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Contribution to the study of the influences of the jet stream on intense rainfall in Tunisia: case studies

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Abstract

The "Medicanes" present a particular type of atmospheric circulation in the Mediterranean area. Not conform to the bases of the specific atmospheric circulation to the temperate latitudes, the "Medicanes" relate to a barotropic atmospheric circulation dynamics as like as the tropical cyclones. These particular atmospheric phenomena are not exceptional only by their dynamics, but also by the heavy rainfall they determine. The "Medicane" genesis requires, among other aerological circumstances, the presence of an "ordinary" Mediterranean cyclone and a "Jet Stream" in the upper layers of the troposphere. The effect of this current, well known in the appropriate literature, activates the system convection and vorticity and initiates the barotropic atmospheric dynamics determining most of the rainfall deluges in the Mediterranean area. The "Jet Stream" current is able not only to act on an already unstable atmospheric situation (beforehand presence of an "ordinary" Mediterranean cyclone); but also, it seems to be able to provoke very strong stormy instabilities even under very strong anticyclonic atmospheric situations. The heavy rainfall events of the 04/10/1996 and the 29/09/2016 in Tunisia illustrate well the role of this current in the intense heavy rainfall genesis in Tunisia. -

Keywords: Jet Stream, rainfall genesis, heavy rainfall, Sousse and Kelibia, Tunisia

Contribution à l'étude des influences du courant-jet sur les fortes précipitations en Tunisie : études de cas.

Résumé

Les « Médicanes » présentent un type particulier de circulation atmosphérique en Méditerranée. Ne correspondant pas aux bases de la circulation atmosphérique spécifique des latitudes tempérées, les « Médicanes » sont liées à une dynamique de circulation atmosphérique barotrope, à l'instar des cyclones tropicaux. Ces phénomènes atmosphériques particuliers sont exceptionnels non seulement par leur dynamique, mais aussi par les fortes précipitations qu'ils engendrent. La genèse des « Médicanes » requiert, entre autres conditions aérologiques, la présence d'un cyclone méditerranéen « ordinaire » et d'un courant-jet dans les hautes couches de la troposphère. L'effet de ce courant, bien documenté, active la convection et la vorticité du système et initie la dynamique atmosphérique barotrope à l'origine de la plupart des épisodes de fortes pluies en Méditerranée. Le courant-jet est capable non seulement d'agir sur une situation atmosphérique déjà instable (présence préalable d'un cyclone méditerranéen « ordinaire »), mais aussi de provoquer de très fortes instabilités orageuses, même dans des conditions anticycloniques très marquées. Les épisodes de fortes pluies du 4 octobre 1996 et du 29 septembre 2016 en Tunisie illustrent bien le rôle de ce courant dans la genèse des pluies intenses en Tunisie..

Mots clés : Lac, Oued, aquifère Côtier, lagune littorale, salinité, Mer Méditerranée.

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INTRODUCTION

Weather and climate modelling and satellite remote sensing have seen significant advances in recent decades. Continuous improvements in space-based atmospheric observation capabilities and the rise of investigative techniques have led to a much better understanding of atmospheric phenomena at different spatial and temporal scales. In-depth observations and analyses of atmospheric phenomena that were previously little known have become possible. Exceptional atmospheric circulations, such as "Medicanes" (*Businger and al., 1998; El Melki, 2014 and 2015*), are now well known, analysed and modelled (*Cavicchia and al., 2012 & 2014; Akhtar and al., 2014; Picornell and al., 2014; Chen and al., 2012; Feser and al., 2008*). Medicanes are a clear example of atmospheric phenomena that could only be observed using satellite technology. They are caused by a particular type of atmospheric circulation, similar to that of tropical cyclones, which is absent from the atmospheric circulation specific to temperate latitudes. These particular phenomena are exceptional both in terms of the properties of the atmospheric circulation that initiates them and the torrential rainfall they cause. However, unlike the showers induced by frontal systems (with temperate dynamics), which can be widespread across the whole country or at least a large part of it, these events have a limited or even localised spatial scope. The transformation of an "ordinary" Mediterranean cyclone (with baroclinic dynamics) into a "Medicane" requires, among other aerological circumstances, the presence of a "jet stream" in the upper layers of the troposphere. It is well established in the relevant literature that the jet stream activates convection and vorticity in the system and initiates barotropic atmospheric dynamics (Fig. 1), which are responsible for most of the heavy rainfall in the Mediterranean region.

The jet stream is not only capable of acting on an already unstable atmospheric situation (prior presence of an "ordinary" Mediterranean cyclone), but also, under certain aerological circumstances, appears to be capable of causing very strong storm instabilities within very clearly anticyclonic atmospheric situations.

The study presented here examines two events: one on 4/10/1996 and the other on 29/09/2016 in Tunisia. The first event was characterised by the highest 24-hour rainfall ever recorded in the city of Kelibia since January 1968, and the second by rainfall rarely recorded in the Sahel region of Sousse. The aerological circumstances of these two extreme rainfall events clearly illustrate the role of this upper-level current in intense rainfall in Tunisia.

