Alma Mater Studiorum · Università di Bologna

Scuola di Scienze
Dipartimento di Fisica e Astronomia
Corso di Laurea in Fisica

Analysis of the Mediterranean tropical-like cyclone Numa from a numerical model simulation

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Anno Accademico 2020/2021

Abstract

I Medicane sono rari cicloni che si sviluppano sul Mar Mediterraneo e presentano caratteristiche dei cicloni tropicali, come la forma a spirale delle bande di nubi, un occhio privo di venti e nubi, venti intensi nella banda che circonda l'occhio e la presenza di un nucleo caldo. Nel presente lavoro, è stata compiuta un'analisi del Medicane Numa, verificatosi nel novembre del 2017, utilizzando gli output della simulazione del modello RAMS-ISAC. L'obiettivo di questa tesi è l'identificazione e la descrizione delle caratteristiche tropicali di Numa, focalizzandosi sulla descrizione dei diversi stadi di sviluppo del ciclone. Il sistema di bassa pressione è stato identificato utilizzando la pressione sul livello del mare, mentre l'anomalia termica e il vento orizzontale hanno permesso una descrizione della struttura del Medicane e del suo nucleo caldo. Un'illustrazione della struttura a spirale delle bande di nubi e dell'occhio è stata ottenuta con il grafico dei rapporti di mescolanza delle idrometeore di nubi e pioggia. Questi parametri hanno consentito di ricavare il diametro dell'occhio, pari a 75 km, mentre il diametro del Medicane è risultato 230 km. Numa ha registrato una velocità massima del vento in superficie di 20 m/s nella banda adiacente all'occhio del ciclone. Il diagramma di Hart dello spazio delle fasi del ciclone ha confermato la natura simil-tropicale di Numa e ne ha descritto l'evoluzione, identificando la transizione da sistema a caratteri tropicali a sistema ibrido. La traiettoria nello spazio delle fasi ha consentito l'identificazione delle sottofasi dell'evoluzione di Numa, confermate dai grafici dell'evoluzione temporale dei parametri menzionati in precedenza. L'analisi ha mostrato il ruolo cruciale della presenza di una struttura organizzata nel determinare l'intensità e la durata delle caratteristiche tropicali. Tutti i parametri hanno evidenziato la simmetria della struttura durante la persistente fase matura di Numa.

Abstract

Medicanes are rare mesoscale cyclones developing over the Mediterranean sea that exhibit tropical-like features, like spiral cloud bands, a windless and cloud-free eye, strong winds in the eyewall surrounding the eye and the presence of a warm core in the central region of the cyclone. In the present work, an analysis of Medicane Numa, which occurred in November 2017, has been carried out using the outputs of the RAMS-ISAC model simulation. The goal of this thesis is to identify and represent the tropical features of Medicane Numa and their time evolution, focusing on the description of the different stages of development. The low pressure system has been identified using the sea level pressure field, while temperature anomaly and horizontal wind speed provided a description of the horizontal and vertical structure of the Medicane and its warm core. An illustration of the spiral cloud bands and the cloud-free eye has been realized plotting the mixing ratios of the cloud and rain hydrometeors. These parameters suggested a diameter of the eye of 75 km, while the diameter of the Medicane was estimated to be $\sim$230 km. The maximum surface wind speed of 20 m/s has been located in the eyewall surrounding the eye. The phase space Hart diagram has been employed to confirm the Medicane nature of Numa and describe its evolution, allowing the identification of a transition from tropical-like to hybrid system. The phase space trajectory allowed the identification of the subphases of the evolution of Numa, confirmed by the plots of time evolution of the parameters previously mentioned. The analysis highlighted the crucial role of an organized structure in the intensity and duration of tropical features. All the parameters investigated evidenced a remarkable symmetry of the structure throughout the long-lasting mature phase of Medicane Numa.

Contents

Introduction

Among the cyclones developing over the Mediterranean sea, a small number show peculiar characteristics, akin to those of tropical cyclones. These tropical-like cyclones (TLCs), often called Medicanes (Mediterranean hurricanes), are characterized by a vertically symmetrical structure, spiral-shaped cloud bands elongating from a calm and generally cloud-free centre (the eye of the storm) and a warm core [1]. The horizontal scale of these systems is smaller compared to that of tropical cyclones, with a typical diameter of 100-300 km. The TLC phase of the storm lasts between a few hours and a couple of days, while the cyclone itself can last several days. Medicanes are capable of producing severe phenomena, as heavy rain, sometimes leading to flooding, and strong surface winds wrapping the eye, generally in the range that classifies tropical storms (17 m/s to 33 m/s).

Many studies tried to determine the meteorological conditions leading to the formation and development of Medicanes. The fundamental role of latent heat release and sea surface fluxes of heat and moisture was shown in many case studies [2], suggesting a process of strengthening and maintenance analogous to that of tropical cyclones [3], for which the latent heat released through convection warms the air causing the pressure to drop, with convection partly fuelled by the ocean surface fluxes. The synoptic patterns prior to Medicane genesis exhibit low vertical wind shear, high moisture, preexistent vorticity and a strong temperature gradient between the sea surface and the mid-upper troposphere [4], generally enhanced by the presence of a cold trough. Cold air in the upper layers of the atmosphere allows the formation of strong vertical temperature gradients, even with sea surface temperatures much cooler than those observed in tropical oceans, highlighting a main difference in the formation of Medicanes compared to tropical cyclones, for which the warm ocean waters are the main driver for vertical temperature gradients. Sensitivity tests carried out on model simulations showed case to case differences regarding the role of orography in the formation of the cyclones.

Medicanes are rare events, with an average frequency of 1.57 per year. The areas of higher Medicane genesis are the western Mediterranean and the Ionian sea, accounting on average for 0.75 and 0.32 Medicanes per year respectively. The seasonal distribution is characterized by the absence of events in Summer, an high activity during Fall, a peak in January and a slow decrease up to May. There is a marked difference in the seasonal distribution of Medicanes in the two areas mentioned above, the Ionian area exhibiting a much sharper peak in January, in contrast with the smoother distribution of the western Mediterranean area.

The marine nature of Medicanes significantly hinders the availability of in-situ measurements. For this reason, simulations by mean of numerical weather prediction models prove to be a valuable tool. High space and time resolution is needed to correctly appreciate the characteristics and predict the evolution of such small-scale and short-lived events.

The goal of the present thesis is to carry an analysis of Medicane Numa, that occurred on November 2017 in Southern Italy, employing the outputs of the simulation used in Marra et al. [5], realized by the numerical weather prediction model RAMS-ISAC. The work is focused on the identification of the peculiar characteristics that define Numa as a Medicane and the evolution of the system during the TLC phase.

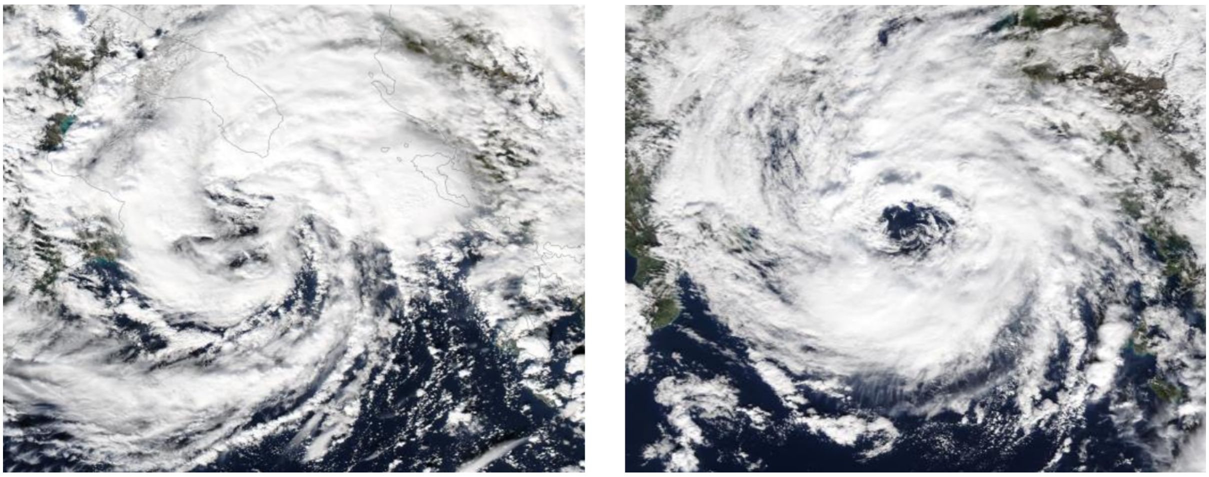
The work is organised as follows. In Chapter 1 an overview of the case study is provided. In Chapter 2 a brief description of the RAMS-ISAC model is presented. In Chapter 3 the results of the analysis are discussed, focusing on the identification of the main characteristics and the evolution of the system, using the phase-space Hart diagram to further highlight the tropical-like nature of the cyclone. Finally, in Chapter 4 the results are discussed and the conclusions are drawn.

Chapter 1

Overview of the case study

The system originated on 15 November 2017 over the strait of Sicily, then moved eastwards, starting to show hybrid characteristics on 16 November. The cyclone subsequently moved towards the Ionian sea, where the favourable conditions allowed a further intensification that led to the start of the TLC phase on 17 November at 12:00 UTC. During this phase, that lasted 24 hours, the system persisted over the Ionian sea, impacting the southern part of the Apulia region. The TLC phase was characterized by a cloud-free eye, a marked warm core and intense winds close to the vortex eyewall. The cyclone later moved eastward, dissipating over Greece on 19 November. Figure 1.1 shows two MODIS Corrected Reflectance (true color) satellite images, illustrating the evolution of the upper-level cloud structure from the acquisition of tropical features to the achievement of a mature Medicane structure. On 17 November at 12:00 UTC, MODIS Aqua (Figure 1.1a) captures Numa showing only some of the tropical features described in the introduction: the cloud bands are arranged in a spiral pattern, with the main rainband in the north impacting the coasts of Apulia, but Numa does not show a clear axis-symmetric structure and a cloud-free area representing the eye. On 18 November at 10:30 UTC, MODIS Terra (Figure 1.1b) evidences a very organized structure, with the spiral cloud bands outlining a clear cloud-free eye. At this time of development, Numa shows two main rainbands, the one on the northern flank of the eye appears deeper compared to the one on the southern flank.

In the early stages of the storm, the synoptic environment presented a broad low pressure area over the strait of Sicily and the Ionian sea, with two distinct sea level pressure (SLP) minima. Of the two minima, the one over the Ionian sea later evolved into Numa, while the one over the strait of Sicily dissipated in the following hours. On 16 November at 12:00 UTC, the geopotential height field at 500hPa featured a cut-off over the two minima, with a closed circulation around it, although without a completely closed circulation around the Numa minimum. As it continued to intensify, on 16 November at 18:00 UTC the storm began to show a warm core and a cyclonic circulation around a well-defined SLP minimum. On 18 November at 00:00 UTC, the Medicane reached a mature



(a) (b)

Figure 1.1: (a) MODIS Aqua on 17 November at 12:00 UTC and (b) MODIS Terra on 18 November at 10:30 UTC.

phase, showing a strong warm core with a significant vertical extension, producing a temperature gradient of $\sim$4 °C/120 km at 700hPa. In the following hours, the storm entered a stationary phase, followed by a progressive loss of the tropical features shifting towards Greece.

