolution convection-permitting models.

The three proposed criteria seem to be useful for identifying medicanes. By means of these criteria, we try to discriminate mainly between medicanes and other small cyclones. The phase diagrams offer a convenient way to describe and classify the cyclone and, jointly with the tracks, give a fairly complete and detailed description.

Having this automatic procedure offers different possibilities to better know and better identify forecasted medicanes. On one hand, the present methodology is expected to contribute to obtain a medicane database and to study some interesting events from high resolution numerical models. On the other hand, this procedure facilitates the identification of the medicanes in the forecasts so rare those sometimes go unnoticed or not predict well in advance. Better prediction of medicanes leads to better forecast of severe weather events, both on the sea and coastal zone. This procedure helps the verification of medicane forecasts and the comparison of capability of numerical models to forecast these small cyclonic structures. Besides it can also be used with sufficient resolution climate models to study the trend of frequency and intensity of these phenomena in different scenarios of future tense as well as with non-hydrostatic models of higher resolution.

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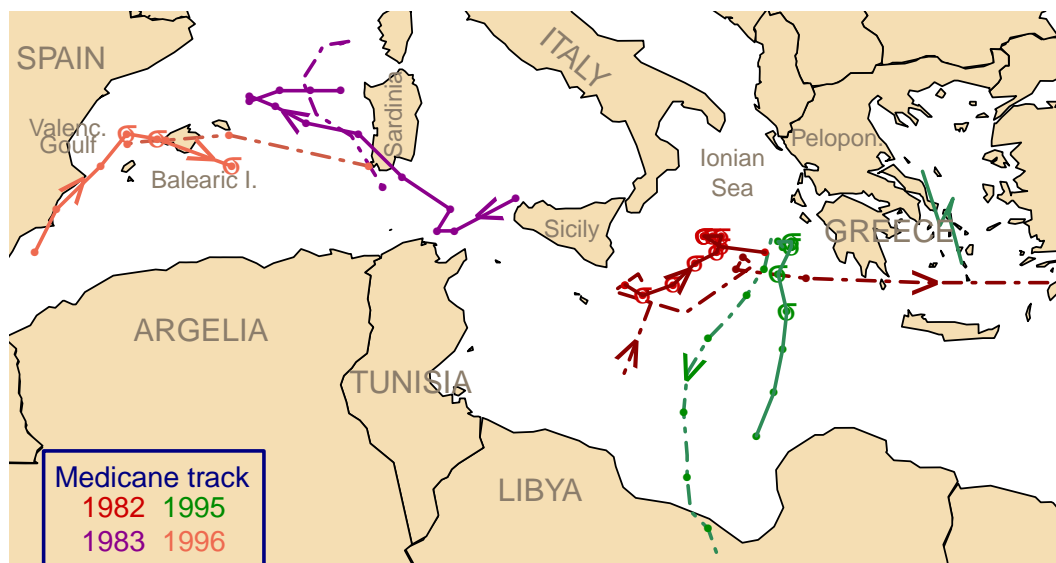
Fig. 1. Medicane tracks in Mediterranean Sea. In red, 1982 event, in violet, 1983 event, in green 1995 event and in orange 1996 event. Simulated cyclone tracks (solid lines) with symbol σ indicates medicane + observed cyclone tracks transcribed from literature (dotdash lines).