1. Data and methodology

1.1. Data

Various types of data were used to conduct this study, including :

Precipitation data and climate measurements

✓ Daily rainfall data provided by the INM, enabling the intensity and spatial distribution of precipitation to be assessed during the episodes of 4 October 1996 and 29 September 2016.

✓ Meteorological parameters, such as minimum and maximum temperatures, relative humidity, evaporation, wind direction and strength, for 4 October 1996 and 29 September 2016.

Satellite data

✓ NOAA-AVHRR satellite images, thermal infrared: (11.5-12.5µm) channel 5, on 16/1/1995 at 09 :06 and on 04/10/1996 at 17 :26, used to analyse the fine structure of cloud systems.

✓ Meteosat satellite images, infrared and visible, on 28 and 29/09/2016, providing continuous monitoring of cloud mass evolution at high temporal frequency.

Aerological data (radiosondes)

✓ Atmospheric radiosondes (Trapani and Tunis-Carthage) on 4 October 1996 at 12 :00 UTC and on 28 September 2016 at 00 :00, providing the vertical profiles needed to assess the nature of the air masses and the conditions of instability.

Barometric and geopotential data

✓ Maps of surface and altitude barometric fields at 500 hPa for 04/10/1996 and 29/09/2016

✓ Jet stream maps (300 hPa level), essential for understanding the role of this high-altitude current in the dynamics of convective systems.

1.2. Methodology:

The methodology adopted in this study is based on a multi-scale synoptic analysis using several types of data simultaneously. The combined use of this information made it possible to examine the structure of cloud systems, characterise atmospheric centres of action and identify the dynamic mechanisms that led to the instabilities observed. The aerological analysis was based on available radiosondes (Trapani and Tunis-Carthage) in order to assess the vertical structure of the atmosphere, instability indices (IA, ICS, CAPE) and characteristic levels (LFC, CCL, EL). All of these sources were cross-referenced to compare the temporal evolution of atmospheric fields with recorded precipitation, thus highlighting the interactions between upper-level circulation, synoptic dynamics and convective processes responsible for the extreme rainfall events studied.

2. RESULTS

2.1. Heay rain event in kelibia: case of 04/10/1996.

On 4 October 1996, the small town of Kelibia, located at the north-eastern tip of the Cap Bon peninsula and Tunisia (36.85°N and 11.08°E), received 179.8 mm of rain in 24 hours. This is the highest rainfall recorded at this station since 1/1/1968. This intense rainfall event was caused by a "Medicane".

2.1.1. Brief overview of "Medicanes"

Medicanes, like tropical cyclones, are a striking example of the interactions between the hydrosphere and atmosphere in the Mediterranean. Under certain conditions, an "ordinary" Mediterranean cyclone (atmospheric depression) can turn into a Medicane when the following conditions are met (*Cavicchia and al., 2014; El Melki, 2015*):

- ✓ Presence of an "ordinary" cyclone over the Mediterranean
- ✓ A strong vertical thermal gradient (difference) between the sea surface temperature and the average troposphere temperature: at 350 hPa
- ✓ A weak vertical wind shear (sudden change in direction and/or speed) (less than 4 ms for speeds)
- ✓ High relative humidity in the atmosphere
- ✓ Very high vorticity/helicity (rotational movement linked to the Coriolis force) of the air column, particularly at 850 hPa.

The first three conditions described above often characterise all "ordinary" Mediterranean cyclones; however, not all of them turn into Medicanes. The "strong vorticity", the last factor listed, is the decisive factor in this evolution. It is defined (*Cavicchia and al., 2014*) as :

- ✓ An average surface wind speed within a circle with a radius of 50 km around the minimum pressure greater than 18 m/s for more than 10% of the trajectory or more than 6 hours.
- ✓ The average wind speed (within a circle with a radius of 50 km around the minimum pressure) at 850 hPa is greater than the wind speed at 300 hPa.
- ✓ A maximum wind speed within a circle with a radius of 50 km around the minimum pressure greater than 29 m/s for a period of > 4 hours.

Modelling work on "Medicanes" (*Chaboureau and al., 2012; Akhtar and al., 2014*) with the aim of improving numerical forecasting of these phenomena has shown that only the passage of an "ordinary" Mediterranean cyclone under a "jet stream" can achieve such vorticity. The latter causes the "explosive deepening" (pressure decrease of more than 18 hPa/day) of the "ordinary" cyclone, the establishment of a barotropic dynamic (Fig. 1) and its transformation into a "Medicane".

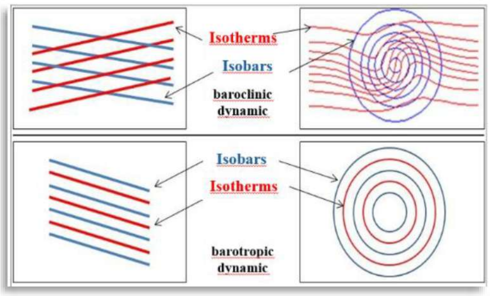

Figure 1. Schematic representation (plan view) of isobars and isotherms in a baroclinic atmosphere and in a barotropic atmosphere.

