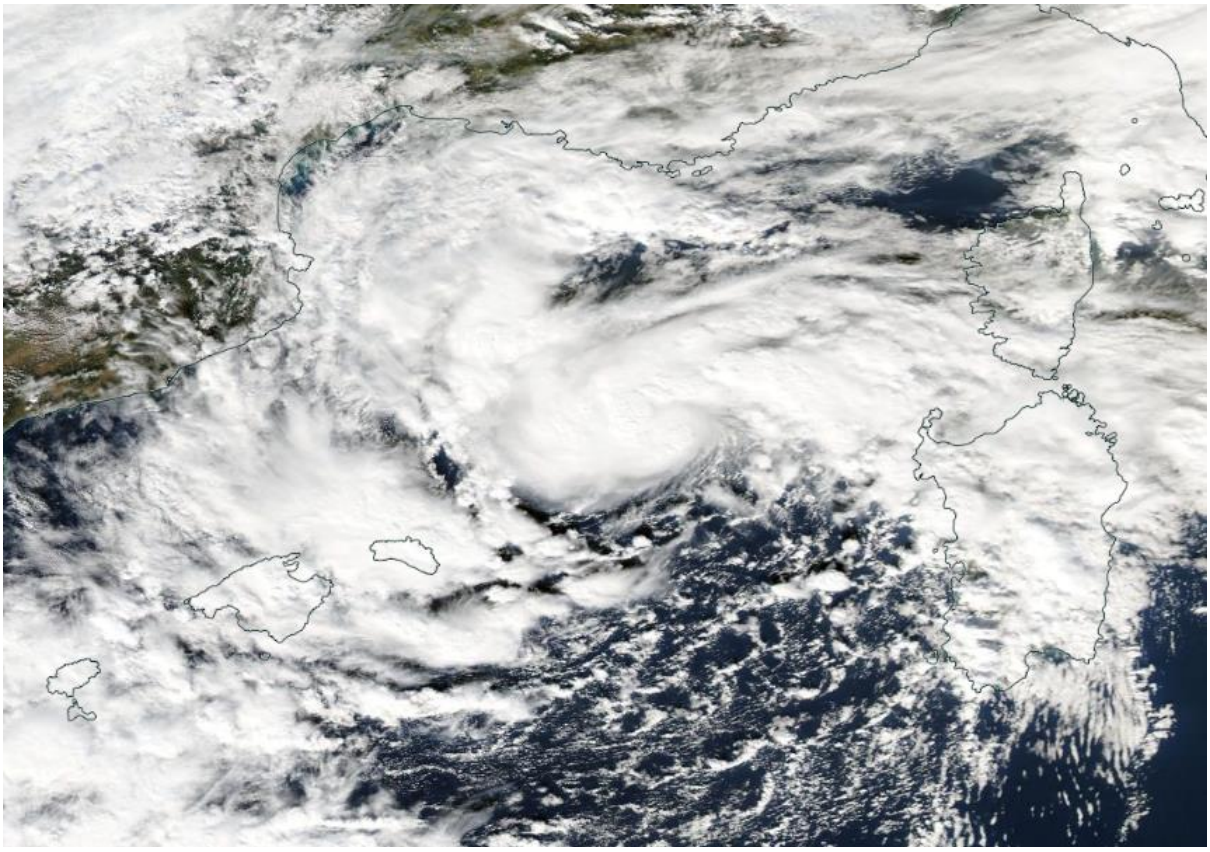
Universitat de Barcelona
Facultat de Geografia i Història

**Bachelor's Thesis**

Degree in Geography

# Medicanes: A Review



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## Abstract

Some small storms forming in the Mediterranean Sea have been spotted with visual and thermodynamical similarities with tropical cyclones. They are called *medicanes*, after *Mediterranean hurricanes*. Research on the scientific literature written about them shows that is still a developing subject, with many open discussed topics on some basic aspects of them. Generally, these cyclones occur as regular Mediterranean cyclones shrink in size and become detached of their frontal structures around their centre. They are known to cause damages to the coasts and lands affected by them, mainly in the form of floods both from the sea, from storm surges and wind-induced waves, and from extreme precipitation, which floods river basins. They occur in average once or twice a year and are most common in the Ionian Sea and the Western Mediterranean, with close to no activity in the East, and are of difficult prediction by weather models due to their small size and the unfamiliarity towards them. Future scenarios based on anthropogenic climate change project fewer, but stronger medicanes forming by the end of the 21st century.


Keywords and concepts: Mediterranean Sea, Medicane, Tropical cyclone, Mediterranean cyclone, Climatology.


## Resum

Al mar Mediterrani, s'han observat alguns petits ciclons, que tenen característiques visuals i termodinàmiques similars a les de ciclons tropicals. Aquests ciclons s'anomenen *medicans*, de l'anglès *Mediterranean hurricanes*. La investigació en la literatura científica sobre aquests sistemes demostra que aquest és un tema encara incipient, i hi ha molts interrogants en algunes de les seves qüestions bàsiques. De forma general, aquests ciclons es formen a partir de ciclons mediterranis d'origen extratropical, que s'encongeixen i perden la seva estructura frontal al centre del sistema. Són capaços de generar danys a les costes afectades, principalment en forma d'inundacions, o bé per acció de l'onatge i el temporal marítim, o bé per acció de les pluges torrencials que poden causar. De mitjana, se'n formen entre un i dos cada any, afectant principalment les sub-conques de la mar Jònica I el Mediterrani occidental, mentre la part oriental no sol tenir medicans. Aquestes tempestes són difícils de predir per part de models meteorològics, per la seva petita escala i per la manca de coneixement que hi ha al seu voltant. Escenaris futurs, basats en el canvi climàtic antropogènic, preveuen menys medicans, però de major intensitat, de cara a finals del segle XXI.


Paraules i conceptes clau: Mar Mediterrani, Medicà, Cicló tropical, Cicló mediterrani, Climatologia.


## Resumen

En el mar Mediterráneo se han observado algunos pequeños ciclones, que presentan características visuales y termodinámicas similares a las de los ciclones tropicales. A estos ciclones se les llama *medicanes*, proveniente del inglés *Mediterranean hurricanes*. La investigación en la literatura científica acerca de estos sistemas muestra que este es todavía un tema incipiente, que tiene muchos interrogantes en algunas de sus cuestiones básicas. Generalmente, estos ciclones se forman a partir de ciclones mediterráneos extratropicales, que reducen su tamaño y pierden su estructura frontal alrededor de su centro. Son capaces de generar daños en las costas afectados por ellos, principalmente en forma de inundaciones provenientes tanto por el mar, a partir de temporales marítimos y oleaje, y por acción de las lluvias torrenciales que pueden provocar. Se forman, de media, entre uno y dos medicanes al año en todo el mediterráneo, de forma más común en la mar Jónica y en el Mediterráneo occidental, mientras en el este prácticamente no se forman. Estas tormentas son difíciles de predecir por su pequeña escala y la falta de conocimiento alrededor de ellas. Escenarios futuros basados en el cambio climático antropogénico prevén que los medicanes serán menos comunes, pero más intensos, de cara al final del siglo XXI.


Palabras y conceptos clave: Mar Mediterráneo, Medicane, Ciclón tropical, Ciclón mediterráneo, Climatologia.

# MOTIVATION

I have been interested in the weather since I can remember. My family remembers and has showed me some weather forecasts I made up from when I was extremely young, maybe three or four years old, depicting the only places I knew at the time. Many weather events that happened in Barcelona and elsewhere I’ve been form a part of my fond memories, even since I was a child. The snow events of 2001, 2010, 2018, and 2021, the heatwave of the summer of 2003, the cold wave of January 2005 and the one in February 2012, the windstorm Klaus in 2009, the very rainy and stormy July of 2011, and many singular thunderstorms that have brought rain, thunder and even hail. I even found extreme precipitation events exciting, as I live in a fully constructed hillside that has little to worry about floods.

I am always looking for the next big event to come in the weather in my area, as every weather event, every rain, every frost, every thunder, every cloud, keeps me aware of the larger things that we cannot control. It could even be considered as a kind of gift from nature, who keeps playing a very exciting, yet sometimes frustrating, game of dice.

My interest of weather events doesn’t end at my doorstep, though, and I see with great admiration and excitement the singular weather events that happen at all parts of the world: the great supercell storms of the Central Plains of North America, the astonishing sandstorms of the Middle East, the never-ending monsoon rains in India. Of course, tropical cyclones were also interesting, yet scary, as they cause destruction along the paths they cross, if they find any land to shed their winds and rains. I remember asking my parents if we could ever be hit by a hurricane, to which they answered that we don’t have hurricanes here. I remember being relieved by those words, but soon they would also turn, somehow, into disappointment.

Soon enough, though, I would start to see things that would contradict what had been said to me when I was a small child. In 2005, the North Atlantic Ocean would see an unprecedented hurricane season. Many storms formed, breaking intensity records, and forming in places where nobody imagined they could be formed before. That year, as I watched the local weather forecast, the forecaster, Tomàs Molina, started pointing at what looked like a small hurricane just out the Spanish southwestern coast, which happened to be Hurricane Vince. Later that year, the news would be filled with the impacts of Tropical Storm Delta in the Canary Islands. That was the first time I heard the possibility of a Hurricane affecting somewhere relatively close to home.

However, that wouldn’t be the end of it. In 2011, after a levanter episode that brought the usual rains and winds into the Catalan Coast, I would see in discussions and articles in weather websites that a tropical storm had formed in the Mediterranean. The idea that the Mediterranean Sea could sustain tropical cyclones sounded like a crazy idea to me at that time, yet there was one happening in front of me, and there were other precedents that supported it. At that time, looking for more information about the phenomenon was very difficult because of the very little information there was online, and it also was a very unknown phenomenon, that only recently has caught the attention of the media, looking for shocking headlines. With this work, I wanted to search for answers many of the questions that I had back in 2011 when I was still a teenager, and to show this exciting phenomenon to geographers, who are still apparently unfamiliar with that concept.

# AGRAÏMENTS

Amb aquest treball, acabo definitivament el grau de Geografia i, de moment, tanco la meva etapa universitària, que va començar l'any 2012 a la facultat de Física de la Universitat de Barcelona, finalment (si no passa res) amb un graduat sota el braç.

En aquests deu anys he passat moments molt difícils, intentant fer un grau de Física que finalment no em vaig veure capaç de superar, prenent la difícil decisió d'abandonar uns estudis després de sis anys intentant-ho, amb menys motivació cada any que passava, i després veient-me obligat a fer part del grau de Geografia tancat a casa, sense poder sortir, per les circumstàncies sanitàries. Tot i això, considero que vaig prendre la decisió encertada, entrant en una carrera que he gaudit des del primer moment fins l'últim.

Per això, vull agrair a tots els professors del departament de Geografia que m'han ensenyat tot el que sé avui, sobre una disciplina de la que sempre n'he sigut un apassionat, però de la qual no en sabia prou fins ara. Sobretot, a tu, Xavi, per mostrar l'interès que has tingut en el tema del meu treball, i per guiar-me en els moments d'incertesa que he trobat durant l'elaboració d'aquest TFG.

També a la meva família, que m'ha donat suport en els moments més complicats, i que ara de ben segur celebrarà l'èxit de la meva graduació després de tants anys. Sobretot a la meva mare, amb la que comparteixo sostre, i que m'ha hagut de suportar en els moments més difícils, fins i tot quan ella també estava patint. També al meu avi Manel, que em va oferir el seu suport incondicional i una confiança cega en què me'n sortiria. Allà on sigui, n'estic segur que n'està ben orgullós de mi, i que ho cridarà als quatre vents.

Als meus amics, que han aguantat les meves bajanades i les meves anades d'olla, tant en les bones com en les males. A tu Adrian, per seguir aguantant-me tot i haver estar rodejats de gent que no ens mereixia. També a tots aquells companys a qui he conegut a la facultat de Geografia, que sempre m'han acollit com un dels seus tot i que m'agradi més estar-me a casa, que m'han ajudat molt a poder treure'm aquest títol, i que s'han preocupat per mi més enllà del que els hagi pogut ajudar en els estudis.

A tots vosaltres, moltes gràcies per ajudar-me a tirar endavant, i per donar-me la força que m'ha permès arribar fins aquí.

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# 1 INTRODUCTION

The main topic chosen for this thesis is related to the field of climatology. Climatology is defined as the geographical understanding and interpretation of atmospheric sciences: a way to explain how weather patterns arise from physical geography. The configuration of the landmasses, water bodies, their elevation and depth changes, their orientation in respect with the global wind patterns determined by astronomical and physical phenomena, and how those, in return, affect and determine the landscape of every place on Earth, and even beyond.

The area of study is the Mediterranean Sea, which for the purposes of clarity, includes all its sub-basins, except for the Black Sea, if it can be considered as such. The geography of the Mediterranean Sea is intricate: an almost fully enclosed body of water, oriented mainly east to west in the mid-latitudes, surrounded by high and sudden mountain ranges in almost all sides, with several large islands and peninsulas dividing it into even smaller sections. A giant desert occupies the entirety of the southern boundary of influence of the sea, and a temperate and fertile continent is situated at its north.

The climate in this region of the world is so idiosyncratic that it receives the very name of its sea, the Mediterranean climate. Known for its hot and dry summers, its cool and wet winters, and a very high climate variability that makes it prone to both floods and droughts. This term has then been adopted to describe the climate of other regions in the world: the Pacific coast of the United States, the Central coast of Chile and some areas around South Africa and Australia.

Convective activity in the Mediterranean Sea is common, as the basin is the one of the areas with the highest lightning density in Europe (Anderson & Klugmann, 2014). Warm temperatures, combined with intrusions of cold air from higher latitudes, and the vertical forcing caused by the air moving into the land and the mountains right behind the coast can cause notable organised storm structures spanning long distances and amounts of time, causing important floods and other kinds of damages.

In this work we're going to discuss maybe the most organised form of convective activity observed in the Mediterranean: one that hasn't been described until recently, and that has still very limited recognition outside of the academics that are actually studying it and trying to understand it. It is traditionally and popularly agreed that hurricanes and other tropical cyclones are a phenomenon reserved to other areas of the world: the American Hurricanes that have affected pop culture come to mind: Hurricane Katrina in New Orleans in 2005, Hurricane Sandy in New York in 2012, not to mention other, even larger and more impactful cyclones that go unnoticed by western media. Even the name itself includes the word "Tropical", a concept that is usually not associated to the Mediterranean. Nevertheless, small circular cloud structures that appear like mini-hurricanes, with eye included, keep appearing occasionally in satellite imagery. These are called *Medicanes*, and they are the topic of the discussion of this work.