Chapter 2

RAMS-ISAC model description

The analysis of Medicane Numa is carried out using the output data of the RAMS-ISAC non-hydrostatic, limited area model, developed at the Institute of Atmospheric Sciences and Climate of the National Research Council starting from the version 6.0 of RAMS (Regional Atmospheric Modeling System). The limited area nature of the model allows to obtain high resolution results, that would be too computationally expensive to be obtained with a global model. The simulation is run on a grid with a 3km horizontal resolution and 40 vertical levels. The model employs the σ_z terrain-following coordinates as its vertical coordinates, defined as

$$z^* = H\left(\frac{z - z_g}{H - z_g}\right) \tag{2.1}$$

where H is the top of the domain and z_g is the local topography height. From (2.1) it is clear that the σ_z coordinate system follows the topography for $z^* = 0$, gradually flattens with increasing z and is completely perpendicular to gravity for $z = H$. The vertical levels are chosen imposing a constant expansion ratio $\tilde{R}_j$ between consecutive levels, defined for any level j as

$$\tilde{R}_j = \frac{z_{j+1} - z_j}{z_j - z_{j-1}} \tag{2.2}$$

A ratio of 1.15 is chosen to increase the resolution close to the ground, while an upper bound between 9 km and 10 km forces the ratio to 1 for z^* exceeding this threshold. The 40 vertical levels allow a description of the vertical structure of the atmosphere from the ground up to ∼26 km of height. The grid has a staggered configuration, meaning that all the thermodynamical and moisture variables relative to a grid point are defined at that point, while the wind components are shifted by half a grid spacing. The domain of the simulation covers the central Mediterranean area. The main parameters of the grid configuration are summed up in Table 2.1. The simulation is run from 17 November at 12:00 UTC to 18 November at 18:00 UTC, producing hourly data output, representing the TLC phase and the subsequent decay phase. The parameterization of microphysics implemented in RAMS-ISAC is the WSM6 [6], which uses six types of hydrometeors: water vapor, rain and cloud for the liquid phase, pristine ice and snow for the solid phase, hail and graupel together for the mixed liquid-solid phase.

NNXP	**NNYP**	**NNZP**	**Lx (km)**	**Ly (km)**	**Lz (km)**	**DX (km)**	**DY (km)**	**CENTLAT (°N)**	**CENTLON (°E)**
851	851	40	2518	2518	$\sim$26	3	3	42.0	12.5

Table 2.1: Main parameters of the RAMS-ISAC grid. NNXP is the number of grid points in the WE direction, NNYP is the number of grid points in the SN direction, NNZP is the number of vertical levels. Lx, Ly, and Lz are the domain extensions in the NS, WE, and vertical directions. DX is the size of the grid spacing in the WE direction, while DY in the SN direction. CENTLON and CENTLAT are the coordinates of the grid centre.

Chapter 3

Analysis of Medicane Numa

3.1 Main characteristics and structure

The track of the storm is reconstructed from the output data of the RAMS-ISAC model used in Marra et al. [5] extracting the sea level pressure (SLP) minimum in the area of the storm every 3 hours. The results are shown in Figure 3.1. The Medicane initially shows an erratic movement from the beginning of the simulation on 17 November at 12:00 UTC up to 17 November at 18:00 UTC, then enters a stationary state, persisting over the Ionian sea until 18 November at 03:00 UTC, when the system starts to shift south-eastward, approaching the coasts of Greece. The longevity of the stationary phase is confirmed by an hourly search of the SLP minimum on a 10-hour time span starting from 17 November at 17:00 UTC, leading to a detection of only 4 distinct SLP positions.

The temporal evolution of the SLP minimum (Figure 3.2) presents a steady and limited increase in value, showing that the simulation describes a mature stage of the cyclone. The increase over 24 hours from the start of the simulation is only 4 hPa, highlighting the stability of the system over the full length of the TLC phase.

The pressure field is furtherly analysed, allowing a description of the Medicane structure. Figure 3.3a shows the SLP field on 17 November at 18:00 UTC, indicating an intense SLP low, with a strong gradient of $\sim$5 hPa/50 km and a marked symmetrical structure. The comparison with Figure 3.3b, displaying the SLP field on 18 November at 05:00 UTC, emphasizes that the system maintains the structure during the mature phase, only marginally losing intensity.

One of the key features that distinguish Medicanes from the much more common Mediterranean extratropical cyclones is the presence of a warm core caused by the release of latent heat, as opposed to the cold core of the aforementioned extratropical cyclones. To highlight this feature, the temperature anomaly with respect to the mean value is computed. The structure of Medicane Numa clearly emerges from the temperature anomaly field at 700 hPa on 17 November at 21:00 UTC (Figure 3.4). The cyclone

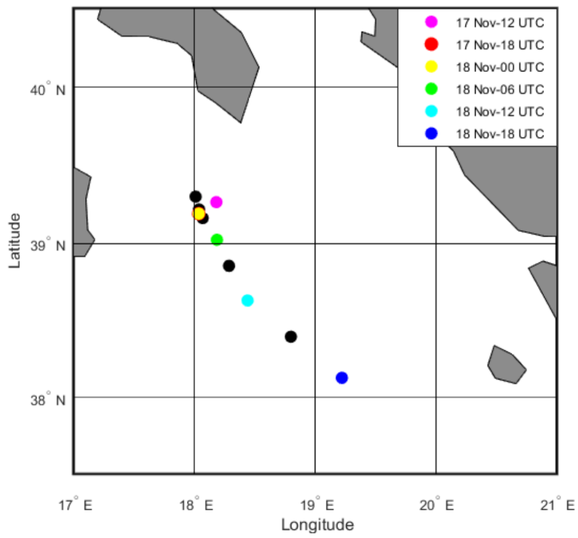


Figure 3.1: Track of Medicane Numa between 17 November at 12:00 UTC and 18 November at 18:00 UTC, represented by the position of the SLP minimum every 3 hours. Specific times are shown in color. The red marker indicating the position on 17 November at 18:00 UTC is made bigger to correctly reproduce the stationarity of the storm.

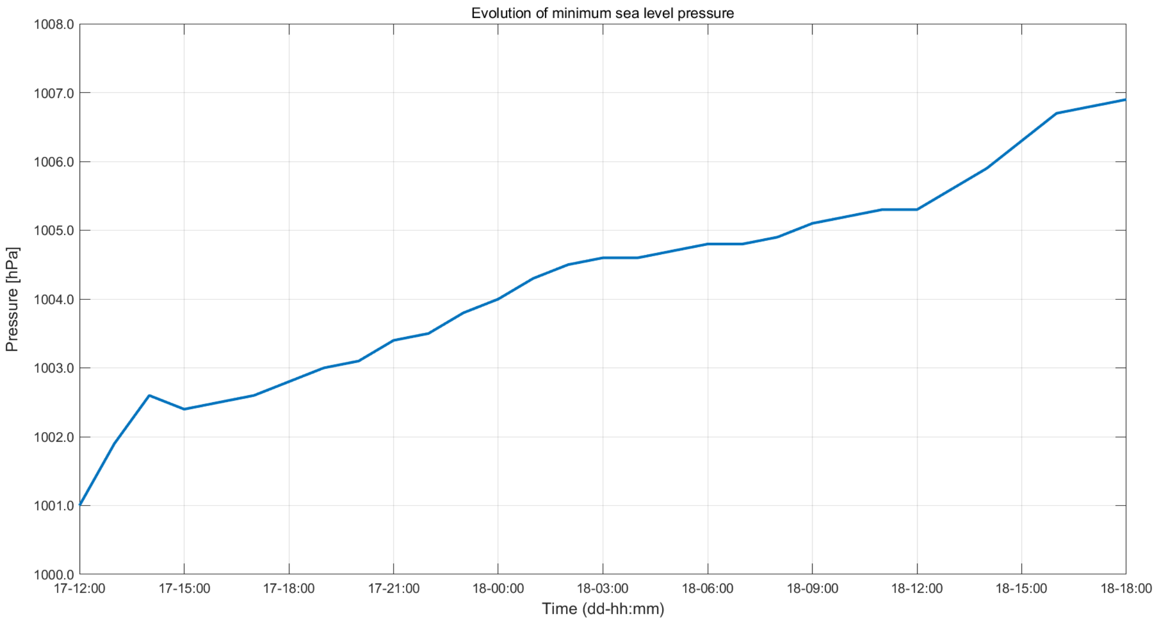
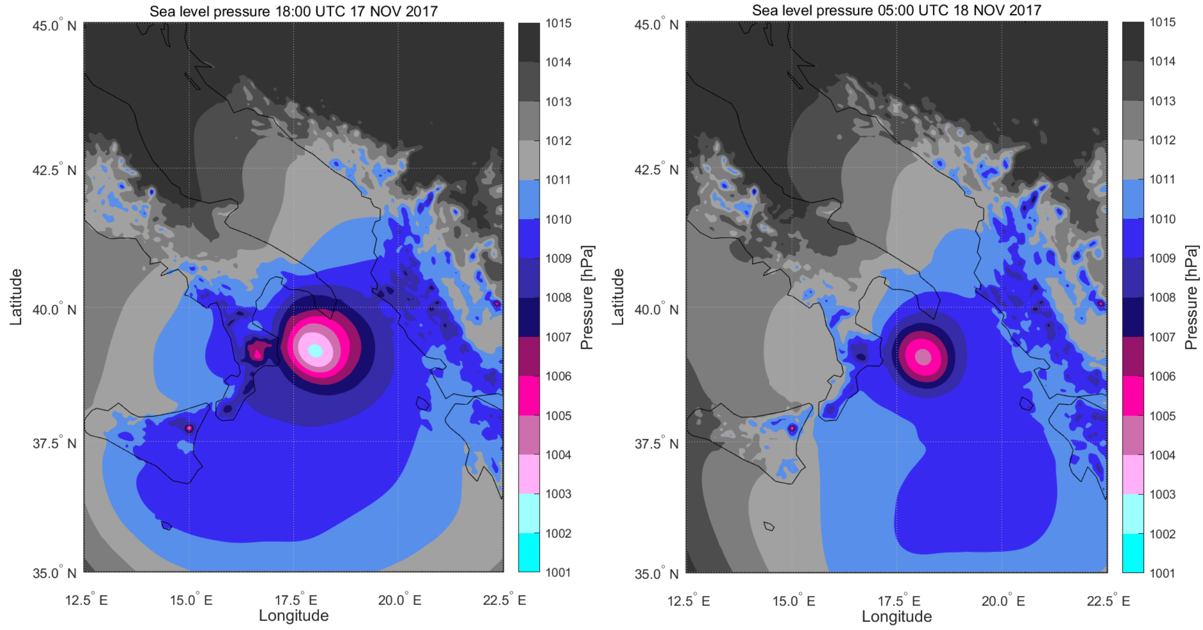


Figure 3.2: Temporal evolution of Medicane Numa minimum sea level pressure (hPa). The SLP minimum is computed every hour.



(a) **(b)**

Figure 3.3: Sea level pressure (hPa) on (a) 17 November at 18:00 UTC and (b) 18 November at 05:00 UTC.

shows a distinct warm core at its centre, with a peak of ∼3 °C of positive anomaly. It is worth noting that the pronounced symmetry encountered in the analysis of the SLP field is retrieved also in the temperature anomaly field: the fact that the axis-symmetric structure is obtained through the analysis of different physical parameters shows that the system is strongly organized, in particular during its mature phase.