As we do not have the means to verify the accuracy of all the genetic criteria mentioned above, this study will be limited to the morphological criteria observable on satellite images and the information provided by available radiosondes.

The example of 16/1/1995 (Fig. 2) in the central Mediterranean is the best example ever observed to date, illustrating the perfect morphology of a "Medicane". It consists of a compact cloud disc tightly wrapped around a cloud-free eye with spiral clouds all around it, reminiscent of the typical structure of tropical cyclones *(Emanuel, 2005; Chaboureau and al., 2012; Romero and al., 2013; etc.)*.

It should be noted, however, that not all phenomena known to be "Medicanes" do not all have such perfect morphology. Collections of satellite images of approved "Medicanes" are currently available on the web and allow us to see a variety of them from this point of view.

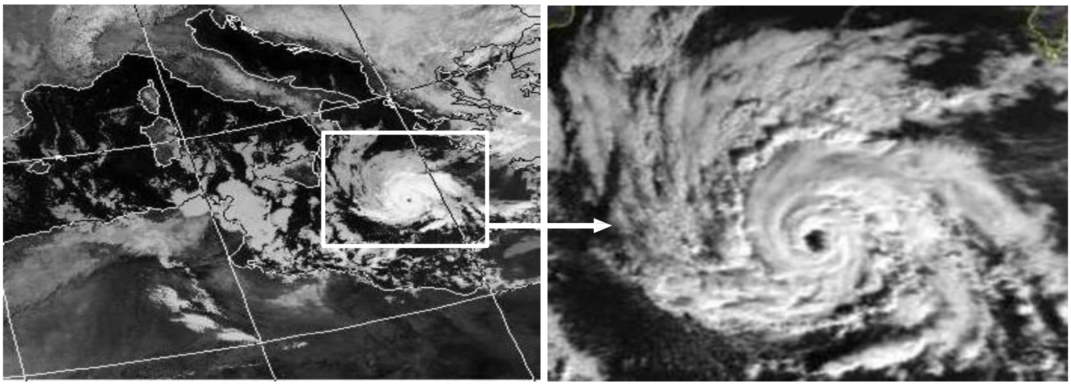

Figure -2. Cloud system over the central Mediterranean. NOAA-AVHRR satellite image taken on 16/1/1995 at 09 :06 Am, channel 5 (thermal infrared : 11.5-12.5µm). The eye of the Medicane is located approximately halfway between Malta and Crete.

2.1.2. Presentation of the Medicane of 4/ 10/ 1996.

The surface barometric field on 4/10/1996 (Fig. 3) is characterised by a barometric ridge connecting two very large anticyclonic areas composed of two elements: a very extensive and powerful Atlantic anticyclone (1040 hPa) centred off the coast of Western Europe and an Eastern European anticyclonic complex, the westernmost element of which is centred on Eastern Europe and the Black Sea. On the southern flank of this barometric ridge/dorsal, in the western Mediterranean, lies a well-developed, fairly deep Mediterranean depression (less than 1010 hPa) centred on Sicily.
This system maintains a rotating flow of Mediterranean origin, i.e. maritime, over the surface of Tunisia. The Mediterranean depression imposes a return circulation responsible for its warming (convective and unstable state of the air mass in place) and humidification.
At altitude (Fig. 3), a depression (probably a cold drop) overlaps perfectly with the surface depression. It activates convection from the lower layers of the atmosphere. An active branch of the subtropical jet stream is located south of Tunisia (Fig. 4). It perfectly frames the surface and high-altitude depressions. It is well known that this current reinforces vertical instabilities on its northern flank (*El Melki, 2007, 2014*).
The tubular and almost perfectly circular shape of the areas of heavy precipitation (Niederschlag in German) and strong convection (Konvektion, idem) framing the western half of Sicily (Fig. 5) and affecting the tip of Cap Bon on 4/10/1996 confirms the presence of this type of barotropic atmospheric circulation induced by the "Medicane". This explains the deluge that fell on Kelibia that day, as well as the remarkably low rainfall totals in the rest of the country (Tab. I).

The central part of a "Medicane", just like a tropical cyclone of perfect appearance, has an area of subsidence and therefore low cloud cover, giving rise to the cloud-free eye of the system. The central part of the Medicane of 4/10/1996 (Fig. 6) also has this property and receives less precipitation (Fig. 5).