Front page image: True-colour image from the MODIS sensor of the Aqua satellite (NASA) taken on November 11, 2011, depicting Medicane Rolf in the Western Mediterranean. Image extracted from EOSDIS Worldview https://worldview.earthdata.nasa.gov/)

# 2 METHODOLOGY AND OBJECTIVES

This work will explore and explain the particularities of Medicanes, mainly from the academical literature published on the topic, and how or why they require attention in a different way from regular Mediterranean storms.

Initially, a brief introduction to the key concepts of tropical cyclones is presented. This work focuses heavily on a subject of meteorology related to cyclogenesis (the formation of low-pressure systems) in the tropics. Therefore, understanding the particularities on how cyclones are structured and develop in tropical latitudes is essential to explain what a medicane is, as the main point of medicanes is its similarity to tropical cyclones.

After that, several definitions of the word *medicane* are read an assessed, and other related terms used to refer to the subject of this work are described, while analysing different definitions from literature about the topic. This concludes with a self-crafted definition highlighting the characteristics of medicanes that are shown in literature.

The introduction of these concepts allows for the explanation of the origin and formation of medicanes, and the mechanisms that are involved in their formation. From there, the methods of identification of medicanes will be explained, from different sources in literature, to further understand the singularities of medicanes.

These methods of identification enable the analysis of the climatology of medicanes, both from the academic sources which have constructed them and also from a self-crafted compilation of all specific medicane cases found in academic papers or webpages that either analyse one or few cases or those that try to compile medicanes to better understand their dynamics and the time and location of their formation. Consequently, two kinds of analysis are made, using the climatological data provided by the consulted sources and the listed medicane cases: a spatial analysis, a study about where medicanes form and which regions they affect, and a temporal analysis, which compares the seasonal behaviour and the frequency of medicanes.

After this, some other discussions from literature in other topics regarding climate and medicanes are made: one is an assessment of the risks that medicanes involve and how they may or may not differ from other storms in the Mediterranean, next is an analysis on how well or poorly medicanes are predicted and how tools from tropical cyclone prediction can improve their forecast, and a last one, discussing the effect that climate change and global warming could have on the frequency and intensity of medicanes.

Medicanes are still seldom known by most people, as described before in the introduction. This project wants to explain in depth what they are and how they behave, by diving into the scientific studies conducted by the current experts on the topic, so that it can be understood outside of the current field of research. Hopefully, geography, as a multidisciplinary field, can give new insights into the research of medicanes, or solve some of the issues that arise from this phenomenon.

# 3 INTRODUCTION TO TROPICAL CYCLONES

*Tropical cyclone* is the generic term for a synoptic-scale low pressure system with no frontal structure, occurring over tropical or subtropical waters with organised thunderstorm activity. They have steep pressure gradients; thus, the wind intensities can be very high. The term that is used to classify them is wind speed. Lows with winds under 62 km/h are usually called *Tropical Depressions*, lows with peak winds between 63 to 118 km/h are called *Tropical Storms*, and storms with winds above 119km/h come by several names, depending on the region of the world: *Hurricanes* in the North Atlantic and East Pacific, *Typhoons* in the West Pacific, and in other areas of the tropics they are called *Tropical Cyclones* or *Severe Tropical Cyclones*.

Tropical cyclones are of interest due to the environmental disasters they leave in their wake: Intense rainfall and storm surge can cause floods in coastal areas, and the strong winds associated to them can damage structures, often levelling towns in the most extreme cases, and are part of the most extreme risks in tropical regions affected by them. The recurrence of this kind of event can be a significant problem when affected areas have not recovered from previous cyclones.

One example of such damage would be the two successive high-intensity hurricanes that affected Central America in November 2020. In that month, hurricane Eta would strike the northern coast of Nicaragua on November 3rd with sustained winds up to 220 km/h. While still trying to recover from the extensive damage of hurricane Eta, on November 16, Hurricane Iota, of similar strength, would affect the same place yet again only two weeks later, worsening conditions in the area and affecting millions of people in Central American countries.

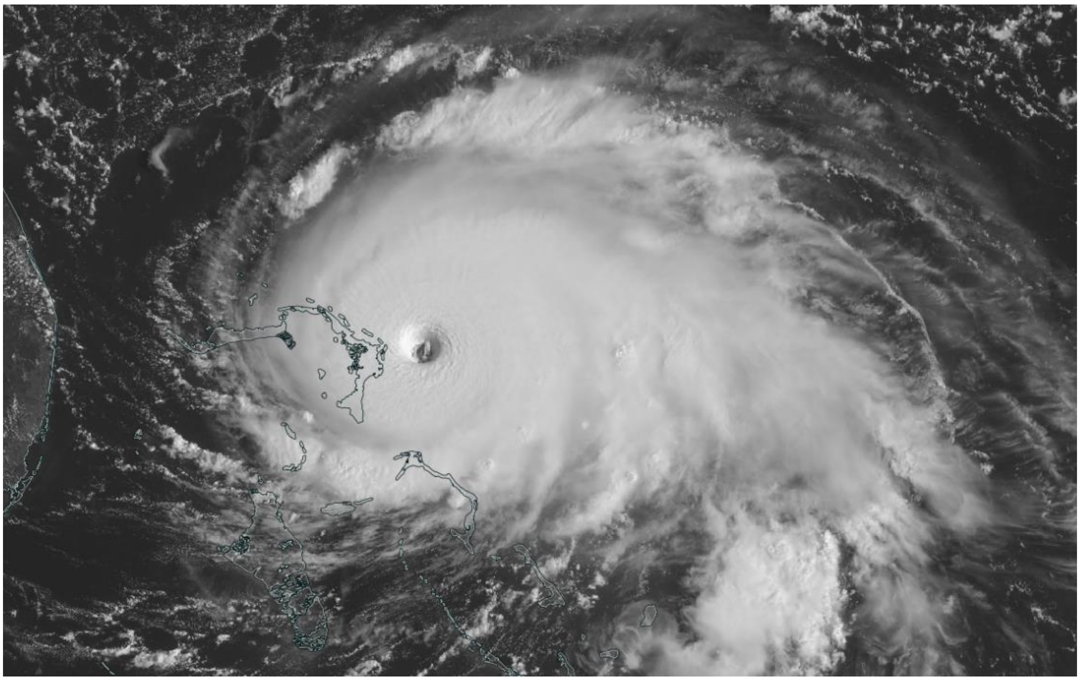


Figure 1 - Visible red band imagery from the GOES-East satellite (NASA) taken on 14:00 UTC September 1, 2019, in the western Bahamas, featuring Hurricane Dorian, one of the most intense and destructive tropical cyclones of 2019. Here the visual structure of a fully mature tropical cyclone is clearly visible: The cloud-clear central eye, and the spiral convective rainbands surrounding the storm, as well as the absence of any frontal structure. Image extracted from EOSDIS Worldview (https://worldview.earthdata.nasa.gov/)

## 3.1 PARTICULARITIES OF TROPICAL CYCLONES

Structurally, tropical cyclones do not possess fronts, and are smaller than extratropical cyclones. The most intense and mature tropical cyclones also possess a central eye, which is a free-cloud region in the centre of the storm. Thermodynamically, tropical cyclones are distinguished by a warmer centre than their surroundings. The reason they possess a warm core is due to the main source of energy in tropical storms, which is the release of the latent heat of condensation from the water vapour content of the air, provided from the warm ocean surface. On the other hand, extratropical cyclones generate from gradients of temperature and wind (this phenomenon is called baroclinic instability), which eventually generate cyclonic circulation, and their centre is usually cold, especially at the upper levels of the troposphere. Tropical storms also distinguish themselves for having their strongest winds near the surface and near the centre of the storm, unlike extratropical cyclones, which have their strongest winds in the upper troposphere.

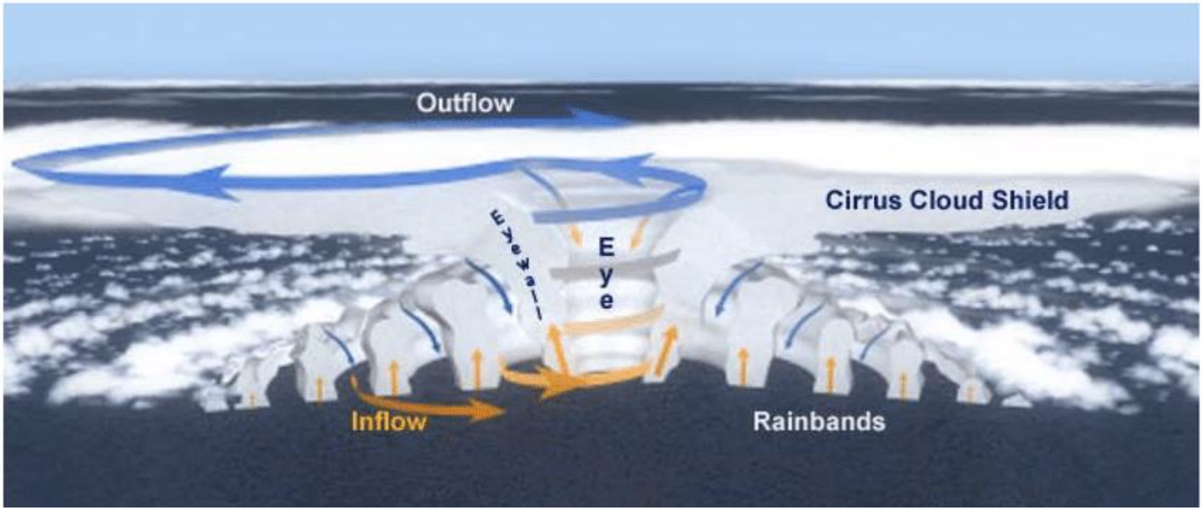


Figure 2: Schematic cross-section of a mature tropical cyclone, showing the main structural features and air flows of the storm: The low-level warm and humid convergent inflow can be seen in orange arrows, and the high-level divergent outflow can be seen as the blue arrows on top. Source: Oguejiofor & Abiodun (2019).

The warm core is formed in and around the centre of the low pressure. This warm air in the centre allows for vertical air movements, that is, for the air to rise, due to convection. These vertical air movements create cumulonimbus clouds, which are the mechanism through which tropical cyclones release their latent heat of condensation. This warm core and convection is maintained through two mechanisms: on one side, there is a divergence of winds in the upper atmosphere, through which the air that has risen inside the cyclone escapes, creating an outflow, and on the other hand, there is an inflow of moist and warm air from the surface due to the low pressure in the centre of the storm, which encourages further convection. This generates a positive feedback loop that keeps the cyclone going.

## 3.2 REQUIREMENTS FOR THE FORMATION OF TROPICAL CYCLONES

The usual requirements for the genesis and intensification of a tropical cyclone are as follows:

- **Location over the ocean:** Tropical cyclones tend to weaken when they reach land, as the moisture from the ocean is no longer available, and that diminishes the amount of water vapour that can reach the storm. Additionally, vertical air movements caused by orography may disrupt the airflow structure of the cyclone.
- **Significant air rotation**: Tropical cyclones do not develop under 5º of latitude from the equator, as the Coriolis force is not strong enough to sustain the rotation of the cyclone.
- **Sea surface temperatures over 27ºC**: The rising air in the core of the storm must be warmer than the air surrounding it up to 10-12km. As the main energy source of the cyclone is latent heat of condensation, the rising air mass also has to be humid. This limits development of tropical storms, theoretically, over waters warmer than 27ºC, that can evaporate more readily.
- **High air humidity**: As mentioned before, the rising air mass has to be humid to generate condensation and therefore, the necessary latent heat to sustain the system.
- **Low wind shear**: The difference between winds in different layers of the troposphere (called *vertical wind shear*) must be low, to allow the development of the system. High wind shear inhibits tropical storm development, as air in a tropical cyclone needs to move vertically to allow the feedback loop that allows it to sustain itself, and any horizontal movements that occur through the layers of the troposphere are going to disrupt the vertical movement of the air and the structure of the cyclone.
- **A previously existing low-pressure centre**: This is usually present in the form of waves and vortices formed in the Intertropical Convergence Zone (ITCZ) in the case of pure tropical cyclogenesis.

While these criteria are usually considered for the formation of a tropical cyclone, there might be situations where tropical cyclogenesis or the sustainment of a tropical cyclone happens despite one or some of these conditions not being met. For example, tropical cyclones might form in waters under 27ºC because of a high instability in the atmosphere that allows for strong vertical air movements despite low sea surface temperatures.

## 3.3 SUBTROPICAL CYCLONES

There is an intermediate kind of low-pressure system that has characteristics of tropical and extratropical storms; these are called **subtropical cyclones**. They originate from baroclinic instability, like extratropical cyclones, but also feature deep convection around their centre, and they might not feature a frontal structure, like tropical storms do. They have the typical structure of a tropical cyclone, usually with a broader eye, surrounded by a band of precipitation. Subtropical storms might turn into fully tropical cyclones when reaching more conducive conditions, in a process called **tropical transition**.