The temperature anomaly field proves to be a suitable parameter to furtherly depict the structure of the storm, this time focusing on the vertical rather than the horizontal structure. The temperature anomaly field is evaluated at each vertical level. Figure 3.5 shows the vertical cross-section along 39.2 °N latitude on 18 November at 00:00 UTC, through the centre of the storm. The cross-section shows the characteristics of the warm core, which starts at ∼1 km of hight, has its maximum of temperature anomaly at 3 km of height and reaches up to 8 km of height. As mentioned in the introduction, the main phenomenon responsible for the strengthening and maintenance of Medicanes is the latent heat release, allowing a thermodynamical analysis to resolve the inner structure of the system. The picture emerging is that of a system much more compact than common extratropical cyclones, the warm core takes only a part of the full extension of the Medicane and exhibits a symmetrical configuration around the centre of maximum temperature anomaly. In particular, the diameter of the inner column of the warm core estimated via this plot is 75 km, while the full extension of the temperature anomaly

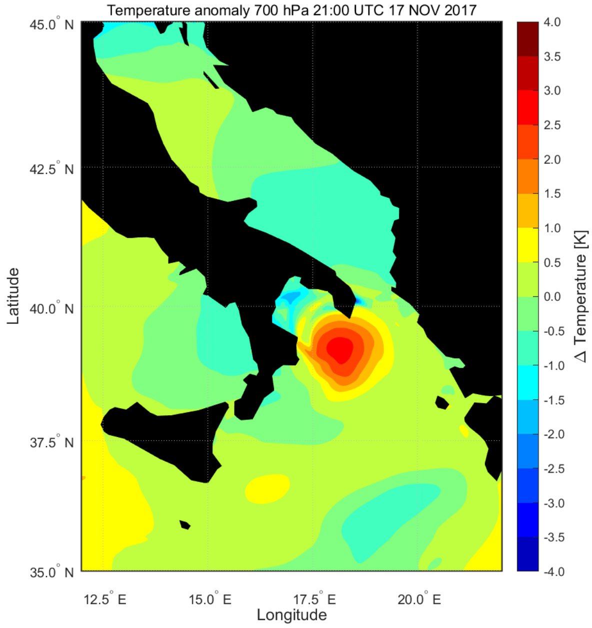


Figure 3.4: Temperature anomaly with respect to the mean value at 700 hPa on 17 November at 21:00 UTC.

is 150 km. The vertical extension of the warm core is linked to the duration of the TLC phase [7], the simulation of Numa shows a considerable vertical extension that contributes to explain the long persistence of the TLC phase and the maintenance of the main characteristics through the long-lasting mature phase.

A deeper understanding of the vertical structure of Medicane Numa can be achieved complementing the temperature anomaly field with another meaningful physical parameter, for this reason in Figure 3.5 the meridional wind speed is superimposed. Positive values indicate a northward wind, while negative values a southward wind. It is immediately evident that the centre of the warm core coincides with the eye of the storm, where the wind is very calm or absent. The core presents a low vertical wind shear up to 6 km of height, a peculiar characteristic of tropical-like systems. The maximum wind speed occurs in the vortex eyewall around the warm core, extending from the surface up to 2 km of height. It is interesting to note how the combined use of the temperature anomaly and meridional wind speed allows to represent the complete structure of the Medicane, highlighting both the warm core and the eyewall. The diameter of the portion of the Medicane that fully includes the eyewall, estimated via this plot, is 230 km, confirming that the temperature anomaly resolves only the inner part of the storm. The region of intense wind is limited to the lower troposphere, as indicated by the rapid decrease of wind speed above 2 km of height.

The analysis above suggests to examine the horizontal wind field in the lower tro-

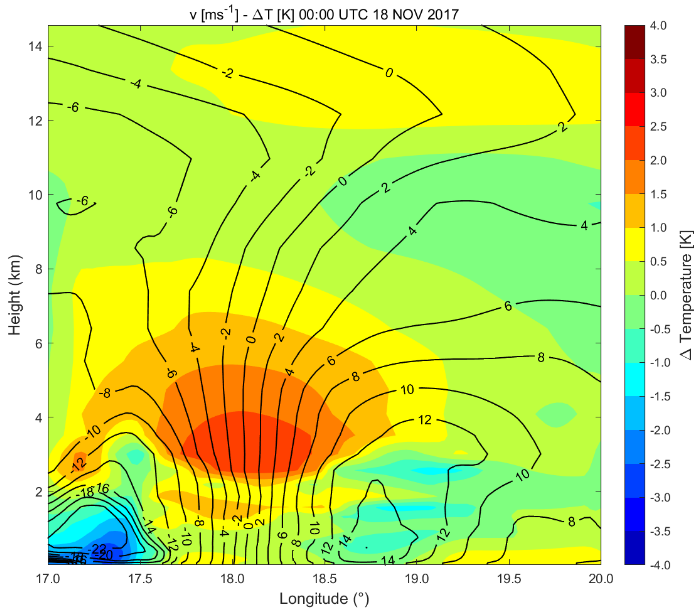


Figure 3.5: Vertical cross section of temperature anomaly (filled contours) and meridional wind speed (black contours) along 39.2 °N on 18 November at 00:00 UTC. The temperature anomaly is computed with respect to the mean value at each vertical level. The wind speed is in m/s, positive values indicate northward wind, negative indicate southward wind.

posphere. The first vertical level of the RAMS-ISAC simulation is at 24 m above sea level, allowing the representation of the horizontal wind field close to the sea surface. On 18 November at 00:00 UTC (Figure 3.6) the area of maximum wind speed forms a narrow band outside the south-western side of the eye, allowing the identification of the eyewall. Despite being noticeable by geometry, the symmetry of the eyewall wind is less marked with regards of intensity, the north-eastern side of the eyewall winds blowing 5 m/s less intense than the 19 m/s of surface wind speed on the south-western side, where the maximum is recorded. The wind field is extremely sensible to external factors, in this instance the orography plays a role in defining the geometry. The presence of the mountains of Calabria region contributes to squeeze the air masses in a narrow band on the western flank of the Medicane, increasing the wind speed due to Bernoulli's principle. The above analysis makes even more remarkable how the wind field is able depict a highly symmetric and distinct region of absent wind, identifying the eye of the cyclone.

All the previous analysis allowed the identification of the main features characterizing Numa as a TLC, with its warm core, the wind arranged in the vortex eyewall, a calm eye, a low vertical wind shear and a marked symmetry. The final feature still lacking is the characteristic spiral pattern of the cloud bands, generally obtained through satellite observation [5]. Exploiting the hydrometeors introduced in the WSM6 microphysics parametrization implemented in the RAMS-ISAC model, this feature is investigated

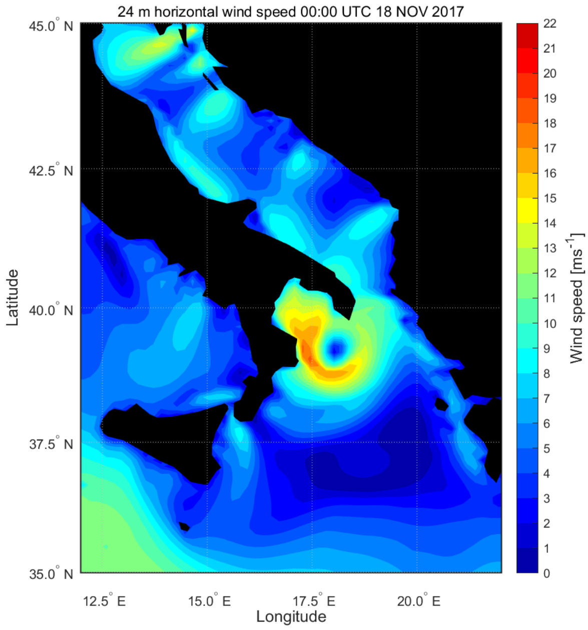


Figure 3.6: Horizontal wind speed (m/s) 24 m above sea level on 18 November at 00:00 UTC.

evaluating the mixing ratios of rain and cloud hydrometeors. Figure 3.7 shows the superposition of the cloud (grayscale) and rain (green contours) mixing ratios at 850 hPa on 18 November at 05:00 UTC. Numa exhibits a spiral configuration with both rain and cloud hydrometeors, consisting of a main spiral band on the north-western flank of the eye, where the highest mixing ratios are recorded, and a split band on the south-eastern flank of the eye. Remarkably, the distinct structure of the spiral bands outlines with impressive definition the shape of the eye, which has a diameter of 75 km at this stage of development. It is worth noting that the analysis above indicates that the system displays a significant organization 17 hours after the start of the simulation, which as previously stated represents only the simulated TLC and the decay phase, showing the persistence of the main features of the Medicane during the mature phase of the cyclone.

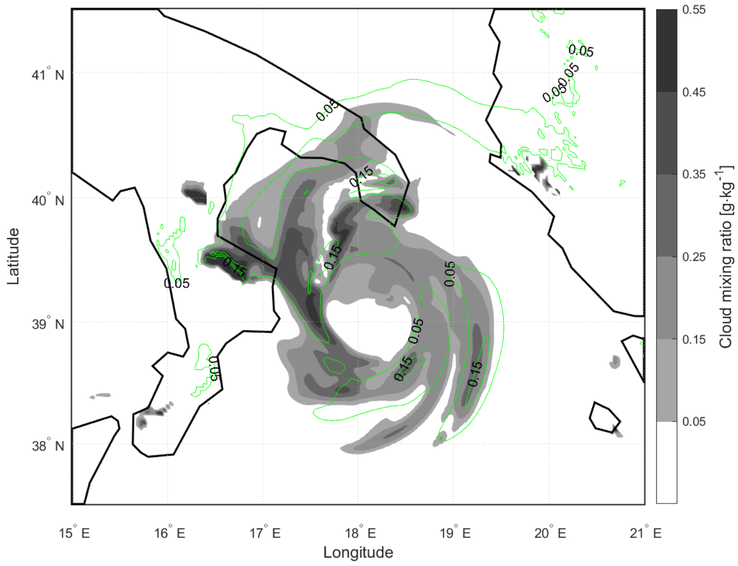


Figure 3.7: Cloud (grayscale) and rain (green contours) mixing ratios (g/kg) at 850 hPa on 18 November at 05:00 UTC.

3.2 Evolution of the cyclone

The previous section illustrated how a generic cyclone can be effectively described studying different physical parameters, in Numa's case all the features indicated that the cyclone was a Medicane at a certain stage of its development. Examining the evolution of a cyclone it is possible to gather more and different information about the characteristics of the system. A first main reason to investigate the evolution of cyclones is that they do not exist exclusively in the conventional tropical or extratropical types, but rather in a variety of types ranging between this two main identifications. Moreover, a cyclone's life cycle can involve multiple phases, it is clear that in these situations a snapshot of the system provides only partial information. A second reason is given by the fact that transitions between phases imply the variation of intensity and relative importance of the processes involved in the cyclone, allowing the identification of the main drivers for development towards the different phases. It is clear from the introduction that these reasons are especially strong for Medicanes, as they are intrinsically hybrid systems. In this section the evolution of Medicane Numa is analyzed, starting from the acquisition of TLC features.