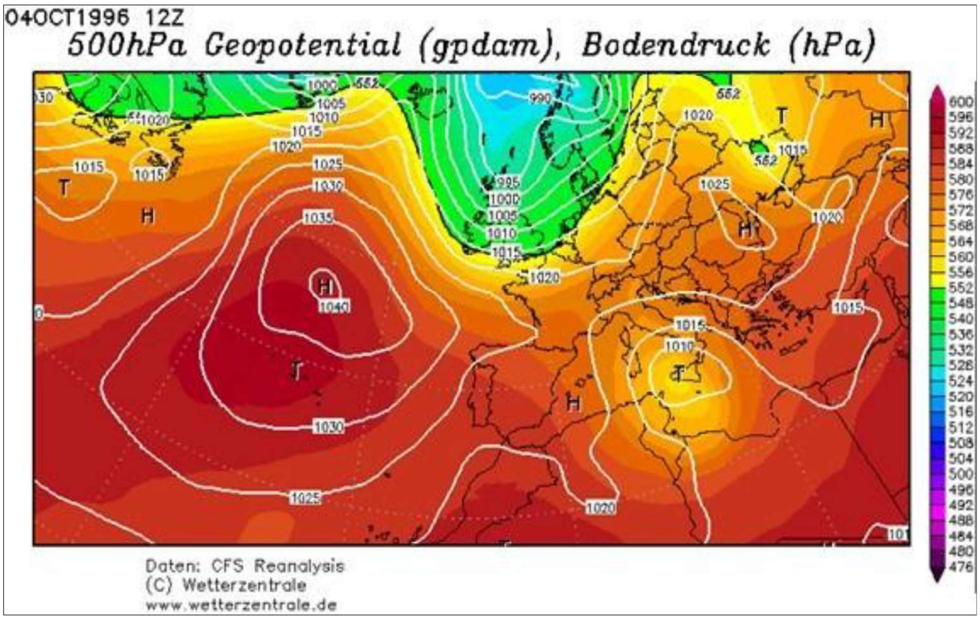

Figure 3. Surface and altitude barometric fields 04/10/1996 at 12:00 p.m.

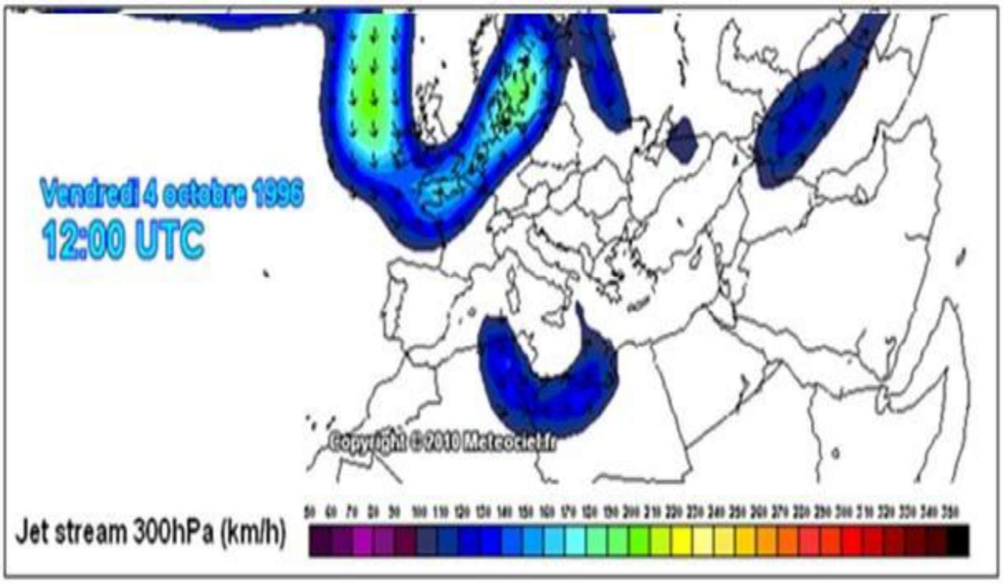

Figure 4. « Jet Stream » du 04/10/1996 at 12:00 p.m.