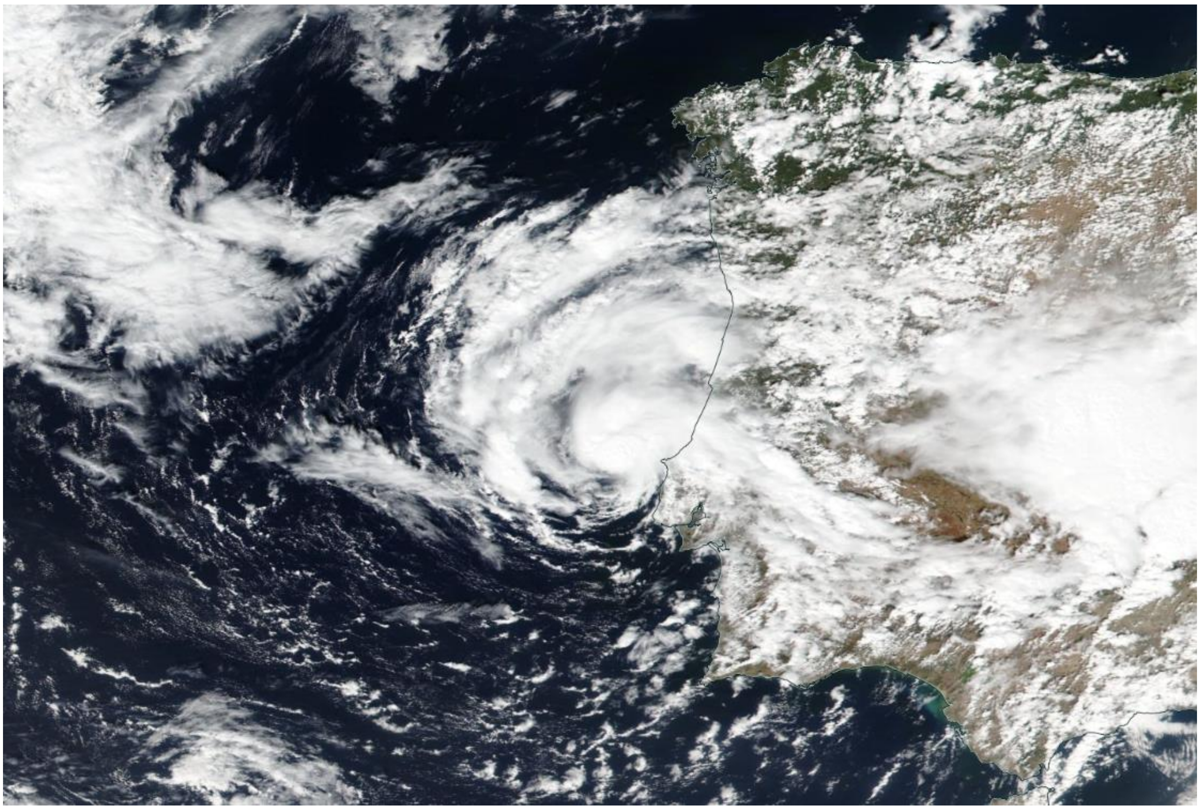


Figure 3 - True-colour image from the VIIRS sensor of the SUOMI NPP satellite (NASA) taken on September 18, 2020, depicting Subtropical Storm Alpha near the coast of Portugal, in a rare occurrence of a subtropical cyclone near the coasts of Europe. While this subtropical cyclone does not feature a clear central eye (as it is not necessary to identify any kind of tropical or subtropical cyclone), similar features to tropical cyclones can be found, as the convective rainbands around the centre of the storm and the lack of fronts around the low-pressure centre. Image extracted from EOSDIS Worldview (https://worldview.earthdata.nasa.gov/)

Subtropical cyclones have more lenient conditions for their formation relative to full tropical cyclones, mainly due to their hybrid nature. For example, wind shear might be needed for the storm to become subtropical, and usually they appear in lower, although still warm, sea surface temperatures (SST).

Research on this kind of cyclones is less abundant than in full tropical cyclones, and identification and tracking of such systems is not as clear, which makes subtropical storms overall less well understood. This might be one of the reasons why medicanes (which is sometimes compared to this type of storms) are such a contentious subject.

There is evidence that further away from 20º of latitude tropical cyclogenesis is influenced by extratropical weather systems. Davis and Bosart (2003) hypothesise that extratropical cyclones develop into tropical cyclones in two different mechanisms. Strong extratropical cyclones, with a deep low-pressure centre, transition into tropical cyclones, developing convective rainbands around the centre and getting rid of their frontal structure, and weaker low-pressure systems organise their convection around its centre in a way that creates a primitive convective disturbance which later will develop into a tropical cyclone.

# 4 DEFINITION OF THE CONCEPT "MEDICANE"

The word being used in this work, Medicane, is one of the many words that have been used to name the particular phenomenon being described and analysed in this work. Nevertheless, this one has become the most common in recent literature. This word is a portmanteau of the words "Mediterranean" and "Hurricane", as many sources mention, but there is no clear reason on how the term came to be (Tous, 2015). Apart from the word "medicane", other, longer terms have been used to describe this phenomenon, usually descriptively, using its location and the similarity to tropical cyclones elsewhere, like "Mediterranean tropical-like storms" (Fita et al., 2007), "Mediterranean Hurricanes" (Emanuel, 2005), or "Quasi-tropical cyclones [in the Mediterranean]" (Homar et al., 2003), although some authors mention this kind of cyclones in a way distinct from Medicanes (Cavicchia et al., 2014b). These names are using terms that are still being used to describe medicanes, like "quasi-tropical" or "tropical-like", instead of the traditional term used for hybrids between tropical and extratropical cyclones elsewhere, which is "subtropical". Literature that uses the concept "tropical" or "subtropical" unequivocally to describe medicanes is still scarce.

To put into perspective what a medicane is, a sample of definitions from literature will be used, to pinpoint which features are considered more important to tell medicanes apart from other meteorological phenomena:

1.- *Medicanes are nearly circular mesoscale cyclones that exhibit a great pressure gradient. The storms generally produce heavy rainfalls and associated winds can reach great intensities, in some cases close to the speeds produced by tropical cyclones. The cloud structures associated with medicane resemble a tropical cyclone in satellite imagery, with a cloud-free eye, and they are usually embedded in mature larger scale cyclones* (Ramis & Tous, 2013).

This definition comes from an article belonging to a series of articles published from the University of the Balearic Islands, deriving from a doctoral thesis about medicanes by Tous (2015). Most of the papers published by this team give similar definitions of the phenomenon, and this serves as an example from one of the most general articles published about the subject.

The definition mainly focuses on the visual shape of the cyclone and describes the features that give its tropical characteristics: symmetry, low pressure, an eye-like feature in the centre; and their extreme weather effects, mainly strong winds and abundant rain. It also emphasises on the fact that medicanes usually are embedded inside larger and broader frontal systems, which gives an insight on their baroclinic origin.

*2.- Medicanes are identified as peculiar cases of Mediterranean cyclones. At first, they were distinguished due to their visual resemblance with tropical cyclones in satellite images. In fact, a Mediterranean cyclone was qualified as a "medicane" if it presented a central "eye" and spiral cloud bands around the core, thus sharing some visual similarities with polar lows. [...] Studies used different methods and datasets [of identification], lacking to reach consensus on the physical definition of medicanes*. (Flaounas et al., 2021)

This definition is described in a paper about Mediterranean Cyclones in general, in a chapter that focuses on the particularities of medicanes. This definition pinpoints the difficulty on identifying medicanes and differentiating them from regular extratropical cyclones in the mediterranean due to the relatively low knowledge and resources available for their identification, and focuses on how they have been traditionally identified using visual features, while reanalysis methods have provided different results.

*3.- Medicanes are a rare and physically unique type of mediterranean cyclone. They show similarities with tropical cyclones with regard to their development (based on the thermodynamical disequilibrium between the warm sea and the overlying troposphere) and the kinematic and thermodynamical properties (medicanes are intense vortices with a warm core and even a cloud-free eye). The "Medicane" term is not referring to a real hurricane over the Mediterranean area, but to a type of cyclone that, when it is fully developed, has similar features to tropical cyclones (TC)*. (Tous, 2015)

This is the definition that the author gives in the introduction of her doctoral thesis about medicanes, probably one of the most exhaustive pieces of literature about the subject published to date. This allows for a definition that describes most of the properties of these cyclones: their similarity to tropical cyclones, their convective nature due to atmospheric instability, and their visual characteristics, focusing on the central eye-like feature. The analysis done in the thesis also allows the author to describe its rarity, and she describes them as "physically unique".

*4.- The Mediterranean Sea occasionally hosts intense cyclones with characteristics similar to tropical cyclones, such as a frontless and axisymmetric structure, deep convection close to their centers with a windless "eye" and sustained wind speeds close to hurricane strength. Such cyclones are often named "medicanes"*. (Lagouvardos et al., 2021).

This definition is given in the introduction of a paper about the case of "Medicane Ianos", formed in September 2020 in the Ionian Sea, which affected Greece. The article (which describes Ianos as a full-fledged "hurricane" in its title), describes medicanes through their structure, and how they resemble tropical cyclones: A lack of frontal structure, rotational symmetry, convective nature of their precipitation clouds, their central eye-like feature, and the strong winds they are associated with.

*5.- [Medicanes] are characterised for its spiral rainband structure, with a central eyelike feature. They're seldom frequent and they develop in maritime areas. They also are characterised by a deep warm core, linked to the release of latent heat, and they are thermally symmetrical. While they can have a lifespan of several days, their tropical characteristics only develop during a short period of time, in which the size of the cyclone reduces significantly* (Picornell & Campins, 2019).

This definition is one of the most complete definitions that could be found in the literature. It goes through all its visual characteristics that make them look like hurricanes (Eye-like feature, spiral rainbands, and symmetry), it defines its meteorological and thermodynamic nature as a warm core cyclone that has transitioned from a regular extratropical cyclone, and also describes its rarity and lifespan.

From these definitions in literature, medicanes can be defined as **a rare kind of low pressure systems in the Mediterranean basin, that have features that make them comparable to tropical or subtropical cyclones**, like: a) the lack of a frontal structure, b) a rotationally symmetrical shape, c) a centre that might become free of clouds forming an eye feature, d) spiral rainbands resembling the ones in tropical cyclones, and thermodynamically, e) the predominance of convective precipitation, and f) a warm core due to the release of latent heat of condensation from the water vapour content in the air. They are also relatively small, as the geographical limitations of the Mediterranean basin limit the size of such storms.

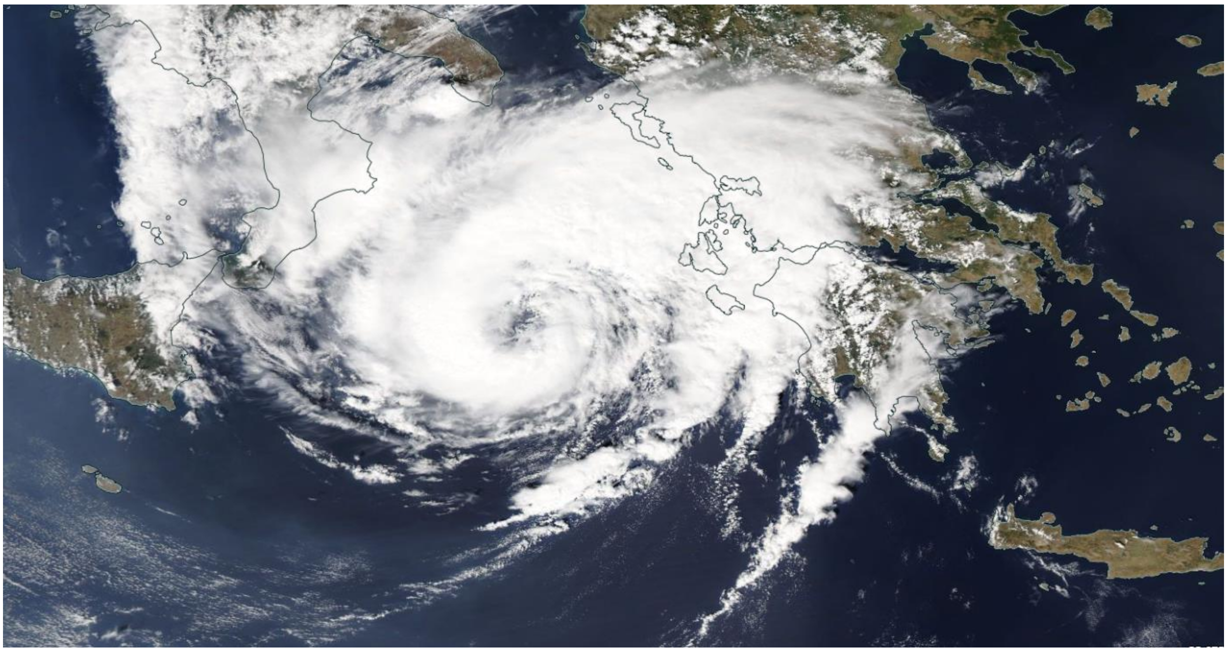


Figure 4 - True-colour image from the MODIS sensor of the AQUA satellite (NASA) taken on on September 17, 2020, depicting "Medicane Ianos", on the Ionian Sea. This is a very clear-cut case of a Medicane, where the structure of the cyclone clearly resembles that of a tropical cyclone, featuring spiral convective rainbands, and a large central eye nearly free of clouds.

# 5 HISTORY OF THE OBSERVATION OF MEDICANES

Noticeable, peculiar structures in the Mediterranean resembling tropical storms have been noticed ever since weather satellite imagery has been available in the area. As early as 1983, Ernst and Manson noticed a possible “Mediterranean tropical storm” through satellite imagery, as a peculiar cloud structure. Despite this early article, literature on this subject has been scarce until the 2000s. Homar et al. (2003) analyse a “small, quasi-tropical cyclone” from 1996 using numerical models; Emanuel (2005) also performs a similar analysis of a system that gets called a “Mediterranean hurricane”. Later, Fita et al. (2007) analyse and track numerically seven different systems suspected to have tropical characteristics, occurred between the years 1995 and 2005.

Nevertheless, it was not until 2011 that medicanes gained significant recognition. That year, the Satellite Information Service of the National Environmental Site, Data and Information Service (NESDIS) of the National Oceanic and Atmospheric Administration (NOAA), the national weather service for the United States and an authority in regard to tropical weather, decided to issue tropical weather bulletins in the Mediterranean Sea. These bulletins identify tropical cyclones around the world based on satellite imagery through a method called the *Dvorak Technique*, which analyses the shape and visual features of a tropical cyclone to determine its intensity.

At 12 UTC, on November 7, 2011, an initial tropical bulletin on an unidentified “INVEST” (an area of perturbation with the potential to become a tropical cyclone) was issued, and six hours later, the next bulletin on the system was issued, identifying the storm as “01M”, and remarking that “Deep convection has persisted enough around the low-level centre for a tropical classification”. Further bulletins would be issued every six hours until 18UTC November 9, 2011, making it the first, and only time, that the NOAA would identify and track a medicane, as the service was discontinued in December 2011. This tropical storm, as identified by the NOAA, would become known as “Medicane Rolf”, from the name that the Free University of Berlin gave to the original depression that would eventually develop into a medicane.

Since then, much more research has been conducted into this topic. The University of the Balearic Islands would release a series of papers on (now properly called) medicanes, that would culminate on the doctoral thesis of Tous (2015), and other papers trying to elaborate climatologies of medicanes (Cavicchia et al., 2013) or trying to figure out the mechanisms that form medicanes in the first place (Chaboreau et al., 2011).