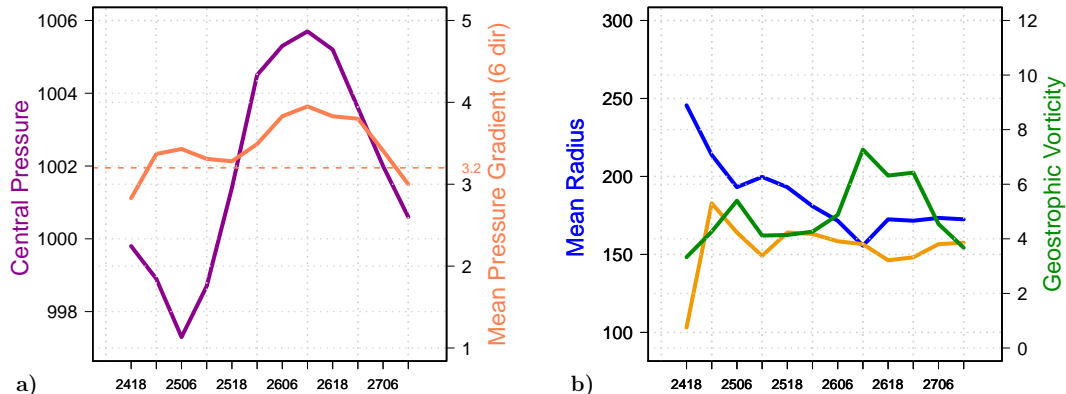
Fig. 2. Evolution over time of **(a)** Central Pressure (hPa) in violet + Mean Pressure Gradient (hPa 100 km^{-1}) in orange **(b)** Mean Radius (km) in blue + Mean Warm Core Radius (km) in orange + Geostrophic Vorticity (10^{-4} s^{-1}); for 1982 event.
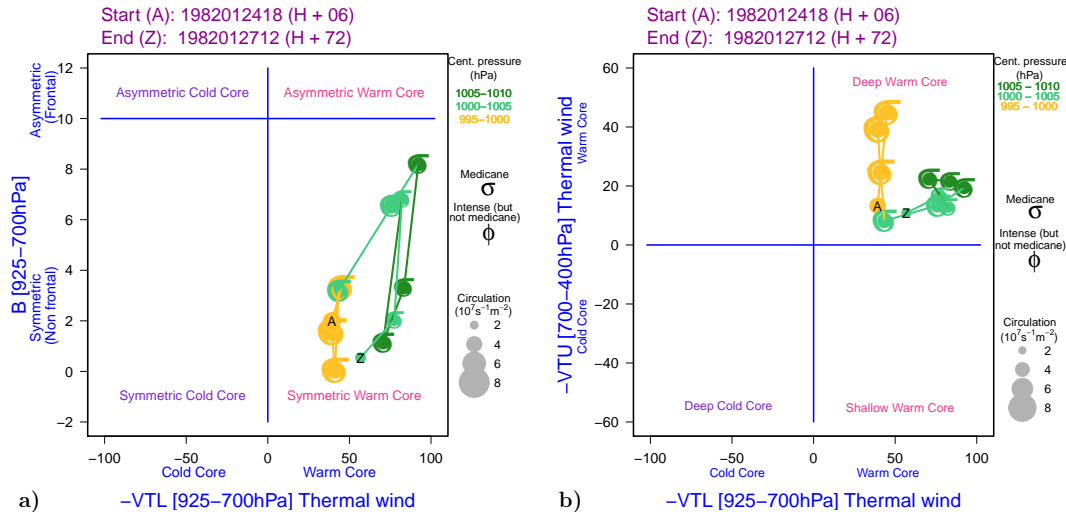
Fig. 3. Cyclone phase diagrams I **(a)** and II **(b)**, for January 1982 event. Circle colour refers to central pressure value and circle size is related to geostrophic circulation value. Symbol σ indicates the presence of medicane.
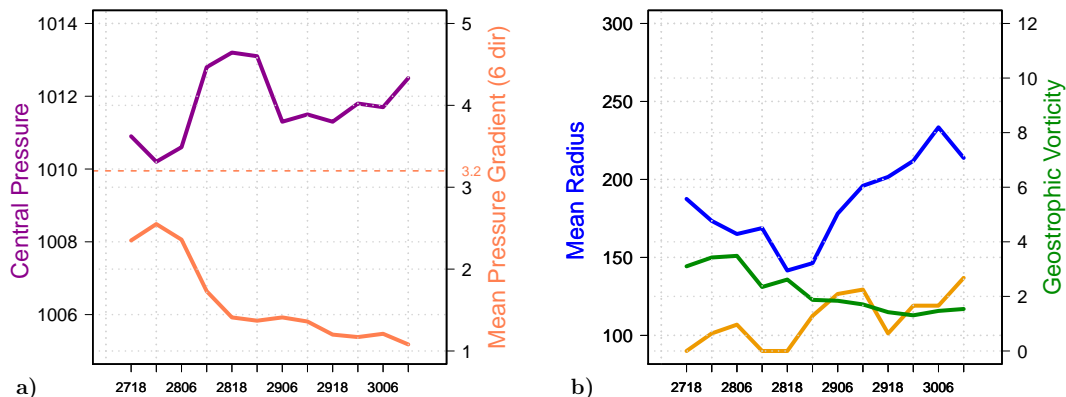
Fig. 4. Evolution over time of **(a)** Central Pressure (hPa) in violet + Mean Pressure Gradient (hPa $100\,\mathrm{km}^{-1}$) in orange **(b)** Mean Radius (km) in blue + Mean Warm Core Radius (km) in orange + Geostrophic Vorticity ($10^{-4}\,\mathrm{s}^{-1}$); for 1983 event.