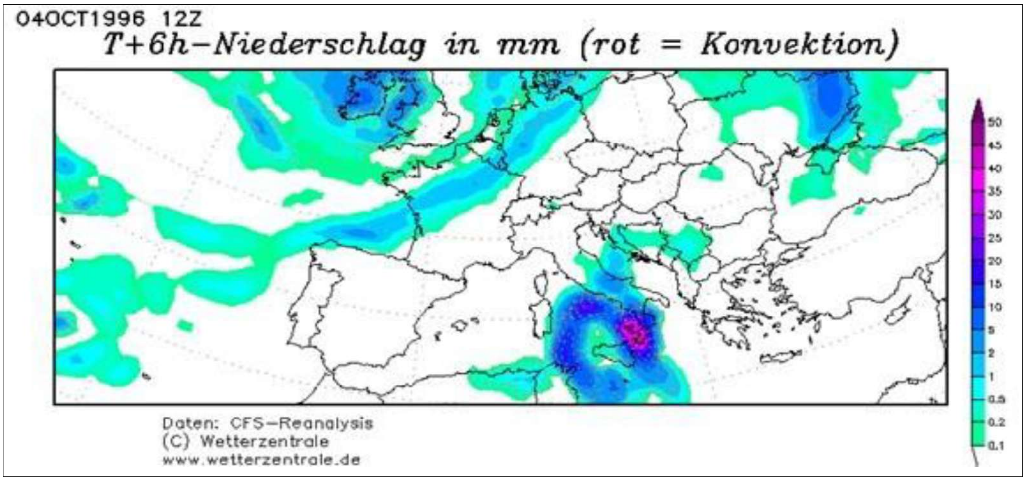

Figure 5. Areas of heavy precipitation 04/10/1996

The NOAA-AVHRR image from 04/10/1996 at 17:26 (Fig. 6) in thermal infrared (11.5-12.5μm) shows a well-developed cloud system over the Strait of Sicily and southern Italy. It is clearly disconnected from other cloud formations further north. The central part of this system (between Tunisia and Sicily) is very compact. The spiral shape and anticlockwise rotation of the system are clearly visible. The white clouds correspond to the part where convection is most active (strong vertical instability) and where cumuliform clouds (cumulonimbus, in particular) are thickest and have the highest and coldest tops (ice crystals). The Kelibia region is fully within this area. The grey clouds correspond to clouds with lower tops.

No radiosonde data from Tunis-Carthage is available for this date. The radiosonde data (Fig. 7) from Trapani (37°90' N and 12°50' E) in Sicily, the weather station closest to Kelibia, shows a humid and very unstable aerological structure of the "Ccm " (convective: warms at the base = unstable, convergent: cyclonic evolution, maritime: humid):

- ✓ Relative humidity varies between 79% at the station (altitude 14 mgep [geopotential metre] and 1005 hPa) and 83% at 700 hPa 2995 mgep).
- ✓ There are multiple indicators of strong vertical instability:

• Presence of a highly convective layer tangent to the ground: air temperature curve (Θ) sloping steeply from the bottom right to the top left: this indicates an air mass warming at the base. The top of this layer is at 721 mgp (925 hPa) and its thickness is 707 mgp (the altitude of the station being 14 m). This layer is very unstable: Absolute Instability (AI).

• The LFC (Level of Free Convection) is very low (481 mgp) and lies to the right of the air temperature curve (Θ). It originates from the convective layer (AI) indicated above. In this position, it indicates the presence of a low-altitude cloud ceiling (cloud base).

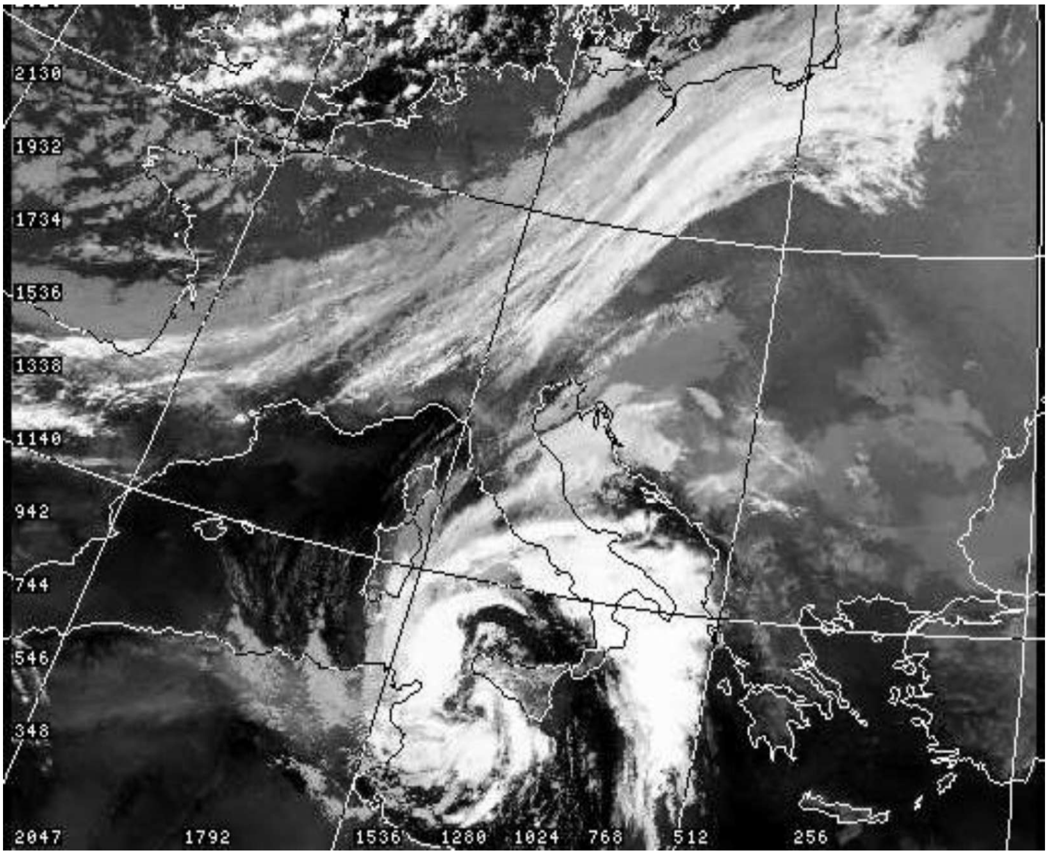

Figure -6. Cloud system over the central Mediterranean. NOAA-AVHRR satellite image from 04/10/1996 at 17:26. Channel 5 (Thermal infrared: 11.5-12.5µm).