A first analysis of the evolution of Numa is carried out using the phase space diagram proposed by Robert Hart [8], which allows to convert three dimensional geopotential height data into information about the structure of the cyclone. The time evolution is translated into the trajectory of the cyclone in the phase space, fully characterizing the history of the storm. Three parameters are defined to describe the structure of cyclones: the lower-tropospheric thermal asymmetry B, the lower-tropospheric thermal wind $-V_T^L$ and the upper-tropospheric thermal wind $-V_T^U$. The thermal asymmetry parameter is introduced to distinguish frontal cyclones from non-frontal ones. It is defined as

$$B = \overline{Z_{600hPa} - Z_{900hPa}}\ |_R - \overline{Z_{600hPa} - Z_{900hPa}}\ |_L \tag{3.1}$$

where Z is the geopotential isobaric height, R indicates right of current storm motion, L indicates left of current storm motion, the overbar indicates the areal mean over a semicircle of radius R_{ex}, called the exploration radius. Equation (3.1) suggests that the thermal asymmetry is essentially the 900-600 hPa thickness asymmetry with respect of the storm motion evaluated in a circle of radius R_{ex}. The exploration radius proposed by Hart is 500 km, which is appropriate for hurricanes and extratropical cyclones, but too large for Medicanes as demonstrated in Section 3.1. Many studies used different approaches regarding the exploration radius, some used a fixed value [4], generally in the 70-100 km range, others used a storm-size dependent radius [9], evaluating the mean radius of the warm core. In the present work the main limitation is the influence of orography, this led to a choice of 50 km and 70 km for R_{ex}. The 70 km radius allows to cover almost the full extension of the warm anomaly, while the 50 km radius covers only the inner core. The B parameter has the dimension of a length, a value for B that is close to zero indicates a mature tropical cyclone featuring thermal symmetry or non-frontal structure, while a large value of B indicates a developing extratropical cyclone featuring thermal asymmetry or a frontal structure. The threshold proposed by Hart to distinguish symmetric from non-symmetric systems is $B = 10$ m.

The $-V_T^L$ and $-V_T^U$ thermal wind parameters allow to ascertain if the cyclone presents a warm or a cold core, respectively in the lower and upper troposphere. The physical parameter used for this analysis, extracted from the model output data, is the geopotential height. Indeed, thanks to the definitions of geostrophic wind

$$\mathbf{V}_g \equiv \frac{g}{f}\mathbf{k} \times \nabla Z \tag{3.2}$$

where f is the Coriolis parameter and $\mathbf{k}$ is the local vertical unit vector (positive upwards), and the definition of thermal wind

$$\mathbf{V}_t \equiv (\mathbf{V}_g)_2 - (\mathbf{V}_g)_1 = \frac{R}{f}\ln\left(\frac{p_1}{p_2}\right)\mathbf{k} \times \nabla(\bar{T}) = \frac{g}{f}\mathbf{k} \times \nabla(Z_2 - Z_1) \tag{3.3}$$

where the subscripts indicate different vertical levels, $\bar{T}$ the vertically averaged layer temperature, R the specific gas constant for air, it is clear that the isobaric geopotential height gradient (thus, the geostrophic wind magnitude) increases with height in presence of a cold core, while it decreases in presence of a warm core.

It is important to point out that cyclones present both a warm and a cold core, depending on the atmospheric layer examined, in this work the focus is on the tropospheric atmosphere, which gives enough information to distinguish the phases of a generic cyclone. The layers examined are the 900-600 hPa for the lower troposphere (consistent with the definition of B) and the 600-300 hPa for the upper troposphere. The cyclone height perturbation

$$\Delta Z = Z_{MAX} - Z_{MIN} \tag{3.4}$$

is evaluated in the circle defined by R_{ex}. Defining d as the distance between Z_{MAX} and Z_{MIN}, ΔZ is proportional to the magnitude of the geostrophic wind

$$\Delta Z = \frac{fd}{g}|\mathbf{V}_g|. \tag{3.5}$$

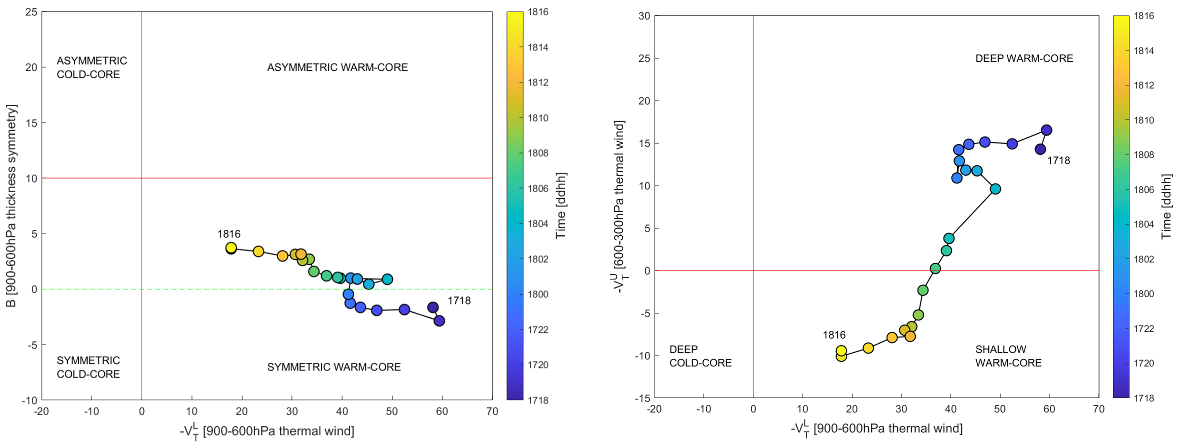
The vertical structure can then be defined as the vertical derivative of ΔZ on the pressure levels, resulting in a scaled thermal wind:

$$\left.\frac{\partial(\Delta Z)}{\partial \ln(p)}\right|_{900hPa}^{600hPa} = -|\mathbf{V}_T^L| \tag{3.6}$$

$$\left.\frac{\partial(\Delta Z)}{\partial \ln(p)}\right|_{600hPa}^{300hPa} = -|\mathbf{V}_T^U|. \tag{3.7}$$

The two parameters can be computed performing the linear regression fit of the vertical profile of ΔZ in equation (3.6) and (3.7), extracting the slope. In the present work, the technique suggested by Hart is followed, employing an interpolating vertical increment of 50 hPa, providing seven pressure levels on which the linear regression was performed and allowing an accurate description of the vertical profile of ΔZ. From the analysis above it follows that $-|\mathbf{V}_T|$ is positive in presence of a warm core and negative in presence of a cold core. The combination of the upper and lower troposphere thermal wind allows to characterize extratropical cyclones as systems with a cold core in both layers, tropical cyclones as systems with a warm core in both layers and hybrid systems when the two layers have opposite sign of themal wind. Due to the sensitivity of the geopotential height to orography, Numa's Hart diagram is realized between 17 November at 18:00 UTC and 18 November at 16:00 UTC, avoiding the periods in which the cyclone is too close to the coasts of Italy and Greece to correctly represent the phase of the system.

To be classified as a Medicane, Numa should present tropical characteristics, with a symmetric structure and a warm core in both lower and upper troposphere throughout the TLC phase. Figure 3.8 represents the Hart diagram with an exploration radius of 70 km. Numa shows a warm core in both upper and lower troposphere and a symmetric structure between 17 November at 18:00 UTC and 18 November at 07:00 UTC, then it assumes hybrid characteristics, showing only a shallow warm core with a degraded but still symmetric structure. The left panel (3.8a) shows that Numa maintains a symmetric warm core throughout the considered period, with a peak in symmetry on 18 November at 00:00 UTC, when B is close to zero, and a progressive loss of organization, faster during the last hours of the simulation, as demonstrated by the larger spacing between

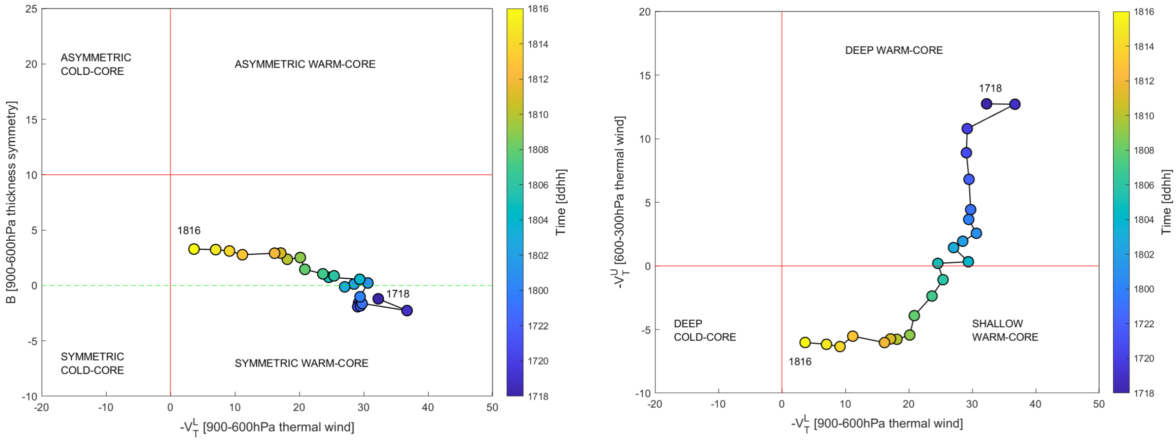


(a) (b)

Figure 3.8: Hart diagram with an exploration radius of 70 km. The diagram represents the phase trajectory between 17 November at 18:00 UTC and 18 November at 16:00 UTC.

the points of the diagram. The right panel (3.8b) shows that Numa presents a weaker upper-tropospheric warm core compared to the lower-tropospheric counterpart. It is also noticeable that after an initial loss of intensity of the lower warm core, the phase-space trajectory describes a faster weakening of the upper warm core, evidencing that the surface fluxes of moisture and heat, and the latent heat released from convection are insufficient to sustain an intense upper warm core. Despite being computed every hour, the trajectory on the Hart phase space presents a limited noise, allowing the identification of some interesting stages of the cyclone. Between 17 November at 21:00 UTC and 18 November at 03:00 UTC Numa goes through a stationary phase, the parameters indicate that the tropical features are maintained and the storm has reached a mature phase of its development. The Hart diagram describes this phase displaying points that are close together and a trajectory that does not show a clear direction (both panels show a "c" shape trajectory). This phase roughly coincides with the stationary phase of the actual trajectory of the storm, indicating that the Ionian sea provided optimal condition for Medicane maintenance. Successively, the storm enters a weakening phase, with an increase of B and a decrease of both thermal winds, the points on the phase space are spread out and indicate a clear direction. Interestingly, this phase does not last until the end of the simulation, instead it is interrupted by a short-lived phase of intensification, noticeable by the sudden stacking up of the points from 18 November at 09:00 UTC and 18 November at 13:00 UTC. The storm then encounters a faster decay until the end of the simulation.

The Hart diagram with 70 km of exploration radius is able to classify Numa as a Medicane, give a clear indication of the overall evolution and even identify the various subphases that occurred during its life. It is interesting to see if the same analysis can be carried out with a 50 km exploration radius, remembering that the different radius implies a different region of the storm investigated: the 70 km R_{ex} covers almost the full extension of the warm core of the cyclone, while the 50 km R_{ex} covers only the inner core. Figure 3.9 shows that the Hart diagram with 50 km R_{ex}, although similar to the previous one, provides less clarity regarding the subphases. The cyclone achieves a Medicane classification, but the hybrid transition gets shifted two hours earlier. All the subphases are detected, but represented in less clear way. The stationary phase is much closer to the hybrid transition and it is represented by points that are more spaced compared to the 70 km case. The weakening phase is correctly displayed, but covers a shorter distance on the phase space, suggesting a less intense weakening of the inner core. Finally, the short intensification phase is obtained with less definition, as the points are more spread out. While the above analysis indicates an overall agreement of the two diagrams, one main difference can be spotted. The initial phase, connecting the acquisition of TLC status and the mature phase, shows a completely different behavior, the 70 km suggests a weakening of the lower tropospheric warm core and a substantially unchanged upper tropospheric warm core, while the 50 km diagram exhibits the exact opposite and a longer duration of this phase, ending on 17 November at 23:00 UTC. This



(a) (b)

Figure 3.9: Hart diagram with an exploration radius of 50 km. The diagram represents the phase trajectory between 17 November at 18:00 UTC and 18 November at 16:00 UTC.

analysis seems to suggest that a complex reorganization leads the cyclone to a mature phase. The successive parts of this section will address this process, trying to give a visual representation using the cross sections of temperature anomaly.