This increased interest in medicanes in the last decade, combined with the increased interest in naming of high-impact storms in Europe in a similar manner to that of tropical cyclones around the world, and especially in the North Atlantic Ocean, has also encouraged the naming of medicanes that are identified as such. Initially, they have been named through an unofficial naming scheme followed by the Free University of Berlin, which has been naming all high and low-pressure centres in Europe since the 1950s and has been the source of the naming of some significant high-impact storms in Europe, even aside from medicanes, on recent years.

More recently, national weather agencies have been starting their own yearly-rotating high impact storm lists. Currently there are three lists of storm names in the Mediterranean Basin, which do not include medicanes exclusively. They are made by collaborations between different clusters weather agencies in Europe, which name the storms when they detect that they can cause impacts to their region. In Southwest Europe, the Spanish and French weather agencies have a naming list, that also names extratropical storms in the Atlantic along with the weather services of Portugal, Belgium, the Netherlands and Luxembourg. In the central Mediterranean, a joint list is organised by the weather agencies of Italy, Slovenia, Croatia, North Macedonia, Montenegro and Malta. The Eastern Mediterranean list is coordinated by the weather services of Greece, Cyprus and Israel. The two latter groups have only started naming storms for the 2021-2022 season for the first time. Medicane Apollo, formed in the Central Mediterranean in October 2021, is the first medicane known to be named from a national weather agency through this method.

# 6 FORMATION

The Mediterranean Sea is one of the most cyclogenetic regions of the world, with a high number of cyclones forming every year. Campins et al. (2011), for example, claim that there are around 1800 cyclones forming on average every year in the entire basin.

Cyclogenesis on the Mediterranean are of baroclinic origin. Different methods of formation exist, usually implying the existence of a trough, a cut-off high-level low, or a larger cyclone from higher latitudes located in Europe. The orography of the Mediterranean basin, surrounded by high mountain chains close to the coast on all sides, allow for the formation of low-pressure centres on the lee of those mountain chains into the Mediterranean. Other cyclones might enter the Mediterranean, especially from the west, pushed by the general circulation on the middle latitudes, from either the Atlantic Ocean, the European continent or the African continent through the Sahara Desert. (Romem et al., 2007).

There is a clear consensus throughout literature that medicane formation requires the existence of a previous cyclone that has formed through baroclinic instability. Despite this, the methods through which a medicane develops its tropical characteristics (its warm core and its symmetrical structure) are not agreed upon, and they might be different valid methods of medicane formation (Miglietta, 2019).

One method from which a medicane might acquire its warm core is through a method of heat exchange from the ocean, so-called Wind Induced Surface Heat Exchange (WISHE). The winds generated near the centre of the baroclinic cyclone, due to convection and pressure gradient, are the ones responsible for the warm core formation through heat exchange (Emanuel, 2005). This is the heat exchange mechanism through which tropical cyclones, thus making medicanes thermodynamically analogous to tropical cyclones.

Another process through which medicanes can develop their tropical-like characteristics is through warm seclusion (Mazza et al., 2017), which is resulted from the frontal structure around the centre of the cyclone wrapping into itself, trapping warm air into the centre of the cyclone, due to a high rate of vorticity (rotation speed) in the centre of the cyclone which detaches the now-wrapped structure of secluded fronts away from the rest of the frontal structure, creating the system’s warm core and therefore its tropical characteristics (Fita & Flaounas, 2018). This method of warm-core development through frontal seclusion has been seen in other transition events elsewhere (Bentley & Metz, 2016).

Sea Surface Temperature (SST) does not appear to be such an important factor for medicane formation compared with traditional tropical cyclones, with medicanes developing over waters as cold as 15ºC (Fita et al., 2007). While there is a significant apparent release of latent heat in medicanes, such low temperatures would not sustain tropical development on itself, and the development of medicanes has been consistently linked to the original baroclinic instability that allows the onset of the heat and air flows that eventually generate the mature, warm-core symmetrical system.

Fita & Flaounas (2018) describe a three-stage sequence for the life of medicanes. The first stage consists of the baroclinic cyclogenesis and the first signs of convective activity that eventually might lead to the development of the warm core in the cyclone. In this stage, the cyclone exhibits the normal characteristics of an extratropical cyclone: A frontal structure, a cold core, and a relatively broad circulation. Central pressure drops quickly as baroclinic instability feeds the cyclone, although some of the deepening of the cyclone is already attributed to latent heat release.

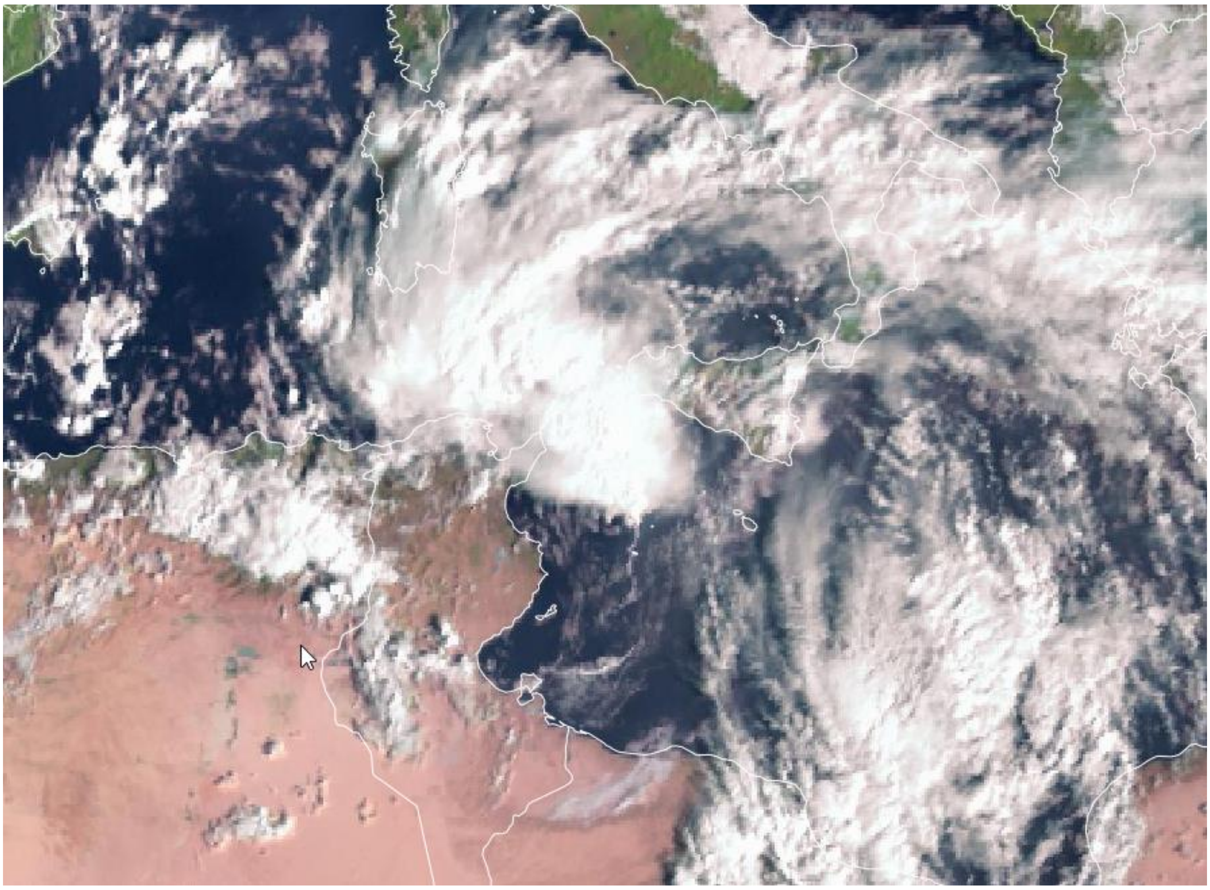


Figure 5: Meteosat Visible Imagery in the Central Mediterranean on 07:30 UTC, October 24, 2021. Cyclone Apollo, still as a regular Mediterranean cyclone, can be seen in the image, with its frontal structure, and some convection near the centre of rotation of the cyclone. Source: EUMETSAT Eumetview (https://view.eumetsat.int/)

In phase II of the life of the medicane, the cyclone acquires tropical characteristics: it acquires its warm core by either mechanism mentioned by literature (either pure heat exchange or a warm seclusion due to an increase in vorticity), becomes symmetrical, loses its frontal structure and reduces in size significantly. In this phase, the cyclone might develop an eye-like feature, free of convection or clouds in its centre. Fita & Flaounas debate whether this eye-like feature, present in many identified medicanes, is either originated from the ascent of air in the centre of the cyclone, or it is rather a result of intrusions of dry air into the medicane, inhibiting convection.

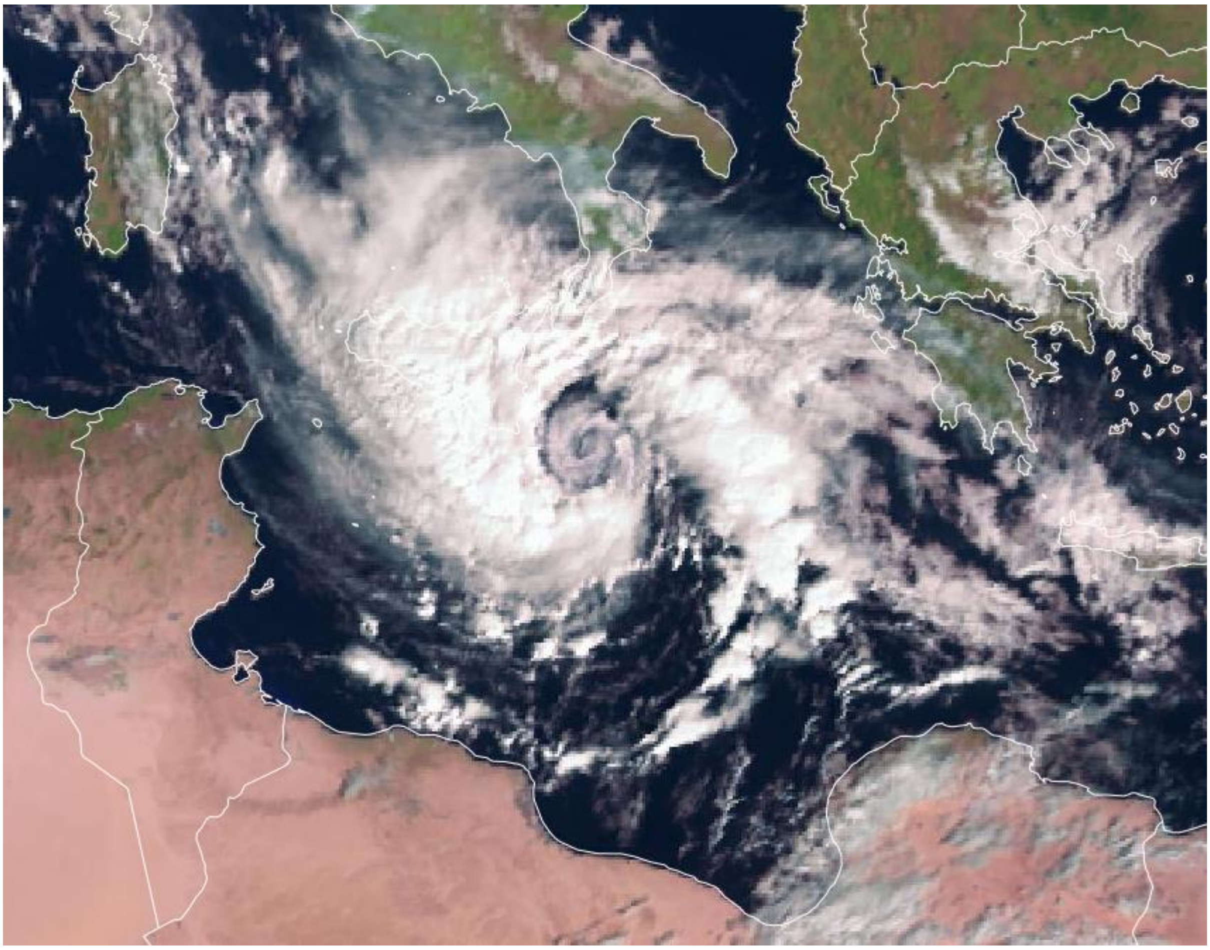


Figure 6: Meteosat Visible Imagery in the Central Mediterranean on 08:15, October 29, 2021. Medicane Apollo is featured in the image, with a familiar spiral cloud structure dominated by convective clouds, without any frontal structures around it. The extent of the cyclone influence has reduced significantly from the one in figure x, as it only affects a portion of the basin and its effects do not extend beyond the visible area, similar in size. An inward-spiralling, relatively free of convection eye-like feature is visible. Source: EUMETSAT Eumetview (https://view.eumetsat.int/)

The last stage in the medicane's life is its decay. As the cyclone moves, it eventually encounters either land, which disrupts its structure through lack of surface heat exchange or the presence of orography, or eventually finds less favourable conditions of temperature, wind shear, instability or humidity and eventually loses its convection and becomes a remnant low, which still preserves some cyclonic rotation on the lower levels.