• Air particles carried by convection from the LFC level can continue their ascent to the LFC-EL (Equilibrium Level) level: this corresponds to the altitude at which the temperature of the particles in convection (which are warmer than the surrounding air) is equal to that of the surrounding air. Convection ends. This is the maximum altitude that can be reached by cloud tops: 8581 m, resulting in cloud formation with a thickness of 8100 m.

• The LFC and lfc-EL levels represent the limits of the layer affected by CAPE (Convective Available Potential Energy). Graphically (Fig. 4), CAPE is proportional to the area (coloured dark red and pink on diagram 761) between the air temperature curve (Θ) and the curve of the "Lift Parcel" (ascending/convective particle) joining the LFC and lfc-EL levels. CAPE corresponds to the latent energy of evaporation (stored in water vapour) and released into the ambient air following the condensation of water vapour due to the cooling effect of rising air particles. It is this energy that allows air particles from the absolute instability (AI) layer tangent to the ground to continue their ascent even in the stable upper layers (ICL: Latent Convective Instability, and SA: Absolute Stability) of the troposphere. In this case, the CAPE is quite significant: 1242 j/kg (joules / kilogram).

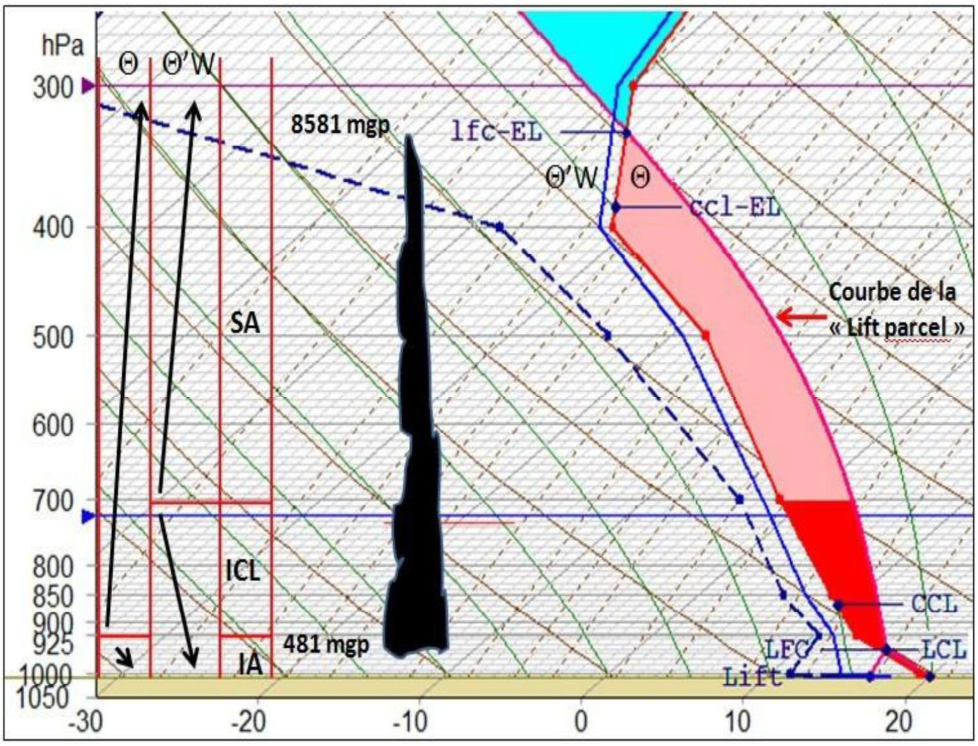

Figure -7. Radiosonde from Trapani (Italy) on 04/10/1996 at 12:00 UTC

The climate table (Tab. I) for this day shows very similar minimum temperatures, maximum temperatures and relative humidity levels at all coastal stations: the whole country is bathed in the same air mass. The Kelibia station was the only one to receive 179.8 mm of rain in 24 hours. It is the closest to the epicentre of the "Medicane" located approximately on the island of Malta. The nearest stations (Nabeul, Tunis-Carthage, Bizerte, etc.) received less than 12 mm. The rest of the country's regions (all stations not listed in the table) recorded nothing.

This example highlights the exceptional and spatially limited nature of the intense precipitation caused by this unusual type of atmospheric circulation.