Many studies pointed out the lower vertical extension of Medicanes compared to extratropical cyclones and hurricanes, sometimes leading to the choice of lower pressure levels compared to the standard ones suggested by Hart. A sensitivity test was carried out on both the 70 km and 50 km diagrams, lowering the highest pressure level to 350 hPa. The diagrams showed no significant differences.

Analyzing the time evolution of the parameters introduced in Section 3.1, it is possible to confirm the validity of the conclusions drawn examining the Hart diagrams and further investigate the evolution of the Medicane, giving a visual representation of the different subphases. Figure 3.10 shows the hourly evolution of the maximum temperature anomaly simulated in the whole system. Without information on the geometry of the system, but looking only at the maximum of temperature anomaly, the plot indicates a remarkably regular decrease of the parameter, which loses ∼0.8 °C over 15 hours, up to 18 November at 09:00 UTC. The time period of the stationary phase represents the only deviation from the almost constant temperature anomaly decrease of the initial hours, as expected considering the marginal phase variation suggested by the Hart diagram. The subsequent phase of intensification is clearly visible, causing an increase of ∼0.3 °C over 4 hours. The value then continues to drop in the latter stages of the development, when the Medicane's final weakening occurs. The phase of intensification gives a numerical indication of the validity of the subphases detected by the Hart diagram, proving how a phase space analysis is able to describe in detail the time evolution of a cyclone, in addition to being

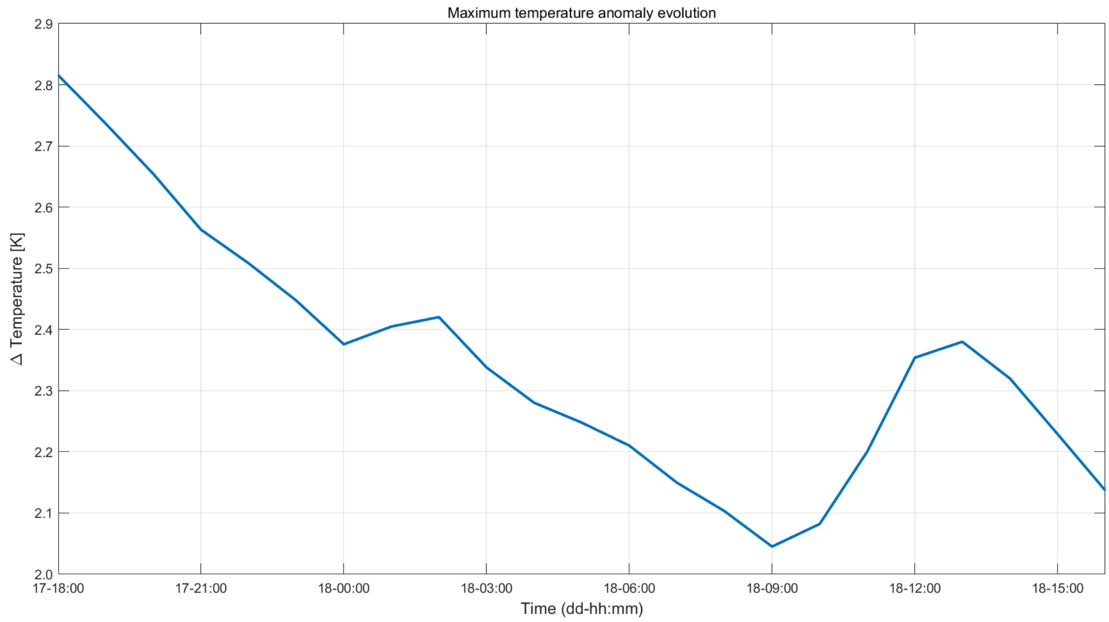
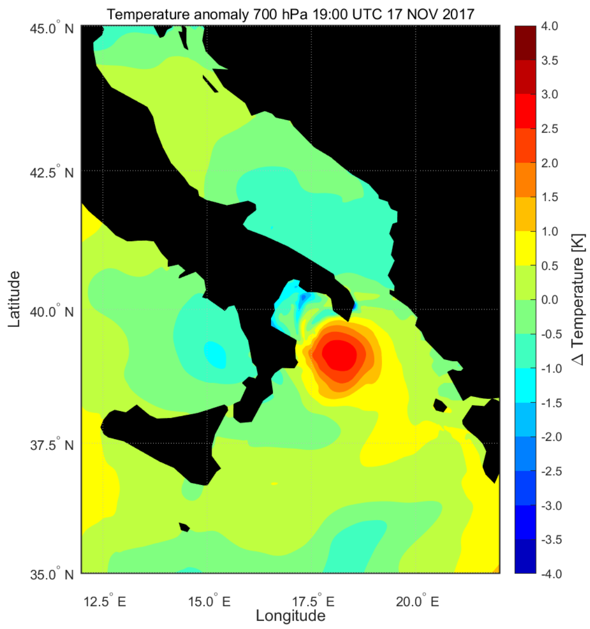


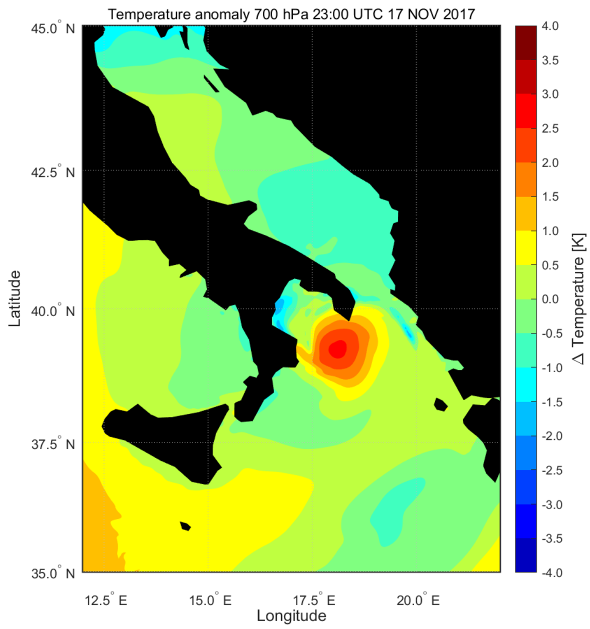
Figure 3.10: Time evolution of the maximum temperature anomaly simulated in Medicane Numa.

capable of assessing the cold or warm nature of the core and the frontal or non-frontal structure of the system.

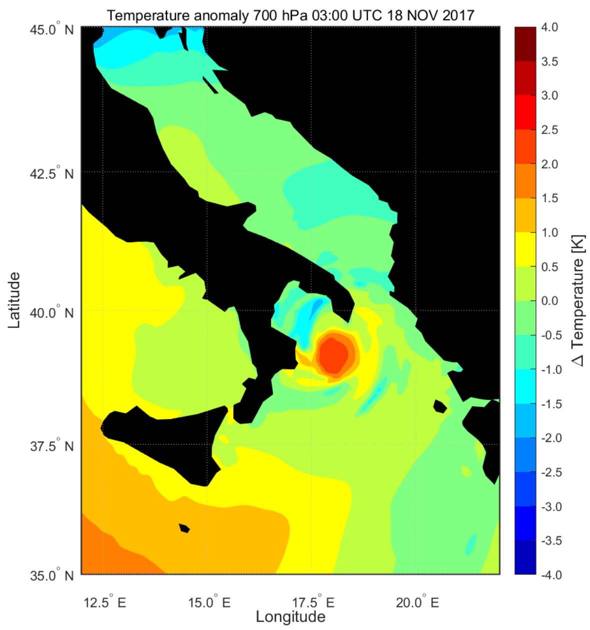
The time evolution of the temperature anomaly computed at 700 hPa is shown in Figure 3.11. It is interesting to note the behavior of Medicane Numa in the initial phase and stationary phase. The system loses both spatial extension and peak magnitude of temperature anomaly in the initial phase (3.11a and 3.4), then the system continues to shrink without losing intensity in the inner core during the initial part of the stationary phase (3.11b), reaching an equilibrium during the last hours of the stationary phase (3.11c), in which the system shows a stable warm core with a temperature anomaly of $\sim$2 °C over its full extension. This analysis describes the process by which the cyclone reorganizes after acquiring tropical features, losing the baroclinic characteristics obtained during the cyclogenesis phase and reaching a very compact structure. Despite being already in the weakening phase, the structure on 18 November at 05:00 UTC (3.12) gives a particularly good example of a Medicane during its mature stage, with a very compact and symmetric organization and a very marked warm core. At this stage of development, the cyclone is far from the coasts, the reduced influence of orography facilitates the achievement of such an organized structure. The successive phase of weakening (3.11d) highlights how, once the cyclone reached its mature stage, the system loses intensity with a remarkably limited loss of symmetry and horizontal extension.


Temperature anomaly 700 hPa 19:00 UTC 17 NOV 2017
Latitude
Longitude
Δ Temperature [K]

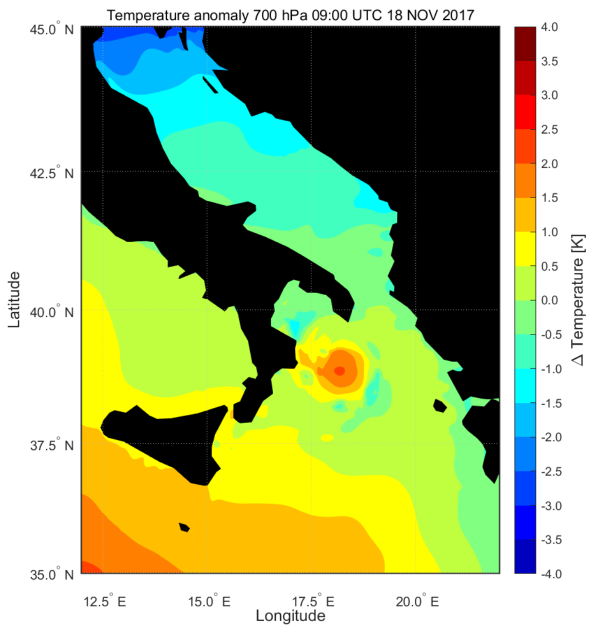
(a)


Temperature anomaly 700 hPa 23:00 UTC 17 NOV 2017
Latitude
Longitude
Δ Temperature [K]