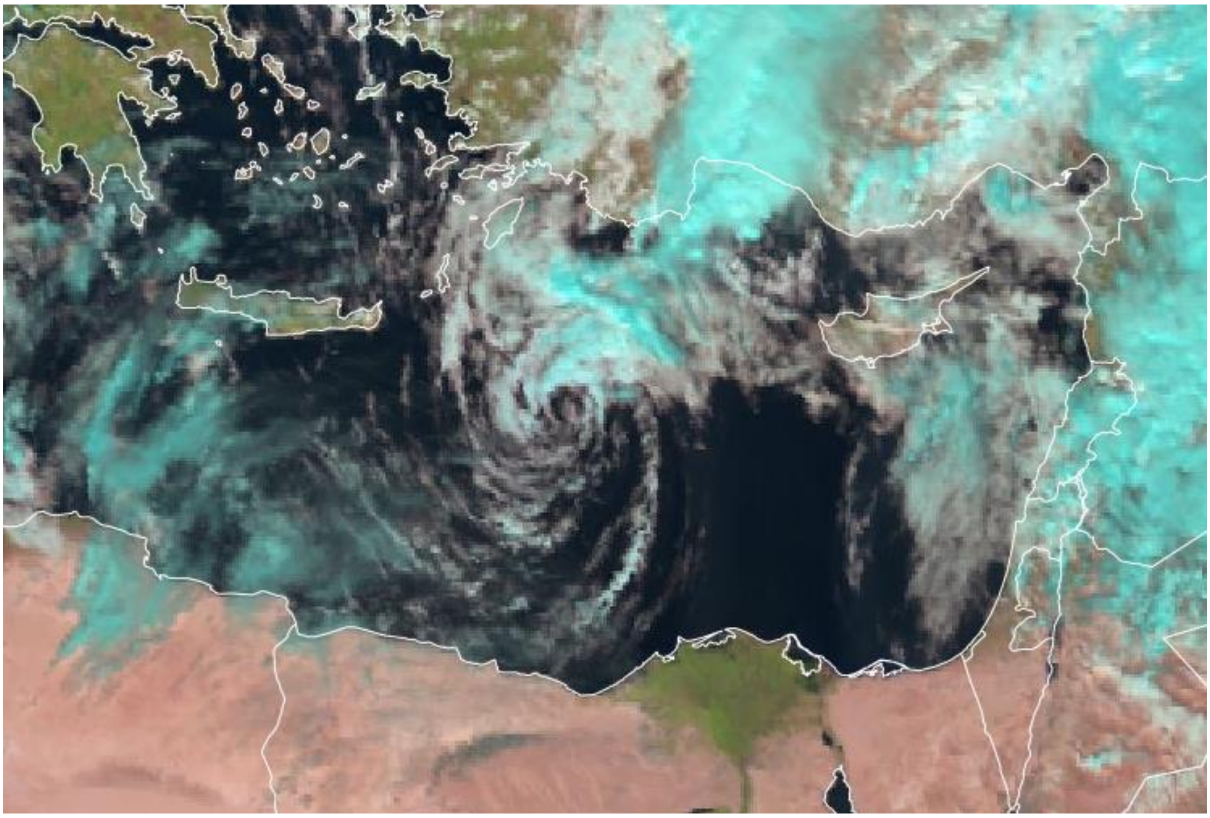


Figure 7: Meteosat Visible Imagery in the Eastern Mediterranean on 09:30 UTC, November 1, 2021. Apollo, on the centre of the image, has moved eastward and has lost almost all convection associated with it, even losing symmetry on its low-level cloud structure. The cyclone is now a remanent low and is no longer showing tropical characteristics in its satellite imagery. Source: EUMETSAT Eumetview (https://view.eumetsat.int/)

# 7 IDENTIFICATION AND CLIMATOLOGY

Some authors have tried, independently, to identify medicanes based on different kinds of methodologies and criteria. Mainly, the two methodologies used to identify medicanes are: 1) identification of low-pressure structures visually similar to a hurricane or tropical storm through satellite imagery, and 2) analysis of the thermodynamics, size and symmetry of low-pressure systems through meteorological historical data processed and archived in a process known as reanalysis. Here, a sample of the methodologies used in literature to identify medicanes is shown, be it to construct climatologies or to analyse the formation, development or predictability of single storms or a set of them.

Tous & Romero (2011) use the Meteosat infrared imagery to identify medicanes. The criteria used are: a) existence of a well-defined eye, b) symmetry of the cloud mass around the eye; c) continuity of the cloud mass, d) diameter less than 300 km, e) duration exceeding 6 hours. - This method identifies, depending on the strictness of the search, between 6 and 12 medicanes between February 1982 and December 2005, out of 410 potential cases.

Di Muzio et al. (2019) use historical data from the European Centre for Medium-range Weather Forecasts (ECMWF) weather model to analyse predictability of medicanes. Criteria are: a) More than 4 closed 1-hPa isobaric lines. b) A gradient of more than 5 hPa over 400 km in at least four out of 12 directions from the centre. c) A small area (less than 500,000 km^2, which is approximately the size of the Iberian Peninsula, and therefore would fit in the Mediterranean Sea). d) The low-level (1000 hPa) and mid-level (500 hPa) pressure centres must be aligned. These criteria remarkably do not take into account the shallow or warm core nature of medicanes while using numerical data for detection. This article identifies seven cases of medicanes between 2011 and 2017, plus an additional case of a similar storm in the Bay of Biscay, which is outside of the scope of this work.

Picornell & Campins (2019) analyse the predictability of medicanes using ECMWF archived forecasts and also other reanalysis databases. The criteria for medicane identification are reduced to: a) High intensity (more than 3.2 hPa over 100 km). b) It must be thermally symmetrical. c) The centre of the storm must be warmer than its surroundings between the levels of 925 hPa and 700 hPa. This article is more general and analyses several cases, rather for predictability, thermodynamics or climatology.

Cavicchia et al. (2014a) uses historical weather reanalysis as a basis to run a mesoscale model in order to detect medicanes. Criteria are: a) Sea level pressure gradient larger than 0.2 mbar over a distance of 30 km. b) More than half of the detected centre points have to be over the sea. c) Symmetry and a warm core must be detected in the inner 100 km of the storm for more than 10% of the storm's lifespan or more than 6 hours. d) The wind speed at the level of 850hPa is higher than the wind speed at 300hPa. e) The maximum wind speeds at a radius of 50km from the centre are at least 105 km/h for longer than 4 hours.

Ragone et al. (2018) also uses a similar method of analysis (running different high-resolution models over reanalysis data), to construct a climatology of medicanes. Medicanes are identified as such when the cyclones are symmetrical, and they possess a warm core in both lower and upper levels of the atmosphere. The radius of the cyclones relevant to the study is set to 100km, but it does not specify any limit in size for the storm.

Additionally, Fita & Romero (n.d.) have an extensive archive of medicane cases from 1983 to 2007, with an archive of at least 29 cases, complete with satellite imagery and animations. While it does not specify a clear methodology for discrimination of medicanes over other extratropical low-pressure systems, it is the most extensive database available from an academic source and most of the systems fulfil the broader criteria given by Tous & Romero (2011).

There is still no clear definition or academic agreement on what a medicane is on either visual or thermodynamic characteristics, and this is the reason why authors are independently making their identification criteria for medicane characterisation and detection. Almost every article in the literature that aims for detection of medicanes, in any way, highlights this lack of agreement in the requirements for medicane classification and then resorts to more or less similar criteria compared to the rest of the literature.

## 7.1 CLIMATOLOGY OF MEDICANES

### 7.1.1 Identified cases of Medicanes

Several sources and articles dedicated on the topic identify and analyse different low-pressure systems in the Mediterranean as cases of medicanes. From literature, up to 41 cases of medicanes have been identified, by either one or more sources, accompanied by either meteorological charts, or satellite images identifying them. The table below shows all distinct cases that have been found, with their respective sources.

| No. | Date | Names given | Basin | References |
|---|---|---|---|---|
| 1 | 1982-01-26 | Leucosia | I | Kuo et al. (2002), Picornell et al. (2014), Pravia-Sarabia et al. (2020), Ramis et al. (2013) |
| 2 | 1983-09-28 | M01 | W | Fita & Romero (n.d.), Picornell & Campins (2019), Picornell et al. (2014), Tous & Romero (2011), |
| 3 | 1984-04-06 | M02 | I | Tous & Romero (2011) |
| 4 | 1984-12-29 | M03 | C | Tous & Romero (2011) |
| 5 | 1985-09-18 | | W | Fita & Romero (n.d.) |
| 6 | 1985-10-28 | | W | Fita & Romero (n.d.) |
| 7 | 1985-12-13 | M04 | C | Fita & Romero (n.d.), Tous & Romero (2011) |
| 8 | 1986-10-02 | | W | Fita & Romero (n.d.) |
| 9 | 1989-10-05 | | Ae | Fita & Romero (n.d.) |
| 10 | 1990-08-22 | | I | Fita & Romero (n.d.) |
| 11 | 1991-12-04 | M05 | C | Tous & Romero (2011) |
| 12 | 1992-10-14 | | T | Fita & Romero (n.d.) |
| 13 | 1994-10-23 | | C | Fita & Romero (n.d.) |
| 14 | 1995-01-16 | M06<br>Celeno | I | Cavicchia & von Storch (2012), de la Vara et al. (2021), Emanuel (2005), Fita et al. (2007), Fita & Romero (n.d.), Picornell & Campins (2019), Picornell et al. (2014), Pravia-Sarabia et al. (2020), Ramis et al. (2013), Tous & Romero (2011) |

| | | | | |
|---|---|---|---|---|
| 15 | 1996-09-12 | M07 | B | Cavicchia & von Storch (2012), de la Vara et al. (2021), Homar et al. (2003), Picornell & Campins (2019), Picornell et al. (2014), Ramis et al. (2013), Tous & Romero (2011) |
| 16 | 1996-10-07 | M08<br>Cornelia | W | Cavicchia & von Storch (2012), de la Vara et al. (2021), Fita et al. (2007), Fita & Romero (n.d.), Flaounas et al. (2022), Mazza et al. (2017), Ragone et al. (2018), Tous & Romero (2011) |
| 17 | 1996-12-09 | M09 | B | Fita & Romero (n.d.), Tous & Romero (2011) |
| 18 | 1997-09-26 | | T/I/C | Fita & Romero (n.d.) |
| 19 | 1998-01-25 | M10 | I | Tous & Romero (2011) |
| 20 | 1999-03-18 | M11 | I | Ramis et al. (2013), Romero & Emanuel (2013), Tous & Romero (2011) |
| 21 | 2003-05-27 | M12 | W | de la Vara et al. (2021), Fita et al. (2007), Fita & Romero (n.d.), Ramis et al. (2013), Tous & Romero (2011) |
| 22 | 2003-09-17 | | C | Fita & Romero (n.d.) |
| 23 | 2003-09-28 | | C | Fita & Romero (n.d.) |
| 24 | 2003-10-18 | | W | de la Vara et al. (2021), Fita et al. (2007), Fita & Romero (n.d.) |
| 25 | 2005-10-27 | | I | de la Vara et al. (2021), Fita et al. (2007) |
| 26 | 2005-12-15 | | C | de la Vara et al. (2021), Fita & Flaounas (2018), Fita et al. (2007) |
| 27 | 2006-02-01 | | C | Fita & Romero (n.d.) |
| 28 | 2006-09-26 | Querida | Ad | Cavicchia & von Storck (2012), Chaboureau et al. (2012), Fita & Romero (n.d.), Flaounas et al (2022), Toomey et al. (2022) |
| 29 | 2007-03-22 | | T | Fita & Romero (n.d.) |
| 30 | 2007-10-18 | | W | Fita & Romero (n.d.) |

| | | | | |
|---|---|---|---|---|
| 31 | 2011-11-07 | Rolf | W | Di Muzio et al. (2019), Flaounas et al. (2022), Koseki et al. (2021), Picornell & Campins (2019), Pravia-Sarabia et al. (2020), Ramis et al. (2013), Ricchi et al. (2017), Romero & Emanuel (2013), Toomey et al. (2022) |
| 32 | 2013-11-19 | Ruven | W/T | Di Muzio et al. (2019) |
| 33 | 2014-01-20 | Ilona | W/T/Ad | Di Muzio et al. (2019), Picornell & Campins (2019) |
| 34 | 2014-11-06 | Qendresa | C/I | Di Muzio et al. (2019), Flaounas et al. (2022), Picornell & Campins (2018), Picornell & Campins (2019) |
| 35 | 2014-12-01 | Xandra | W | Di Muzio et al. (2019), Picornell & Campins (2019) |
| 36 | 2016-10-30 | Trixie | I | Di Muzio et al. (2019), Flaounas et al. (2022), Picornell & Campins (2019), Stathopoulos et al. (2020) |
| 37 | 2017-11-18 | Numa | I | Di Muzio et al. (2019), Flaounas et al. (2022), Picornell & Campins (2019), Stathopoulos et al. (2020), Toomey et al. (2022) |
| 38 | 2018-09-29 | Zorbas | I | Flaounas et al. (2022), Statophoulos et al. (2020) |
| 39 | 2020-09-15 | Ianos | I | Flaounas et al. (2022), Lagouvardos et al. (2021), Toomey et al. (2022) |
| 40 | 2020-11-22 | | C | Bachmeier (2020) |
| 41 | 2021-10-29 | Apollo | I | Faranda et al. (2022) |

Table 1: List of mentioned identifiable medicane events in literature, with their dates, names (if given), sub-basins (shown in figure x) and the articles that feature them.

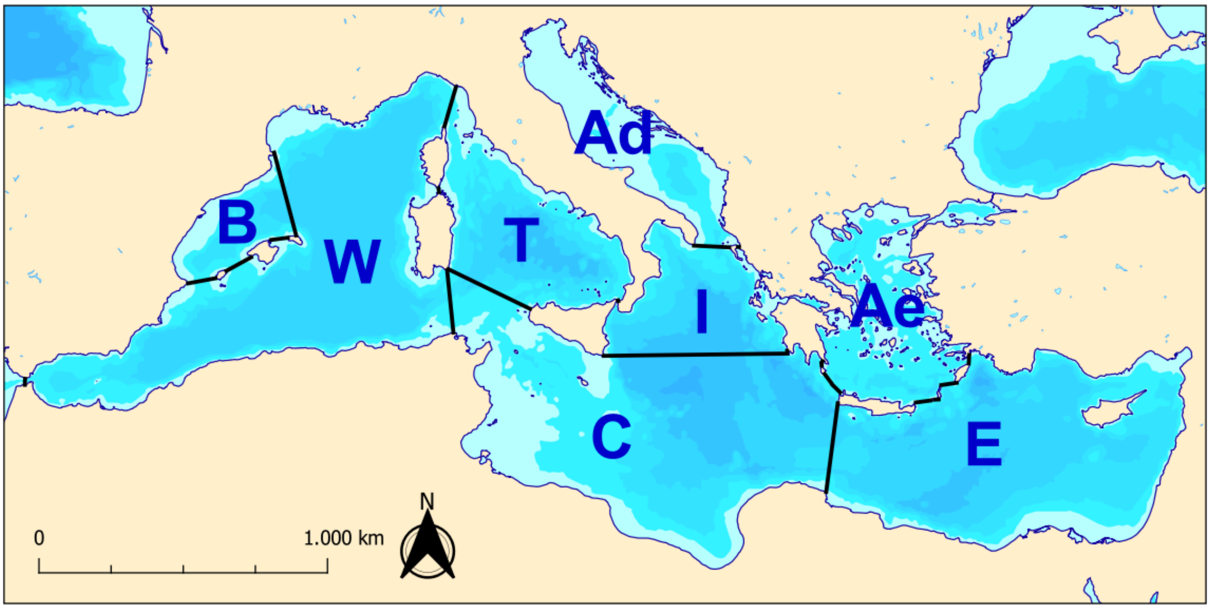



Figure 8. Sub-basins of the Mediterranean used for Table 1. B: Balearic Sea, W: Western Mediterranean, T: Tyrrhenian Sea, Ad: Adriatic Sea, I: Ionian Sea, C: Central Mediterranean, Ae: Aegean Sea, E: Eastern Mediterranean. Own work.