Table I - Weather conditions at several Tunisian stations on 04/10/1996 at 12:00 UTC (data source: INM Tunis)

Stations	Min Temperature (°C)	Max Temperature (°C)	Precipitation (mm)	Thunderstorm	Piche Evaporation (mm)	Relative Humidity (%)	Wind Direction (°)	Wind Speed (m/s)
KELIBIA	13,8	18	179,8	1	1,6	90	29	9
JENDOUBA	12,2	20	11,8	0	2,9	82	30	9
BIZERTE	15,6	19,5	11,5	0	6,1	74	34	14
NABEUL	14,1	18,7	10,9	0	2,4	86	30	9
LE KEF	9,2	19	9	0	1,8	85	31	3
TUNIS CARTHAGE	13,6	19,4	8,9	1	4,5	82	31	15
SILIANA	9,6	18	8,8	0	6,8	88	30	11
ZAGHOUAN	13,1	19,4	2,5	0	6,4	74	30	11
MONASTIR	15	21,5	2,3	0	3,6	70	33	13
THELA	6,7	18	1,8	0	5,7	75	34	26
BEJA	13,2	21,8	1,4	1	9,1	77	36	12
TABARKA	13,1	20,4	0,4	0	6,9	74	32	12
MAHDIA	14,6	21,7	0,1	1	3,1	80	37	9

2.2. Heavy rainfall in the sahel region of sousse : case of 29/09/2016.

The heavy rainfall event of 29/09/2016 in the Sahel region of Sousse (Fig. 8) appears to be exceptional both in terms of the daily rainfall totals recorded on that day and the nature of the factors that caused it.

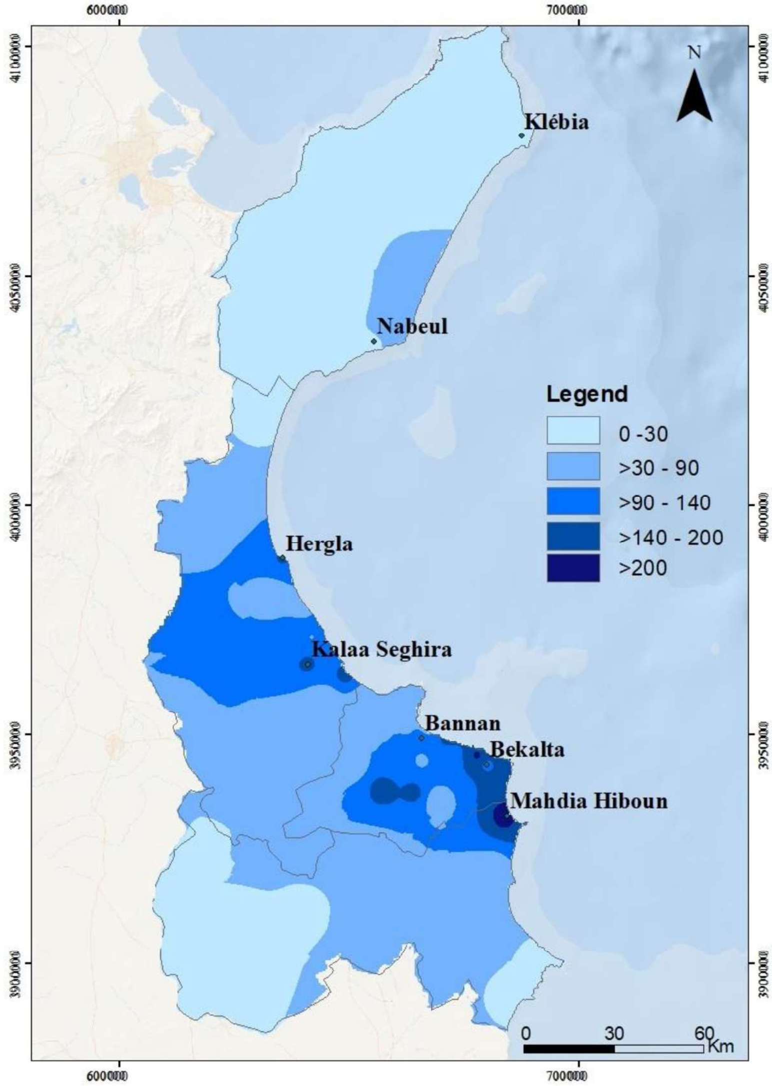

Figure 8. Rainfall (mm) on 29/09/2016 in the Sahel region of Sousse.

The surface barometric field (Fig. 9) is characterised by a large anticyclonic area formed by the junction of a very large and powerful Atlantic anticyclone (1036 hPa) and an equally powerful (1033 and 1031 hPa) and extensive Mediterranean anticyclone. These two systems cover the entire Mediterranean and Black Sea regions, as well as their continental peripheries in North Africa, the Sahara, the Middle East and Europe. The whole of Tunisia is included in the 1020 hPa isobar and the Sahel region of Sousse, which was flooded on that day, is located well within the 1024 hPa isobar. Such high pressure does not, in theory, favour the occurrence of the torrential rains recorded on that day. The very moderate maximum temperatures for that day along the entire eastern coast of the country (24°C in Kelibia and Monastir, 25°C in Sfax and Gabes) rule out the possibility of thermo-convective storms, especially since these most often occur in inland regions.