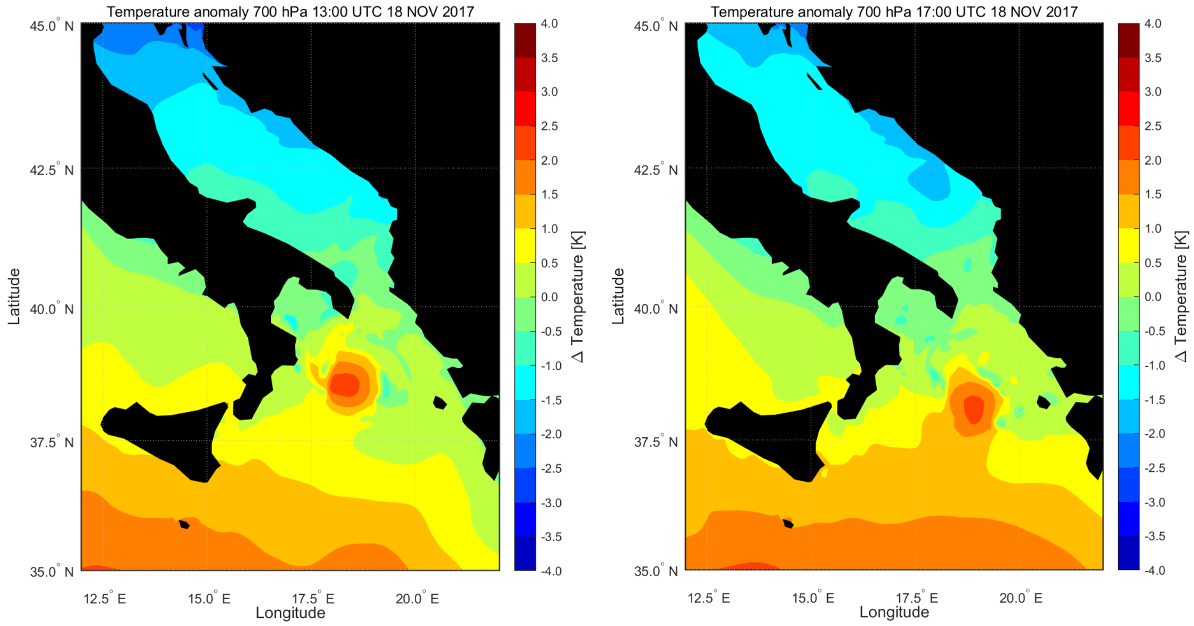
(b)


Temperature anomaly 700 hPa 03:00 UTC 18 NOV 2017
Latitude
Longitude
Δ Temperature [K]

(c)


Temperature anomaly 700 hPa 09:00 UTC 18 NOV 2017
Latitude
Longitude
Δ Temperature [K]

(d)



(e) **(f)**

Figure 3.11: Temperature anomaly with respect to the mean value at 700 hPa on (a) 17 November at 19:00 UTC (b) 17 November at 23:00 UTC (c) 18 November at 03:00 UTC (d) 18 November at 09:00 UTC (e) 18 November at 13:00 UTC (f) 18 November at 17:00 UTC.

This process is visually represented by the significantly less intense warm core displayed by the system on 18 November at 09:00 UTC, with only a small portion above 2 °C of temperature anomaly, while the structure is almost the same showed on 18 November at 03:00 UTC. Figure 3.11e shows the significant impact of the brief intensification, leading to a substantial strengthening of the warm core. On 18 November at 13:00 UTC the region of the warm core with a temperature anomaly over 2 °C has a much larger spatial extension compared to the hours ahead of the strengthening phase. It is worth noting that the system exhibits a degraded but still organized structure even during its hybrid phase, more than one day after the acquisition of TLC status. The longevity of the symmetric structure, obtained in the analysis of the Hart diagram with the thermal asymmetry never exceeding the 10 m threshold, is now successfully retrieved directly studying the temperature anomaly at 700 hPa. The final weakening of the cyclone is characterized by a quick loss of organization. On 18 November at 17:00 UTC (3.11f) the system shows a poor symmetry, while the intensity of the warm core is less affected, illustrating a different course compared to the previous weakening process.

As seen in the previous section, the temperature anomaly field can be furtherly used, this time to investigate the time evolution of the vertical structure of Medicane Numa. The time evolution of the vertical cross-section of temperature anomaly is showed in

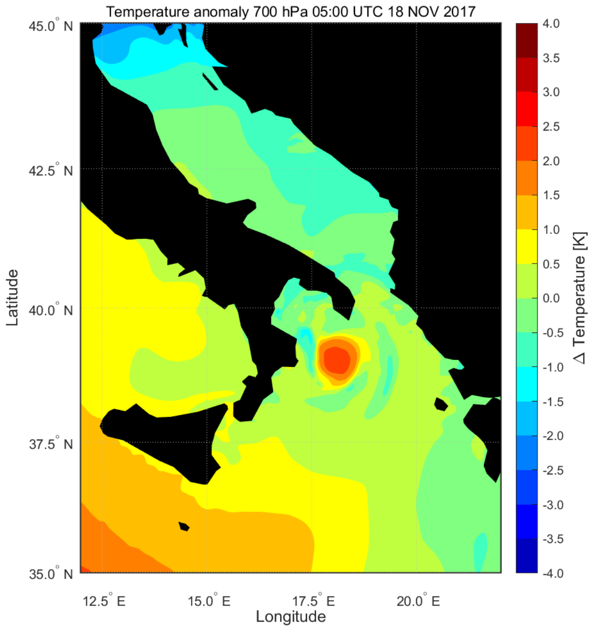
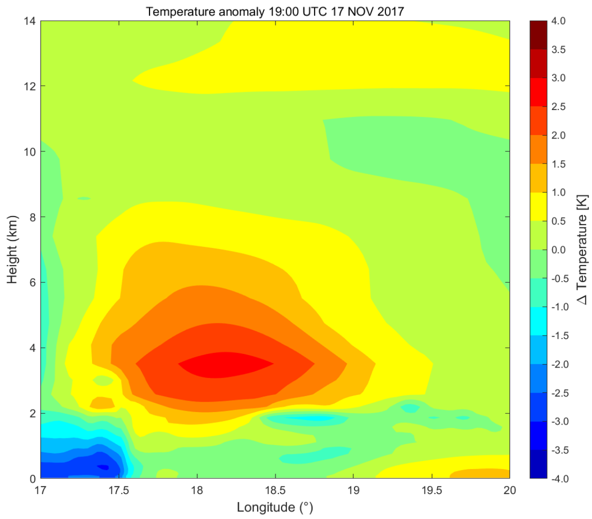
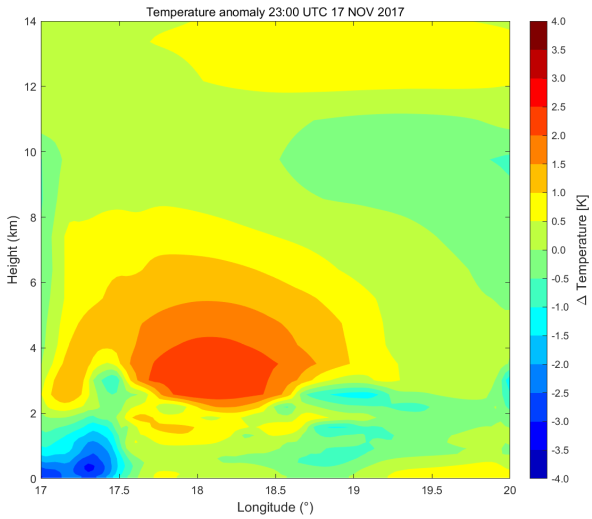


Figure 3.12: Temperature anomaly with respect to the mean value at 700 hPa on 18 November at 05:00 UTC.

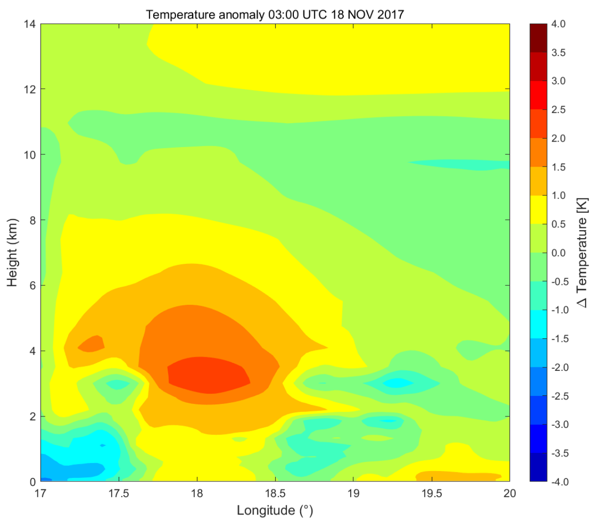
Figure 3.13. Each plot represents the vertical cross-section at constant latitude, through the centre of the cyclone. The plots describing the initial phase (3.13a and 3.13b) and the stationary phase (3.5 and 3.13c) provide valuable insights on the crucial process described in the analysis of the 700 hPa temperature anomaly. On 17 November at 19:00 UTC Medicane Numa features a very intense and organized warm core, with a peak value of temperature anomaly over 2.5 °C. The warm core has a large horizontal extension between 2 and 4 km of height. On 17 November at 23:00 UTC, which marks the end of the initial phase, Numa presents a weaker warm core, with a maximum temperature anomaly lower than 2.5 °C. The system has lost part of its overall extension, but most importantly the horizontal extension of the lower warm core is significantly reduced. This behavior explains the discordance of the two Hart diagrams: while the 70 km exploration radius is able to record the shrinking of the lower tropospheric warm core, the 50 km one is restricted to the inner part of the core and misses the phenomenon. Surprisingly, even if the Hart diagram with a 50 km exploration radius provides a worst representation of the phase evolution of the storm, the combination with the diagram realized with a 70 km exploration radius allows the identification of the process that brings a system that has recently acquired tropical characteristics to its mature tropical phase. Numa displays a pronounced symmetry in both plots, proving that the initial phase does not degrade the axial symmetry of the Medicane. The cross-section on 18 November at 03:00 UTC shows the situation at the end of the stationary phase,


Temperature anomaly 19:00 UTC 17 NOV 2017
Height (km)
Longitude (°)
Δ Temperature [K]

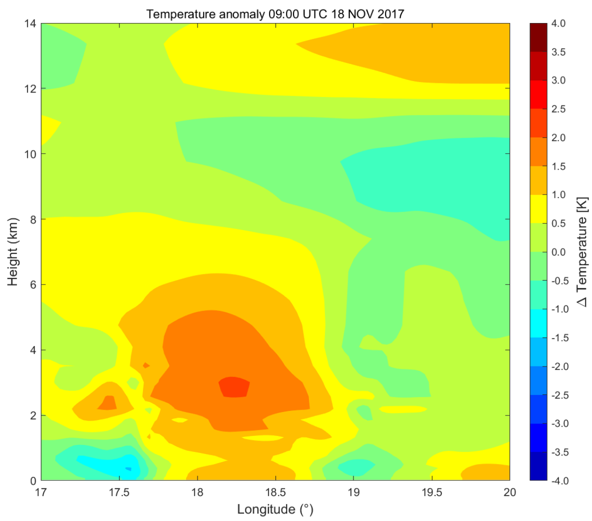
(a)


Temperature anomaly 23:00 UTC 17 NOV 2017
Height (km)
Longitude (°)
Δ Temperature [K]