A simple climatology for Medicanes has been constructed from the registered identified cases from academia, featured in Table 1, classified by their area of formation and their time of formation within the year. In order to verify them, they will be compared against climatologies of medicanes constructed by academia.

### 7.1.2 Spatial climatology

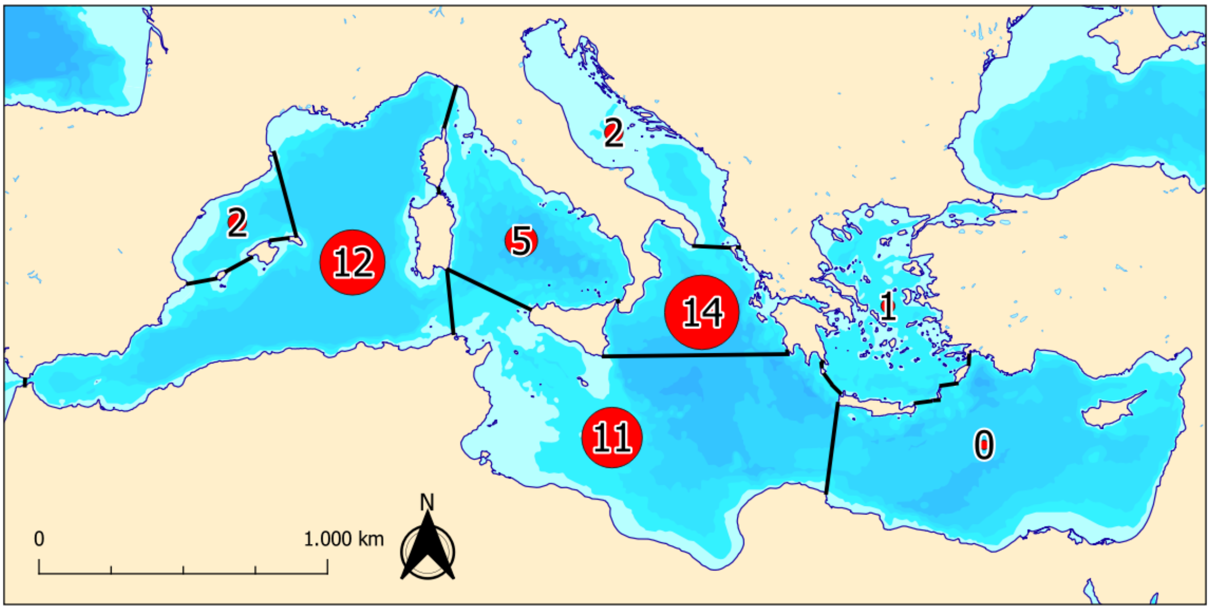



Figure 9: Number of Medicanes from Table 1 classified by the basins they were active in (following the basin classification in Figure 8). Own work.

According to the data from the featured medicanes in Table 1, there are two main areas of medicane activity: The Western Mediterranean on one side and the Central and Ionian basins on the other. Combined, they feature 35 out of the 41 found cases, and they are the three most active basins.

These results are consistent with most of the analysis in academia on regions of formation. As an example, Cavicchia et al. (2014a) defines similar two main areas of medicane development: The western area, comprising the entire area of the Mediterranean west of the islands of Corsica and Sardinia, and an *Ionian* area, which comprises the Ionian Sea and the waters of the Central Mediterranean Sea immediately south of it. Cavicchia et al. consider that the western area is the most active basin in terms of cyclone formation. It also identifies the Adriatic Sea and the Aegean Sea as areas of lesser medicane activity and remarking that the Eastern Mediterranean does not show much activity at all. Other academic studies have independently reached similar conclusions, often agreeing with these results. (Tous & Romero (2013), de la Vara et al. (2021), Zhang et al. (2021)).

Given the need for open seas for the development of medicanes, it would be logical to think that they are the most active basins as they give more room for cyclones to develop over water. Despite this, the eastern basin, which is similarly sized, does not feature any medicanes, and the only one that developed east of the Balkans has been on the Aegean Sea, which features several islands with rough elevation profiles. This might indicate that there are either climatic factors that inhibit the formation of medicanes on the Eastern Mediterranean, or that medicanes on that region are overlooked or understudied.

### 7.1.3 Seasonal climatology

Based on the data gathered on Table 1, a total of 41 identifiable medicane events have been registered from 1982 until 2021, a period of 40 years, giving an average slightly above one medicane per year (1.03 medicanes per year). Literature gives slightly higher averages than the one given here: Cavicchia et al. (2014a) reports an average of 1.57 cyclones per year, similar to Zhang et al. (2021), at 1.5 cyclones per year. De la Vara et al. (2021) features a lower frequency, but still above the reported from Table 1, at 1.17 cyclones per year. There is, however, a large variability in the amount of medicanes that can form on a single year.

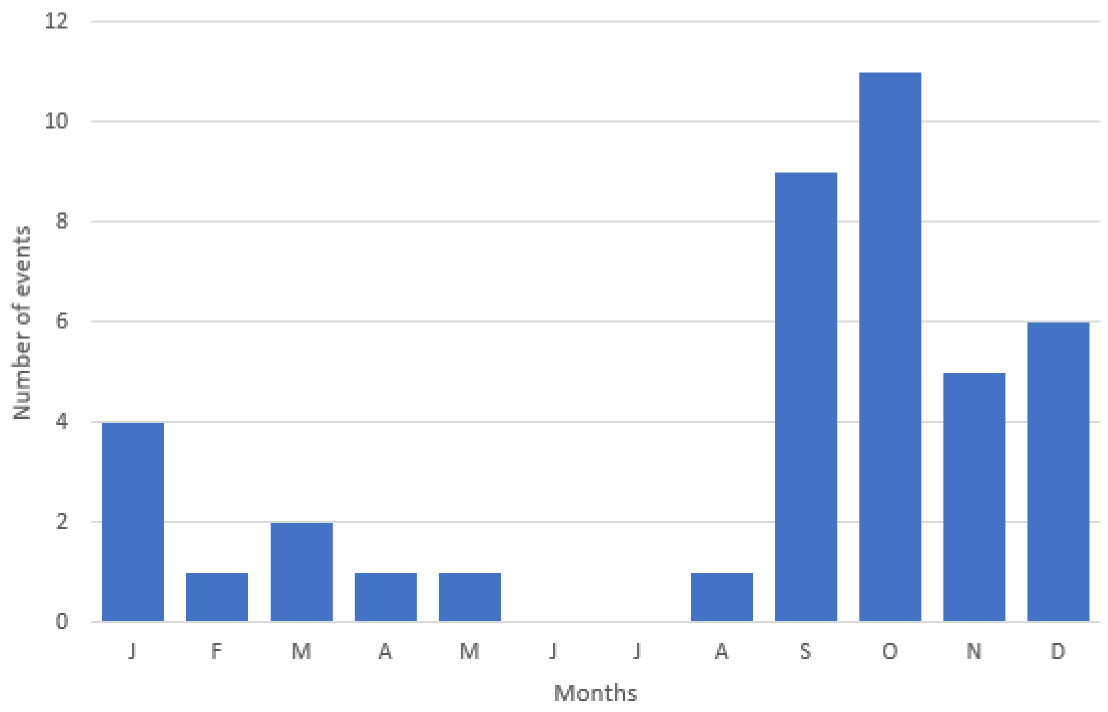



Figure 10: Medicanes from Table 1 classified by month of formation

The graph from the months of formation of all medicanes indicates that most of them form in the autumn or early winter months, concentrating from September to January. There are few cases of academia medicanes forming during the months of spring, but there are no recorded cases of medicanes formed during the months of June or July, and only one recorded case in August, which would imply that the summer months are not a period of medicane formation.

Cavicchia et al. (2014a) shows an annual cycle that spans from autumn to spring, with the most active time of formation in the beginning of winter, and a significant number of cyclones in the spring months. De la Vara et al. (2021) finds the highest activity in the winter months, with an intermediate activity in spring and autumn, and no activity in the summer months. A large spike in activity is found in the month of April, which makes the spring season more active than the autumn season in their study. Zhang et al. (2021) also reports high activity during the early and late parts of a year, with no activity in the summer months.

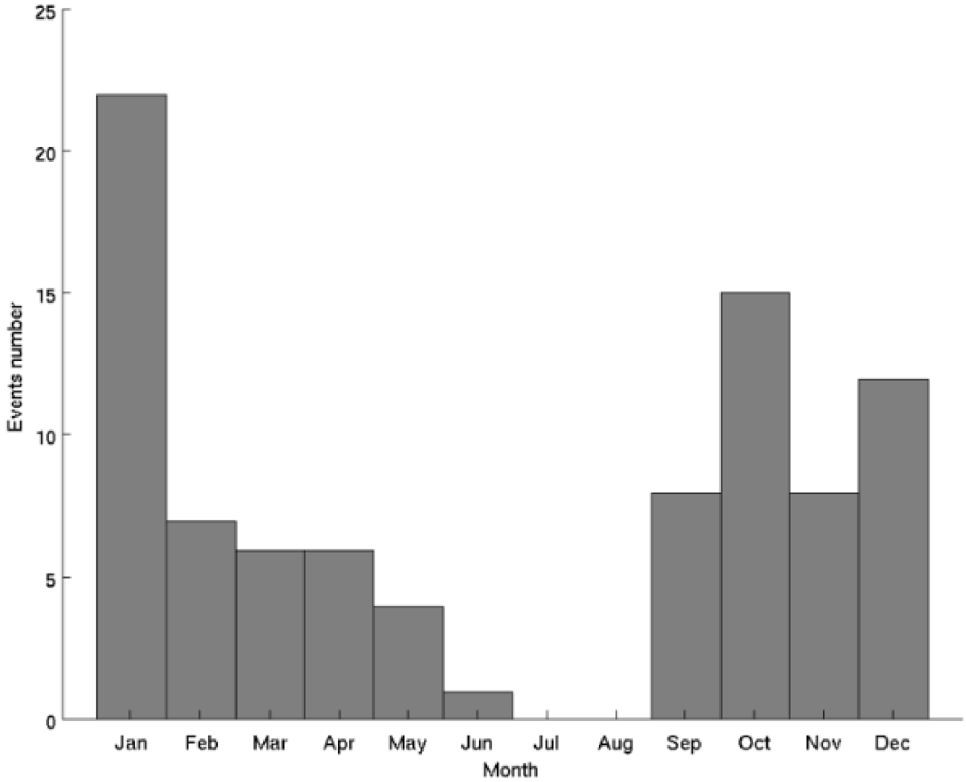



Figure 11: Monthly frequency of medicanes from the climatology of Cavicchia et al. (2014a). The winter and spring months have a significantly higher frequency of medicanes than that of the climatology from Table 1, which shows a lower activity compared to the autumn months.

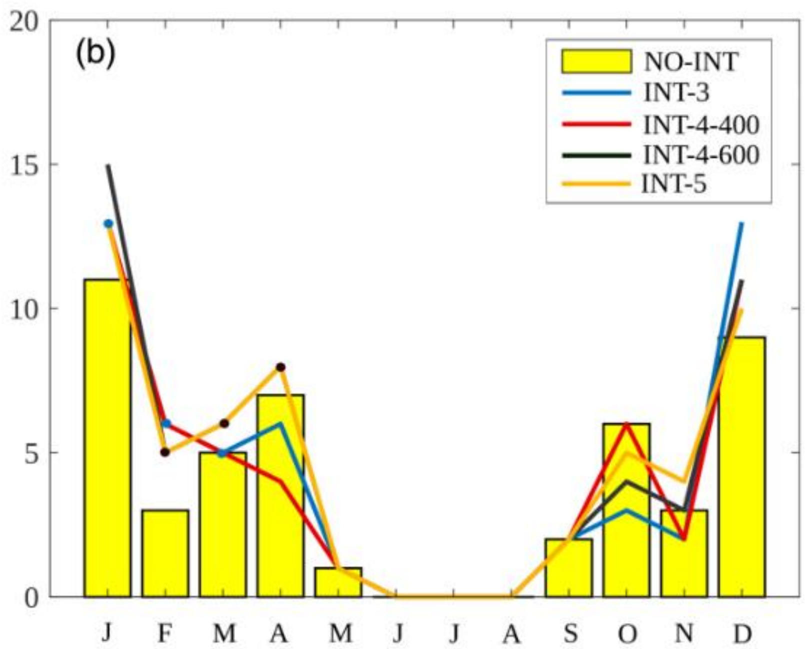



Figure 12: Monthly frequency of medicanes from the climatology of de la Vara et al. (2021). The different lines on the graph represent the different models run, which use different atmospheric levels to characterise medicanes.

These seasonal patterns follow the logic of Mediterranean climatology, that usually features stable weather in the summer months, and most of the storm activity concentrates on the months following summer, when there is potential for cyclogenesis and the sea surface temperatures are still warm after the summer. Despite this, the climatology from the data gathered suggests that medicanes could form at any time of year, unlike tropical cyclones in most of the world. Conditions for Mediterranean cyclogenesis are apparently less dependent on SST than tropical cyclones elsewhere, as even in the months where the SST would be lower there is some cyclone formation. Therefore, it would be implied that the existence of instability is a larger factor in medicane formation or inhibition than temperature.

# 8 EFFECTS

As a meteorological phenomenon, medicanes pose natural risks to the areas affected by them. The main risks associated with medicanes are flooding events induced by heavy rainfall, high sea waves and storm surge. These impacts are not exclusive of medicanes in the Mediterranean, but some studies suggest that those effects might be more intense than the ones of regular Mediterranean storms that affect the same areas (Scicchitano et al., 2021). Precipitation, particularly, is the most studied effect of medicane activity.