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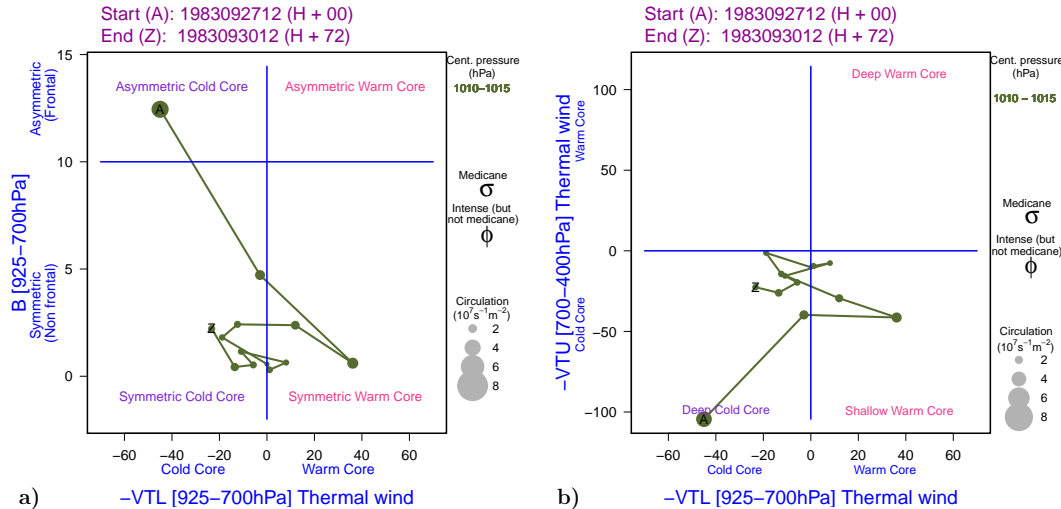
Fig. 5. Cyclone phase diagrams I **(a)** and II **(b)**, as Fig. 3, for September 1983 event.
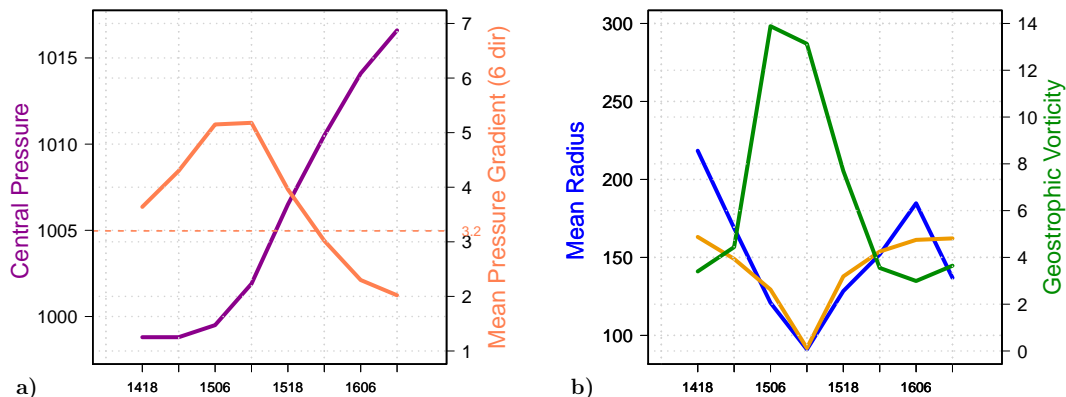
Fig. 6. Evolution over time of **(a)** Central Pressure (hPa) in violet + Mean Pressure Gradient (hPa $100\,\mathrm{km}^{-1}$) in orange **(b)** Mean Radius (km) in blue + Mean Warm Core Radius (km) in orange + Geostrophic Vorticity ($10^{-4}\,\mathrm{s}^{-1}$); for 1995 event.