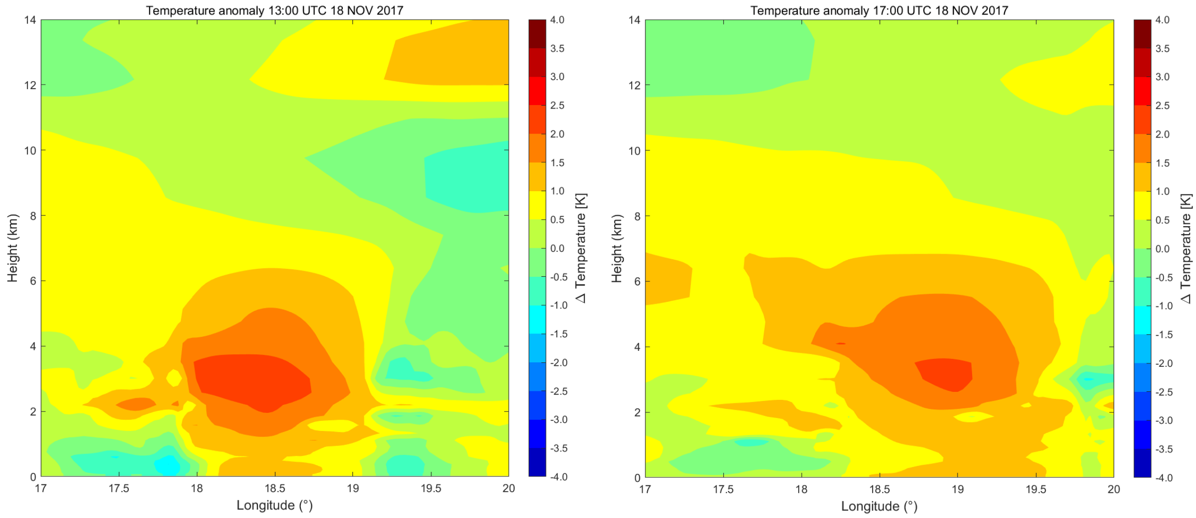
(b)


Temperature anomaly 03:00 UTC 18 NOV 2017
Height (km)
Longitude (°)
Δ Temperature [K]

(c)


Temperature anomaly 09:00 UTC 18 NOV 2017
Height (km)
Longitude (°)
Δ Temperature [K]

(d)



(e) (f)

Figure 3.13: Vertical cross-sections of temperature anomaly on (a) 17 November at 19:00 UTC along 39.2 °N (b) 17 November at 23:00 UTC along 39.2 °N (c) 18 November at 03:00 UTC along 39.2 °N (d) 18 November at 09:00 UTC along 38.9 °N (e) 18 November at 13:00 UTC along 38.6 °N (f) 18 November at 17:00 UTC along 38.2 °N.

allowing a further description of the consequences of the process that leads Numa to lose its initial baroclinic characteristics. Removing the outer regions, the Medicane has reduced its horizontal extension but not the intensity of the warm core, still showing over 2 °C of temperature anomaly, reaching a compact and intense form. The successive weakening, which ends on 18 November at 09:00 UTC (3.13d), significantly reduces the intensity of the storm, with only a very limited part of the warm core recording over 2 °C. As discussed previously, the weakening phase subsequent to the acquisition of a mature structure acts on the intensity of the storm, but keeps its horizontal extension mostly unchanged. It is interesting to note that even if the structure is still symmetric, it starts to show signs of tilting, drifting the cyclone away from the vertically stacked structure, characteristic of tropical systems, towards the tilted structure of extratropical cyclones. The remarkable persistence of an axis-symmetric structure is confirmed by the limited magnitude of the effect described above, remembering that on 18 November at 09:00 UTC almost a full day has elapsed since the acquisition of TLC features, and that the system has completed the first weakening phase. Another interesting feature is the progressive increase of temperature anomaly in the lowest section of the Medicane, below 2 km of height, showing the role of surface fluxes in the maintenance of the Medicane. On 18 November at 13:00 UTC (3.13e) the cyclone presents a considerably more intense warm core, with most of the structure recording a temperature anomaly over 2 °C. The comparison with Figure 3.13d illustrates how strong the phase of brief intensification is,

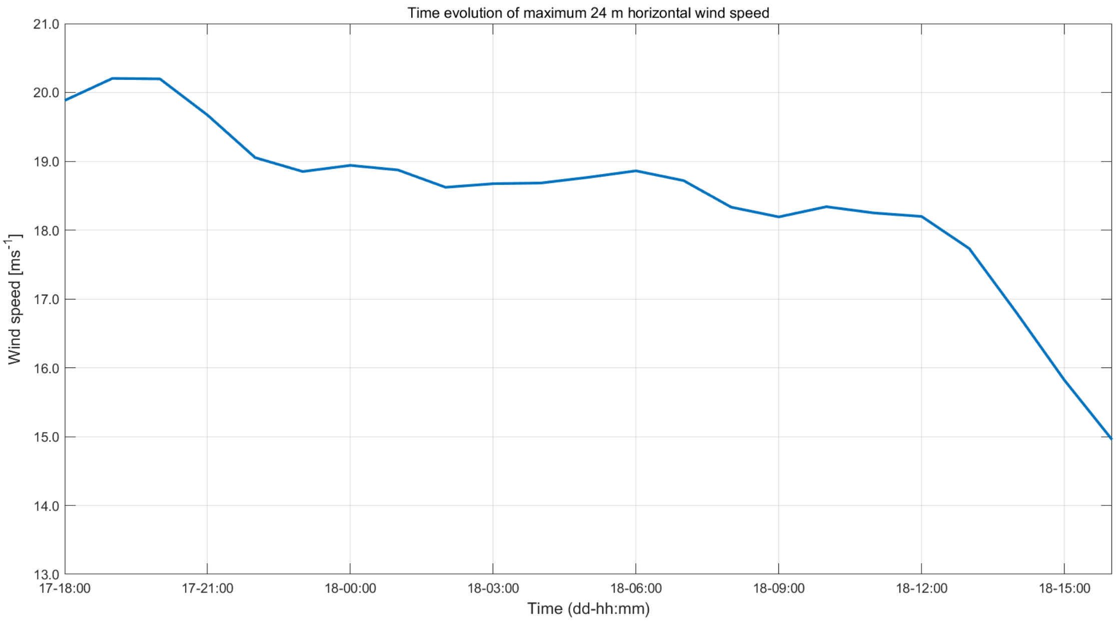
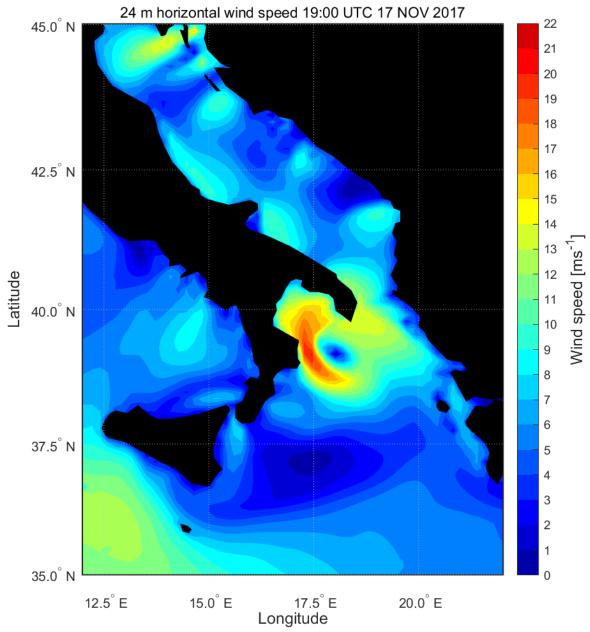


Figure 3.14: Time evolution of the maximum horizontal wind speed 24 m above sea level.

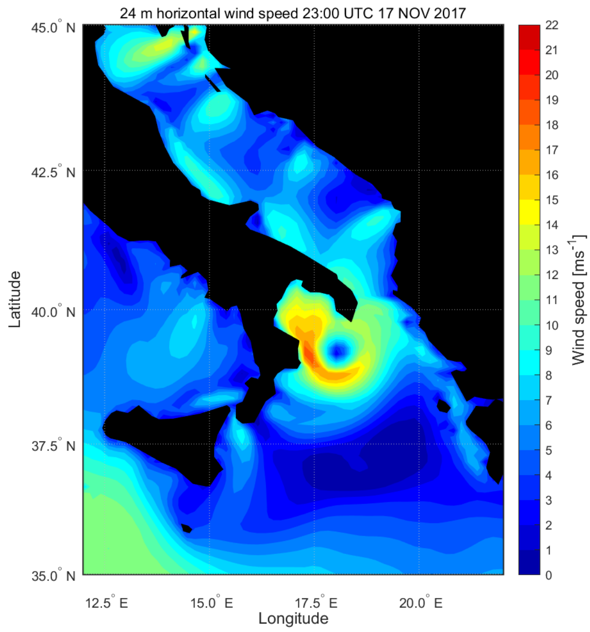
as the warm core shows an intensity comparable with the stages before the weakening. The symmetric structure is present, but degraded compared to the mature phase, with the most intense region of the warm core shifted left rather than being central. The cross section on 18 November at 17:00 UTC (3.13f) describes the quick decay of the storm during the final hours of the simulation. The weakening of the warm core is evident, with a very limited region recording a temperature anomaly over 2 °C. The structure has lost most of its symmetry and compactness, while the tilting of the structure is more marked compared to the first weakening phase.

As discussed in the previous section, the temperature anomaly proves to be a useful parameter to examine both the horizontal and vertical structure of the warm core, but is not able to represent the region of the eyewall, where the maximum wind speed is achieved. For this reason, the time evolution of the maximum wind speed 24 m above sea level is reported in Figure 3.14. The most evident feature is the stability of the maximum wind speed, which remains between 18 and 19 m/s for most of the life of the Medicane. The only two deviations from this constant pattern are the limited increase during the initial phase and the rapid decrease during the final phase of decay. It appears that the maximum surface wind speed is much more sensible to the structure of the cyclone rather than its intensity. A clear example of this behavior is given by the fact that the first weakening, in which the structure was mostly preserved, is not detectable, while the second weakening, in which the structure was significantly degraded, is evident, with a marked decrease of maximum wind speed. This plot evidences even more the persistence of the Medicane, producing winds in excess of 18 m/s throughout most of its life.