In some articles which analyse particular medicane cases, there are more or less lengthy descriptions or analysis of the effects caused by them. As some examples, Homar et al. (2003) analyse a medicane which affected Spain in September 1996 (No. 15 in Table 1, named “M07” by Tous (2015)). In the coast of Valencia and the Balearic Islands. Precipitation affecting western Spain, and winds and pressure readings from the Palma observatory, where the centre of the medicane nearly crossed. Related to this event are the floodings in the town of Tavernes de la Valldigna (province of Valencia, Spain), on September 11, 1996.

Lagouvardos et al. (2021), study Medicane Ianos, and mention the effects on both the field and in meteorological stations to demonstrate the tropical nature of the cyclone. They show the registered winds and rain in and around the places where the core of the storm crossed, and a collection of damaging events caused by it. The featured effects are floods, landslides and damaging winds. It is indicated that some of those incidents had caused mortal victims.

Other studies analysing catastrophic events do evaluate those caused by medicanes, even if medicanes are not the central component of study on the work. An example is a study by Llasat et al. (2014), which analyse a flooding event in November 2011 affecting the Muga River basin, in Catalonia, which was caused by Medicane Rolf.

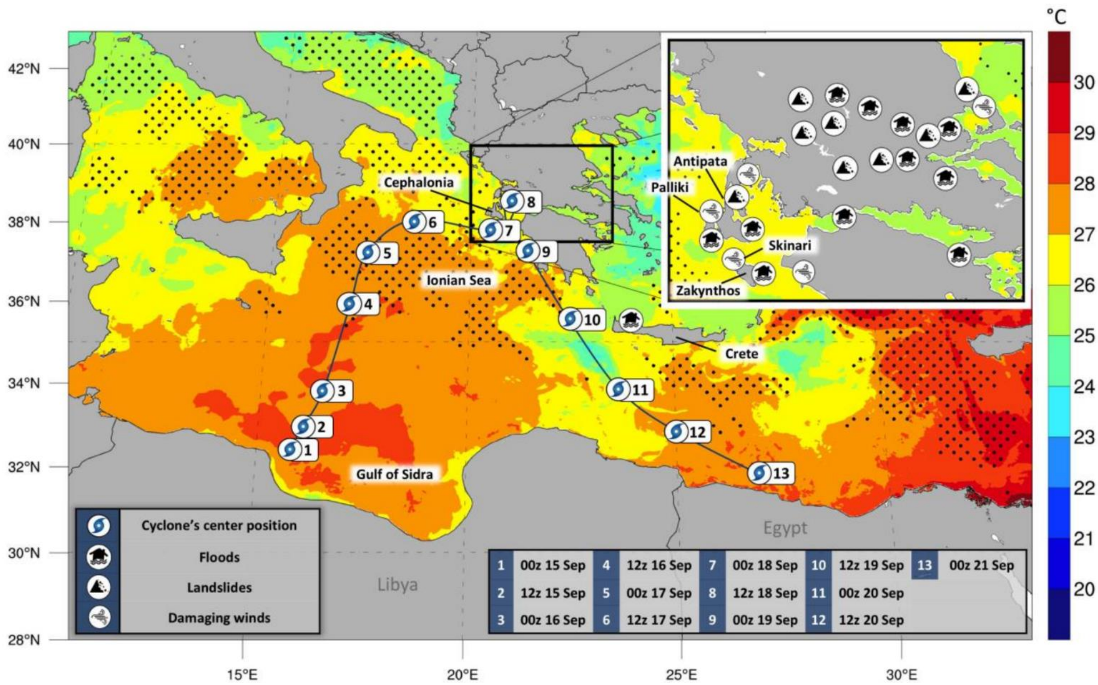



Figure 13: Track of Medicane Ianos from September 15 to September 21, 2020, made by Lagouvardos et al. (2021) The inset in the top right corner shows the places where weather events related to the storm were felt.

## 8.1 PRECIPITATION AND FLOODINGS

Precipitation, as stated before, is one of the most studied effects of medicanes, as many models used to try to detect or construct medicanes can also elaborate precipitation models derived from them, either included in analysis of particular standalone medicanes, along with other effects, as explained in the previous section. As an example, Zhang et al. (2021) study the contribution of medicanes into extreme precipitation events from their reanalysis-based climatology.

In this study, regions in the Central and Western Mediterranean, like Central Italy, Corsica and Sardinia, the Western coast of the Balkans, Western Turkey or the Mediterranean coast of France, observe up to 20 days of medicane-related floods in the period from 1979 to 2017. These precipitation effects are, according to the article, smaller in comparison to tropical cyclones. Nevertheless, they provide an insight into precipitation patterns caused by medicanes, and the areas vulnerable to medicane-related heavy rainfall.

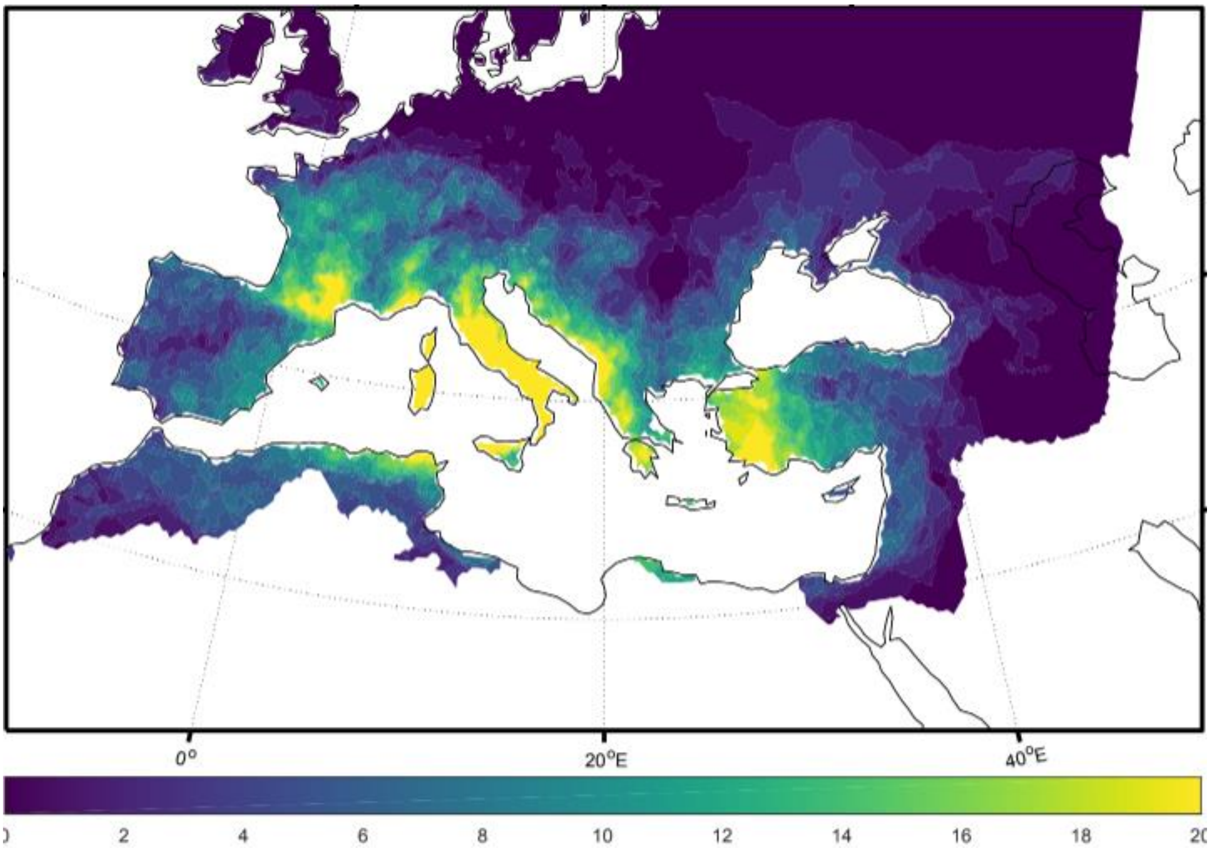



Figure 14: Number of days with extreme precipitation events caused by medicanes, according to Zhang et al. (2021).

## 8.2 COASTAL EFFECTS

Toomey et al. (2022) have studied the potential damage of coastal effects of medicanes through the elaboration of models that calculate the storm surge and wave height along the coasts of Mediterranean, through the simulation of both real cases and synthetic situations. The study finds that most coastal areas in the Mediterranean basin can be significantly affected by wind-based waves and points out areas with shallow continental shelves that extend along the ocean as the most exposed areas to medicane-induced storm surge, such as the Adriatic Sea, the eastern coasts of Spain, or the Gulf of Lion.

Scicchitano et al. (2021) compare the coastal effects of two medicanes in south-eastern Sicily, Qendresa and Zorbas, with the effects of significant regular seasonal storms between 2014 and 2019. The study concluded that coastal flooding effects from the sea in medicanes are higher than those of other storms in the area due to higher storm surges, and higher than expected on simulations in the same areas.

Despite the examples given, research into medicane effects is generally recent and scarce, and only the latest cases have brought the attention of academics in the sense of comparing or assessing the damages caused by medicanes compared to those of other Mediterranean systems that can cause similar types of damage. Further work will be needed in order to grasp the scope of gravity of the impacts caused by medicanes, and what kind special attention will be needed from a public safety perspective.

# 9 PREDICTABILITY

One of the most difficult aspects of medicane detection is the relatively small size of the low-pressure systems, radius of winds, and the reach of their rainfall bands. Such localised events on the scale of just a few hundreds of kilometres combined to the complex thermodynamic structure of medicanes, with their tiny warm cores, make their predictability, specially from general synoptic scale models, very difficult, and result in poor predictions.

There are sudden increases or decreases in ensemble members which predict medicane formation in consecutive runs, which lead to a lack of consistency and high uncertainty. As medicanes are a rare event and they need high resolution of both the model and the initial atmospheric conditions, models might not have enough information to distinguish a certain medicane formation until only a few days before the medicane actually forms. The actual position of the medicane centre, also a very important variable for predictability, and crucial to determine which areas will be affected, also does show significant jumps, but appears more gradual in its run-by-run evolution than the certainty of formation. (Di Muzio et al., 2019).