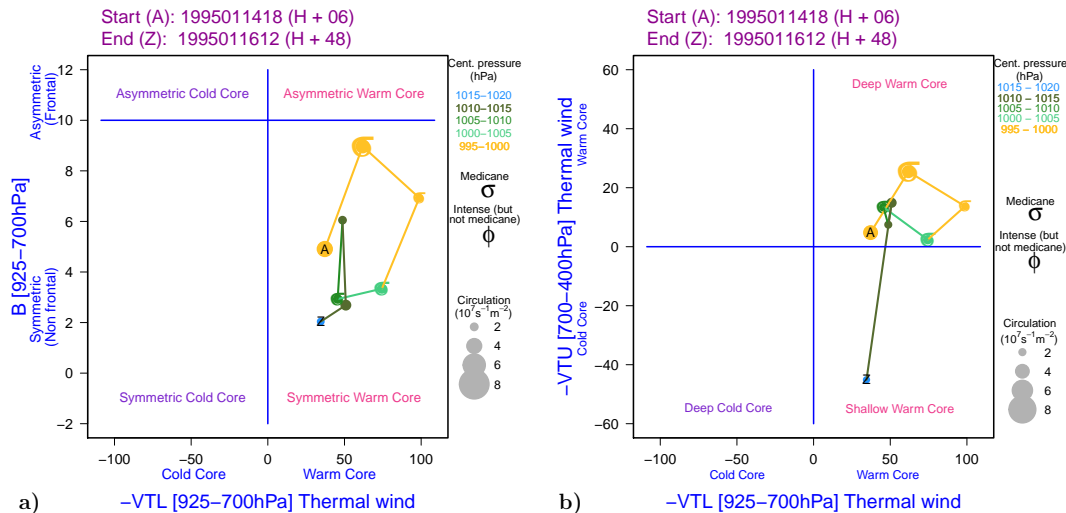
Fig. 7. Cyclone phase diagrams I **(a)** and II **(b)**, as Fig. 3, for January 1995 medicane.
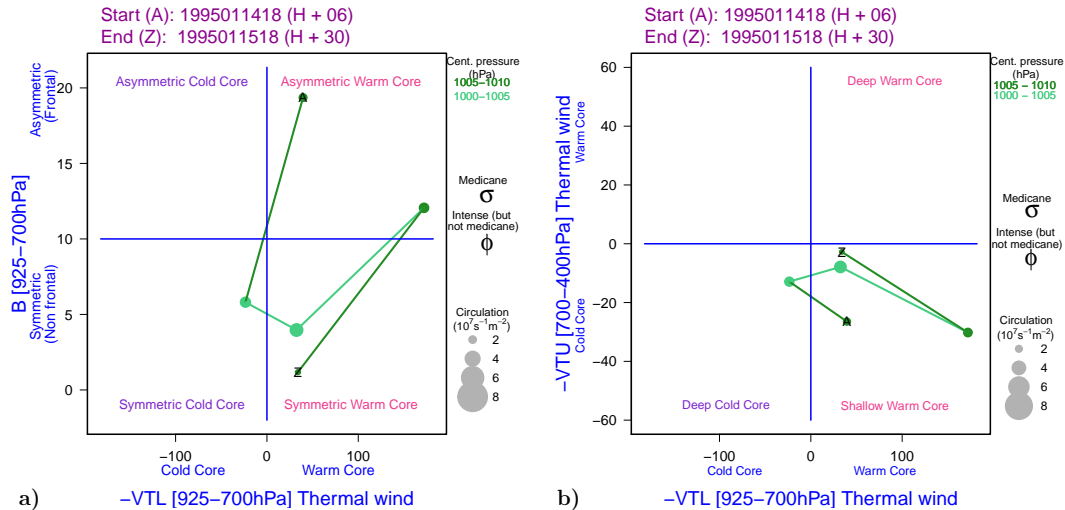
Fig. 8. Cyclone phase diagrams I **(a)** and II **(b)**, as Fig. 3, for January 1995 orographic cyclone.