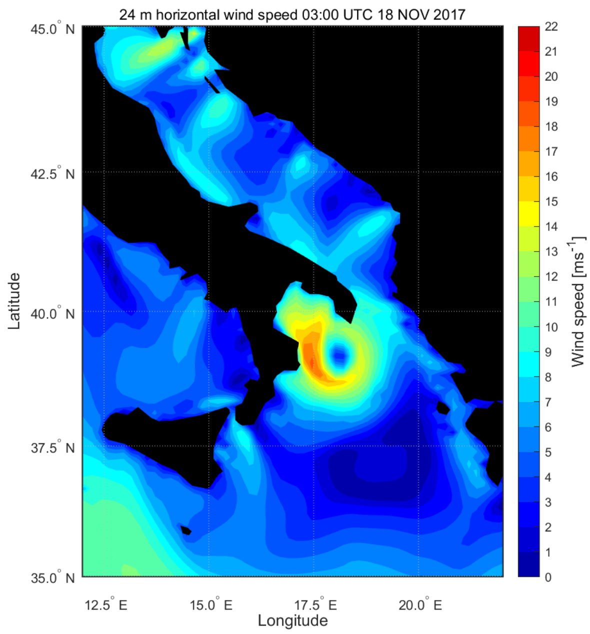
A further understanding of the relation between the eyewall wind speed and the organization of the cyclone can be achieved considering the full horizontal plots of the wind speed 24 m above sea level, represented in Figure 3.15. The structure of the eyewall of Medicane Numa during the initial phase is shown in Figure 3.15a on 17 November at 19:00 UTC. The cyclone presents a well-defined band of strong wind speed on the western flank of the eye, while the rest of the eyewall exhibits significantly less intense wind. The transition to a mature phase (3.15b, 3.6 and 3.15c) is marked by the narrowing of the band, that surrounds completely the eye of the storm. On 17 November at 23:00 UTC, the structure is remarkably organized, with a very defined and circular eye and a very narrow band of strong wind forming a vortex around the eye. On 18 November at 03:00 UTC, during the final hours of the stationary phase, the structure discussed above is almost completely preserved, while the overall horizontal extension of the system is significantly reduced, highlighting how the loss of baroclinic features, despite modifying the dimensions of the cyclone, causes an improvement of organization and affects only slightly the intensity of the Medicane. The analysis of the surface wind field during the final hours of the first weakening phase (3.15d) confirms the conclusions drawn previously thanks to the temperature anomaly field, as the cyclone on 18 November at 09:00 UTC continues to display an organized structure. The comparison with the previous surface wind plots evidences a larger eyewall band, while the south-eastern flank of the eye shows a weaker section of eyewall wind field and the eye of the storm is elongated. Despite being degraded, the structure of the cyclone is still pronounced. The successive phase of brief intensification (3.15e) exhibits an interesting behaviour. Despite leading to a significant increase of the temperature anomaly inside the warm core, the eyewall exhibits a less intense surface wind speed and an marked loss of organization. The organized structure is still present, but the eyewall band has increased in width, the eastern flank of the eye presents a section of much weaker winds and the overall wind structure is significantly less compact compared to the one exhibited throughout the mature phase. The fact that the structure is considerably degraded partly explains the rapidity of the successive final weakening, especially if compared with the organized structure encountered during the first weakening phase. The final stage of weakening (3.15f) strongly modifies the structure of the cyclone, which loses most of the symmetry and compactness that characterize tropical-like systems. The band on the western flank of the eye becomes very wide, in clear contrast with the narrow band displayed during the mature phase, while the eastern flank of the eye becomes almost windless, diverging from the structure of the eyewall which surrounded the eye in the previous stages of development. The quick loss of intensity of the eyewall wind is clearly noticeable on 18 November at 17:00 UTC, the band on the western flank of the eye loses more intensity in the few hours of the final weakening than over the entire life cycle up to 18 November at 13:00 UTC. The analysis above indicates the crucial importance of an organized structure in the maintenance of


24 m horizontal wind speed 19:00 UTC 17 NOV 2017
Latitude
Longitude
Wind speed [ms^{-1}]

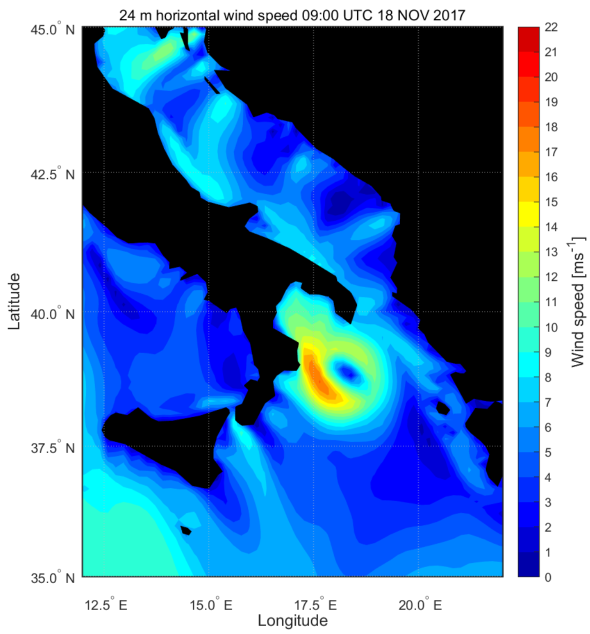
(a)


24 m horizontal wind speed 23:00 UTC 17 NOV 2017
Latitude
Longitude
Wind speed [ms^{-1}]

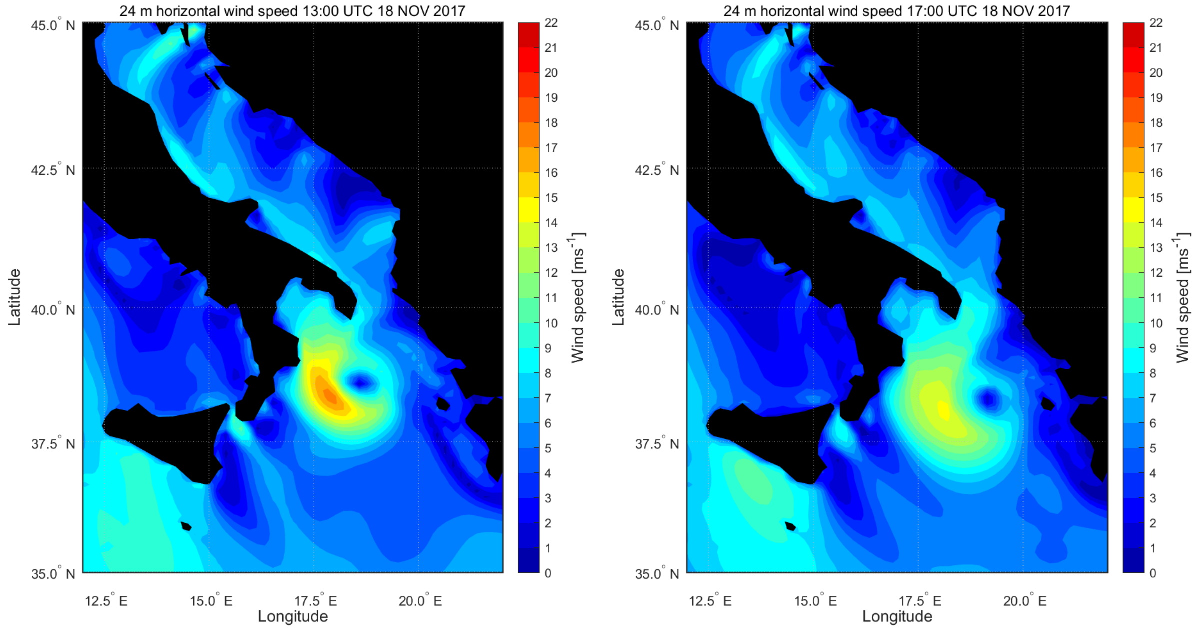
(b)


24 m horizontal wind speed 03:00 UTC 18 NOV 2017
Latitude
Longitude
Wind speed [ms^{-1}]

(c)


24 m horizontal wind speed 09:00 UTC 18 NOV 2017
Latitude
Longitude
Wind speed [ms^{-1}]

(d)



(e) **(f)**

Figure 3.15: Horizontal wind speed 24 m above sea level on (a) 17 November at 19:00 UTC b) 17 November at 23:00 UTC (c) 18 November at 03:00 UTC (d) 18 November at 09:00 UTC (e) 18 November at 13:00 UTC (f) 18 November at 17:00 UTC.

tropical features. It is worth pointing out that the increased distance from the mountains of Calabria region during the final stages of the storm contributes to the widening and weakening of the band on the western flank of the cyclone, due to the lower effect of squeezing of the wind discussed in Section 3.1.

The time evolution of temperature anomaly and surface horizontal wind speed provided a complete description of the evolution of Medicane Numa structure, proving the correctness of the subphases detected using the Hart diagram.

Chapter 4

Conclusions

In this thesis, the analysis of a Medicane event, named Numa, which occurred in November 2017, has been carried out using the outputs of the simulation realized by the RAMS-ISAC numerical weather prediction model. The focus of the study has been on the stages of the storm from the acquisition of tropical features to the final weakening of the cyclone.

The main features that characterize Numa as a Medicane have been identified and illustrated plotting the fields of various parameters. The sea level pressure field described Numa as a deep low pressure system, arranged in a well-organized axis-symmetric structure. The presence of a warm core was evidenced by the analysis of the 700 hPa temperature anomaly field, which showed a positive anomaly at the centre of the cyclone, disposed symmetrically around its vertical axis. The model simulated an highest temperature anomaly of $\sim$3 °C associated with Medicane Numa warm core. The cross-section of temperature anomaly provided a description of the compact and symmetric vertical structure of the system, with a warm core starting at $\sim$1 km of height and reaching up to 8 km of height, while the section of maximum temperature anomaly was located at 3 km of height. The diameter of the inner warm core was estimated from the cross-section to be 75 km, while the full extension of the positive anomaly had a diameter of 150 km. The study of the vertical structure was completed with the analysis of the meridional wind speed, superimposed over the cross-section. Numa presented a region of weak or absent wind at its centre, located exactly in the region described as the inner warm core, allowing the identification of the eye of the Medicane. The maximum wind speed was recorded in a band outside the eye extending from the surface up to 2 km of height, defining the region of the eyewall. The plot evidenced that the region of positive anomaly of temperature describes only a part of the storm; taking in consideration the eyewall, the diameter of the storm was estimated to be 230 km. The vertical structure presented a low vertical wind shear up to 6 km of height, a characteristic feature of tropical-like cyclones. A further illustration of the eye and eyewall regions was given by the plot of the horizontal wind speed 24 m above sea level. The eye was represented as a circular windless area, surrounded by a band of strong wind. Overall, the analysis of the horizontal wind showed the intensity of the system, with surface winds consistently in excess of 18 m/s. A visual representation of the spiral cloud bands was given plotting the mixing ratios of the cloud and rain hydrometeors. The bands outlined a clear cloud-free region, providing another tool to estimate the diameter of the eye, confirming the value of 75 km. The analysis highlighted that Numa showed all the features characterizing a Medicane: an axis-symmetric and compact structure, spiral cloud bands elongating from a cloud-free eye, a distinct warm core, low vertical wind shear, intense winds located in a band outside the eye.

The time evolution of Medicane Numa has been investigated using the Hart diagram. The trajectory on the phase space confirmed the Medicane nature of Numa, indicating a transition from a tropical-like system to an hybrid system on 18 November at 08:00 UTC. This transition was descripted as the evolution from a deep warm core non-frontal cyclone (Medicane) to a shallow warm core non-frontal cyclone (hybrid system). Some interesting subphases were detected studying the trajectory on the phase space: a reorganization phase, a stationary phase, a first weakening phase, a phase of brief intensification and a subsequent final weakening. All the subphases were successfully detected evaluating the time evolution of temperature anomaly and horizontal surface wind. The initial reorganization phase allowed Numa to lose the baroclinic features obtained during the cyclogenesis, reducing its horizontal extension and achieving a stable and organized mature structure. During the stationary phase, Numa preserved symmetry and intensity, persisting over the Ionian sea. The first weakening phase produced a reduction of temperature anomaly in the warm core, while the structure was only slightly degraded and the wind intensity was mostly unmodified. During the brief intensification phase the temperature anomaly in the warm core increased substantially, but the structure was more degraded and the wind field was starting to show a less organized structure, leading to a decrease of maximum horizontal wind speed. The final weakening phase produced a marked loss of organization and symmetry, causing a quick diminution of the maximum surface wind speed. The analysis of the time evolution of Medicane Numa highlighted the long duration of its mature stage, characterized by a remarkably symmetric structure, indicating the importance of an organized structure on the duration and intensity of Medicanes.

Acknowledgments

I wish to express my deepest thanks to Prof. Federico Porcù for the opportunity I was given. I am extremely grateful for the guidance given by Dr. Stefano Federico, whose words inspired an even deeper interest in atmospheric sciences.

An heartfelt thanks goes to my parents and my brother, for their never-ending support and love. Also, I wish to acknowledge the kindness of my entire family, which I always felt close despite the distance.

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