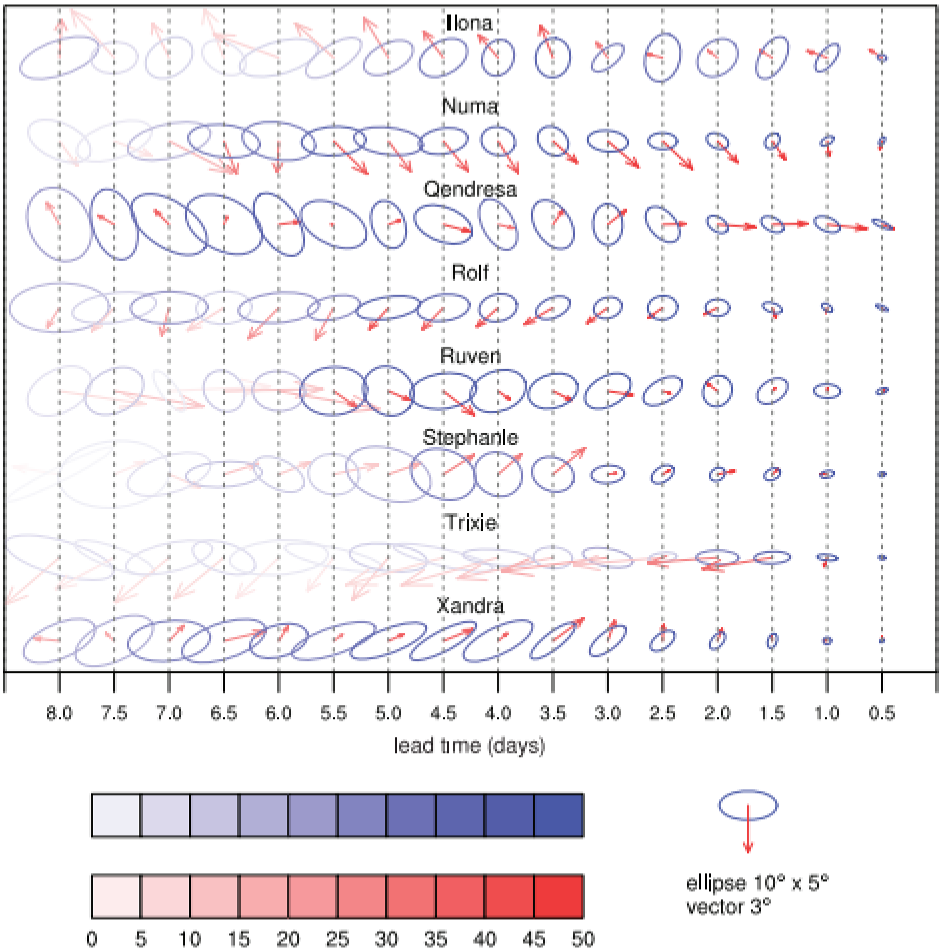
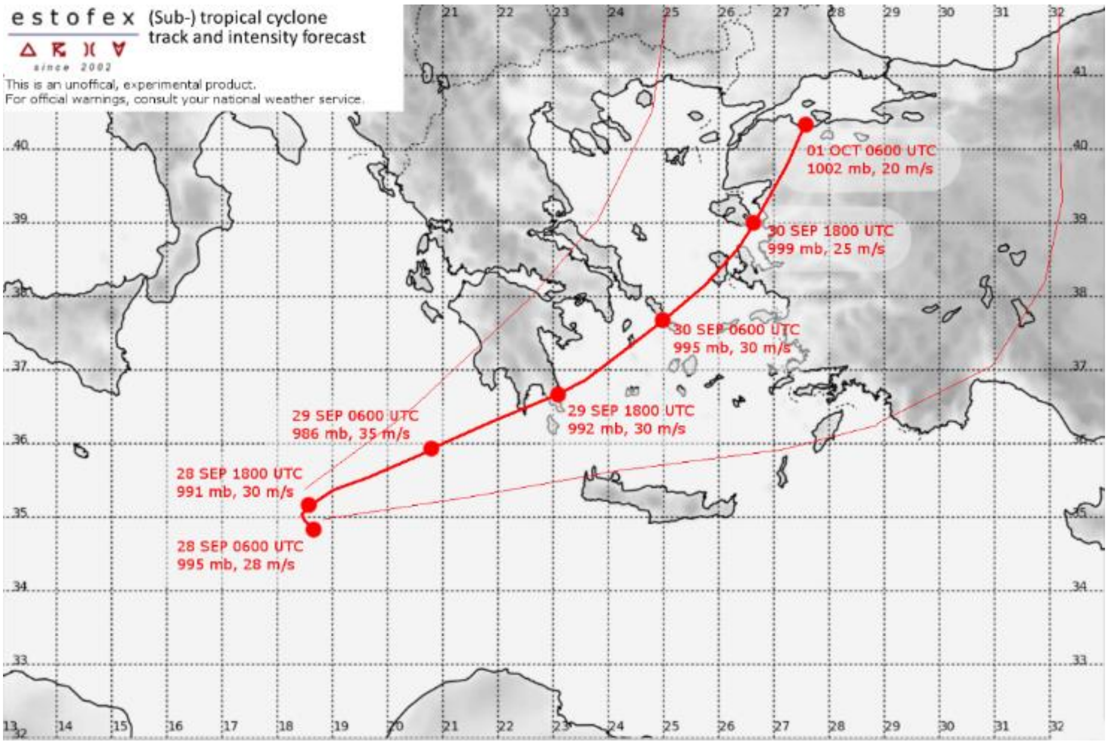
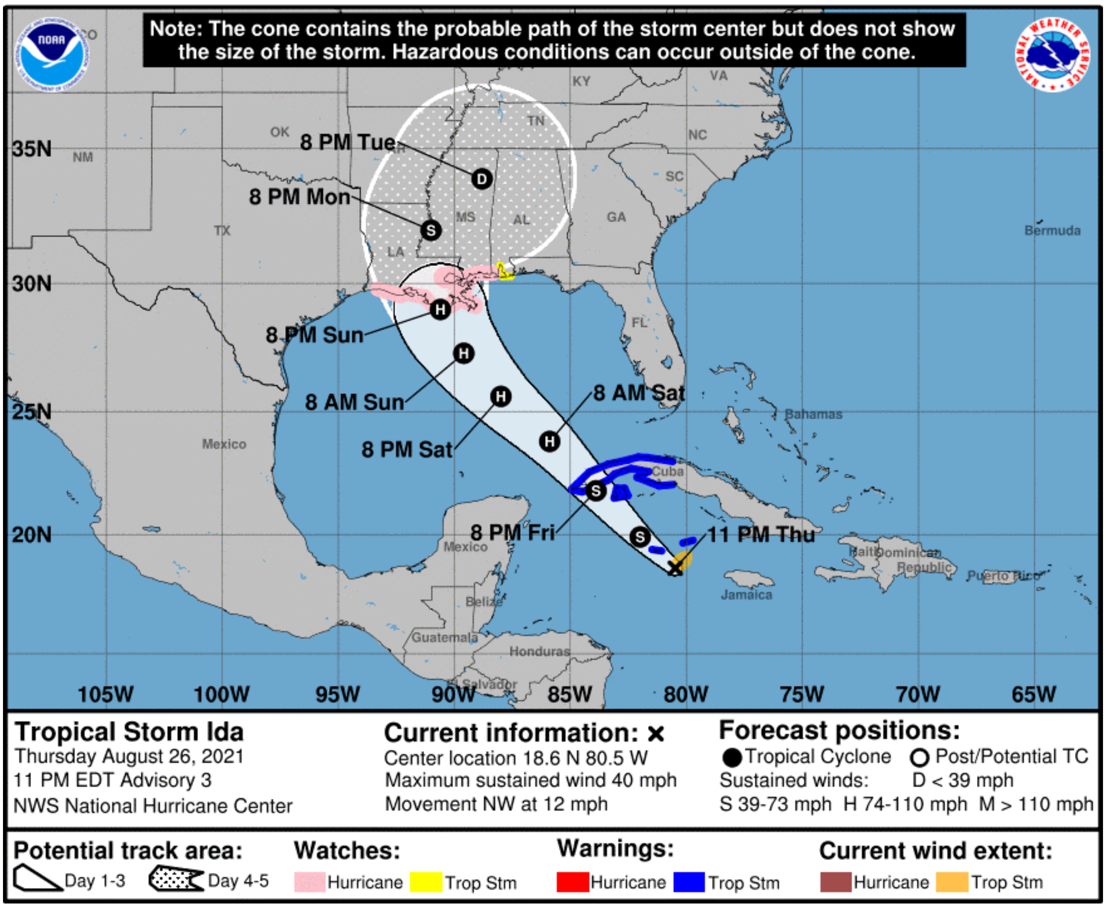



Figure 15: ECMWF model ensemble median forecast position errors (arrows) and spread errors (circle) for the formation of a collection of medicanes and an Atlantic storm ("Stephanie" is a medicane-like cyclone in the Bay of Biscay, in the Atlantic Ocean) on the 8 days before formation happened. Opacity of the figures corresponds to the number of members that predict that the medicane will form. Source: Di Muzio et al. (2019).

Once the medicane has formed, predictability focuses on the position and intensity of the medicane, in a similar manner to tropical storms. This kind of approach has not been done yet by an official weather agency in the Mediterranean, but some unofficial organisations have actually crafted tracks and probability cones or areas for predicting the effects of hurricanes. One such example is the European Storm Forecast Experiment (ESTOFEX), an unofficial research organisation that makes daily severe weather forecasts in Europe. They made a series of forecast bulletins on Medicane Zorbas, in September 2018 (Fig. 16), in the fashion of those made in the North Atlantic by the National Hurricane Centre (NHC) of the United States, in order to track and warn about the effects that the medicane could bring to the potentially affected areas.

Such an approach to medicane forecasting is also supported by academia, which supports the use of weather forecast models and their ensemble products to construct predictions with dispersion cones to elaborate uncertainty cones and issue the appropriate weather warnings to the areas that might be affected by them. (Picornell & Campins, 2018).



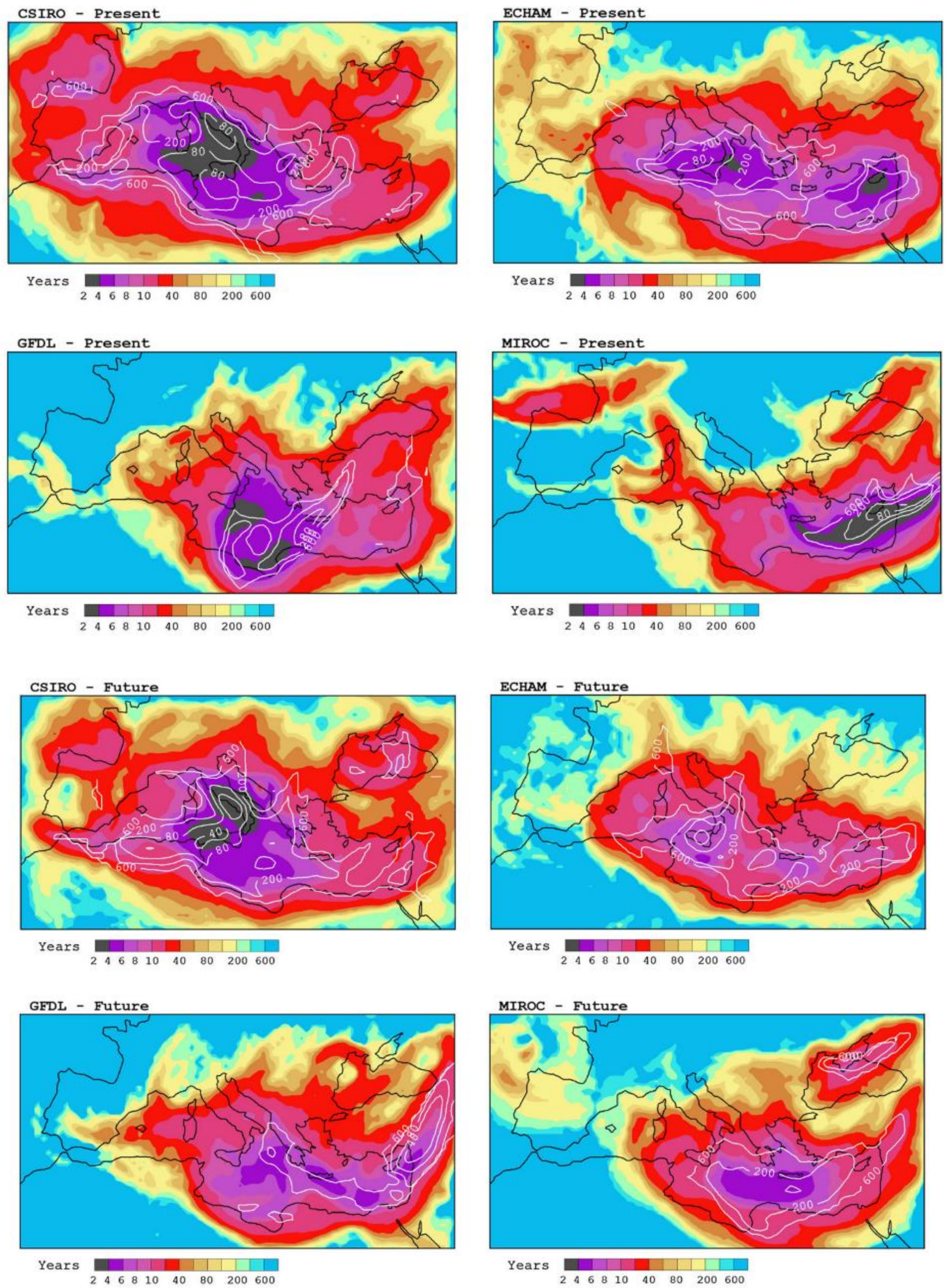

Figures 16 and 17: On the top, track forecast for Medicane Zorbas, released by ESTOFEX on September 28, 2018. On the bottom, graphic track forecast and warnings for then-Tropical Storm Ida, on the standard format issued by the NHC, showing the probability cone and potential intensity of the cyclone. Similarities between medicanes and tropical cyclones allow for such similar approaches on medicane forecast.

# 10 FUTURE PROSPECTS

One of the concerns about medicanes are the implications that climate change and global warming could bring into their formation, frequency and intensity over the next decades, as the world faces warmer temperatures, and a change in atmospheric conditions.

Future climate simulations suggest that medicane frequency could decrease from the current numbers up to 40% by the end of the 21$^{st}$ century. Nevertheless, the same models also suggest that frequency of more violent medicanes will increase. (Romero & Emanuel, 2013). González-Alemán et al. (2019) also support the theory of a decrease in general activity but add some more nuances. In addition to the higher number of intense storms, they also predict an increase on the duration of medicanes, with a significant number of cyclones that reach up to 36 hours in duration, and a doubling of the number of lows that surpass 24 hours in duration. They also add the potential for an increase in precipitation in medicanes that would develop more prominent tropical characteristics compared to the ones observed currently and create more precipitation. They also observe a spatial shift towards the Ionian Sea and the Central Mediterranean, reducing the number of medicanes in the western Mediterranean. However, these effects are only observed in the far future, and for the few next decades, there is no such significant behaviour change in the formation or intensity of medicanes.

Cavicchia et al. (2014b) make a more detailed insight, using different climate scenarios derived from the emission scenarios made by the Intergovernmental Panel on Climate Change (IPCC) to understand the differences between future scenarios for the end of the 21$^{st}$ century. There is also a reduction in medicane cases in the warmer scenarios, up to a 60% in scenario A2, the one which predicts a higher emission of greenhouse gases. The argued reasons for this decrease in overall storm formation rate with a higher number of intense medicanes might be explained by two factors: a) A reduction in moisture available and instability related to temperature differences between the low and high troposphere, and b) an increase in vertical wind shear due to a warmer climate. This study does not observe an increase in high-intensity medicanes overall, but the average intensity of medicanes increases in the warmer scenarios.




Figures 18 and 19. Return period for medicanes in the Mediterranean basin in present (top) and future (bottom) scenarios. Shading represents the return period for 34kt (tropical storm force) winds, while white lines represent the return period for 60kt (close to hurricane-force) winds, as simulated by four different models. All models show a decrease in the return period for 34kt winds, but the areas for 60kt winds see their return periods generally decrease, which would imply a higher frequency of hurricane-force medicanes. Source: Romero & Emanuel (2013)

# 11 CONCLUSIONS

Medicanes are an exciting and developing topic in the atmospheric sciences, which have highlighted a particular, previously unknown phenomenon in the Mediterranean. Despite this, there are some aspects of the topic in which there is still discussion and disagreement on. One of the most important factors that has not been sorted out yet is on *what* actually counts as a medicane. Unlike in tropical cyclones, windspeed intensity is only a factor in some definitions of a medicane, and there is no clear classification of the intensity of medicanes whatsoever. Additionally, most of the identifications made on medicanes are based on climate reanalysis instead of satellite imagery analysis, which would be useful for methods of identification of medicanes as they happen, similar to the Rolf event in 2011 covered by the NOAA.

As a result of this, identification of medicanes varies from source to source, from some authors identifying up to hundreds of medicanes over the last four decades, while some others only identify a few on the same period. A more concise and detailed study on discrimination of medicanes would be needed to identify them in case they form, in a similar way to tropical storms, to better understand them, or otherwise, have a more clear-cut convention to identify them.

Another point of disagreement about medicanes in academia is whether they are truly tropical in nature, or how much they are. While it is understood that the origin of all medicanes is baroclinic, as they form from earlier extratropical lows developed in the Mediterranean or migrated from elsewhere, the method through which they acquire their characteristic warm core is not completely well defined. The two main opposing views of the phenomenon, warm seclusion and surface heat exchange, would give a different nature to medicanes, giving it either a more similar nature to tropical cyclones (through surface heat exchange) or making them a more differentiated phenomenon not as worthy of consideration as tropical systems, if they develop from warm seclusions, trapping warmer air on their interior. It is not even clear to which extent either phenomenon exists in singular events, if both can happen in the formation of the same medicane, or if there are some medicanes that undergo one process and some others that undergo the other.

As a climate phenomenon, medicanes need to be studied more closely in order to have a better understanding of them. Understand their potential effects, be able to issue warnings that can be appropriately attributed to them, and prepare coastal areas for its effects are essential to face the medicanes of todays, and the fewer, although stronger, medicanes of tomorrow. Hopefully, future research can point in the right direction on how to address medicanes from a risk assessment perspective, and come to a more clear concept into what implications medicanes have in the environment that is affected by them.

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