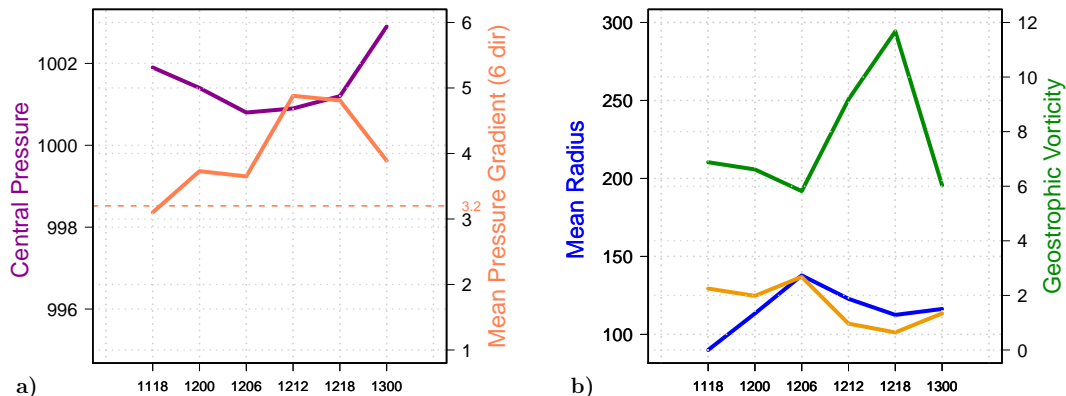
Fig. 9. Evolution over time of **(a)** Central Pressure (hPa) in violet + Mean Pressure Gradient (hPa $100\,\mathrm{km}^{-1}$) in orange **(b)** Mean Radius (km) in blue + Mean Warm Core Radius (km) in orange + Geostrophic Vorticity ($10^{-4}\,\mathrm{s}^{-1}$); for 1996 event.
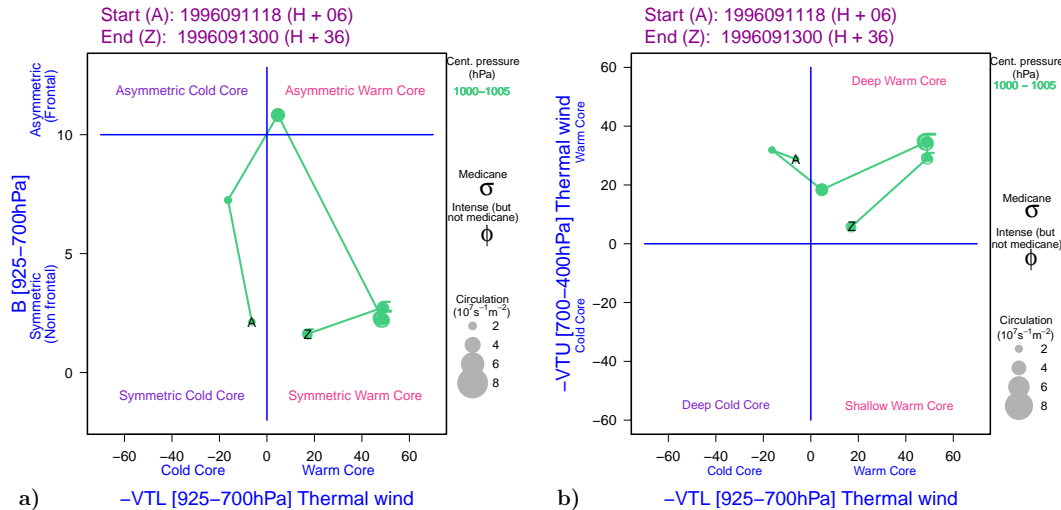
Fig. 10. Cyclone phase diagrams I and II medicane **(a, b)**, as Fig. 3, for September 1996 event.