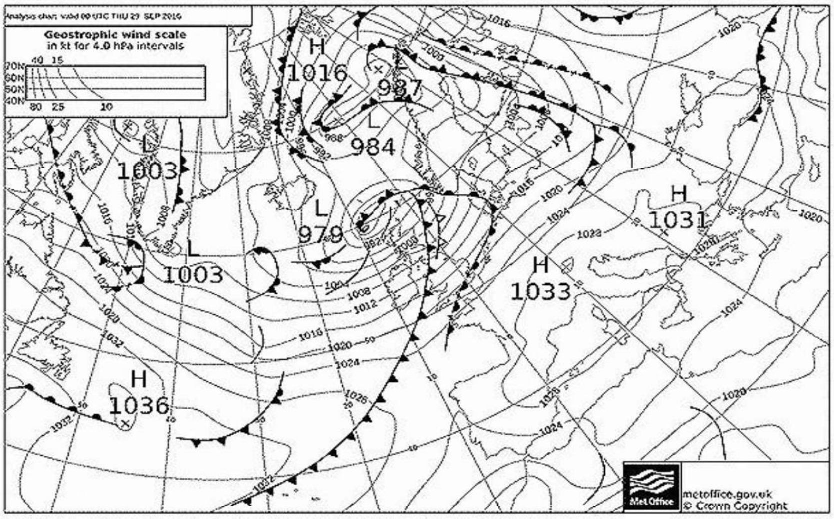

Figure 9. Surface barometric field on 29/09/2016 at 00:00 GMT.

At altitude, the barometric field (Fig. 10) is also characterised by a very high geopotential: Tunisia is located in the 500 hPa surface altitude range between 584 and 588 dam (5840 and 5880 mgp). Under these conditions, theoretically, nothing unusual can occur in terms of cloud cover and precipitation. The configuration of the barometric field at this altitude is characterised by the presence of a low but undeniable altitude depression (almost latitudinal in nature: WSW-ENE) where there is a slight relative drop in the 500 hPa level (572 to 580 dam) compared to the general context described above (5840 and 5880 mgp).
Countless configurations, closely related to the properties of surface and altitude barometric fields described above, occur daily and according to regional atmospheric circulation patterns in these regions and throughout all seasons, without causing such intense and spatially concentrated rainfall events.

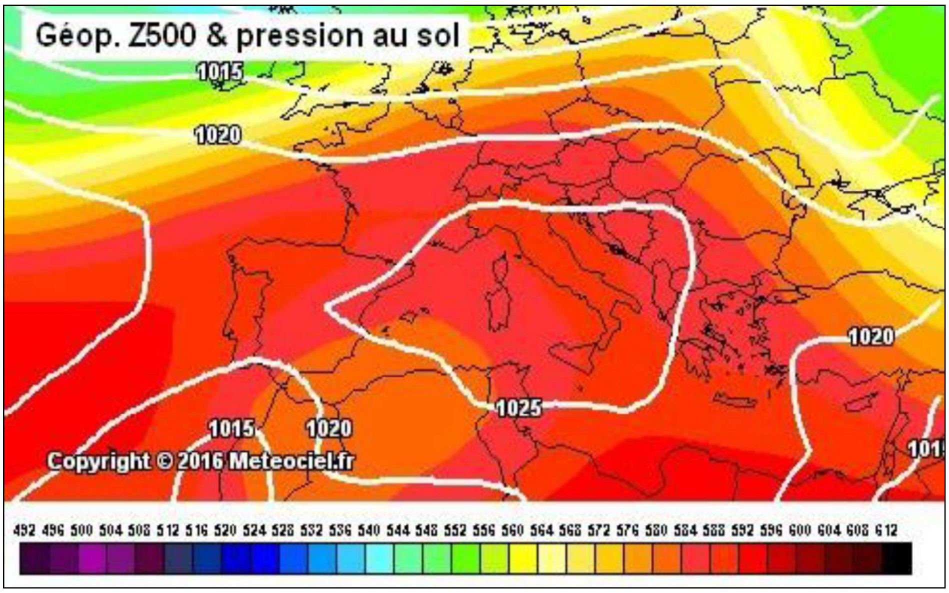

Figure 10. Surface barometric field and 500 hPa geopotential on 29/09/2016 at 12:00 GMT.

This upper-level low appears to be closely related to and well superimposed on the subtropical jet stream (surface 300 hPa) above it (Fig. 11). It is widely accepted that the latter plays an important, if not essential, role in shaping spatial configurations and in the temporal evolution of barometric fields, both at the surface and at altitude, in the regions it overhangs.

The jet stream on 29/09/20016, at 12:00 noon, had a rather unusual configuration (Fig. 11). It describes a very narrow "meander" (very similar in appearance to the loop of an "abandoned meander" of a river) over the Sahara, the Mediterranean and southern Europe, with a quasi-latitudinal direction: WSW-ENE, similar to that of the barometric valley described above. Tunisia and Algeria are located right in the middle of this "meander". The driving effect of the two "descending" (over the western Mediterranean) and "rising" branches (over the Sahara) has created two independent cells of vortex circulation (cyclonic /depressive)

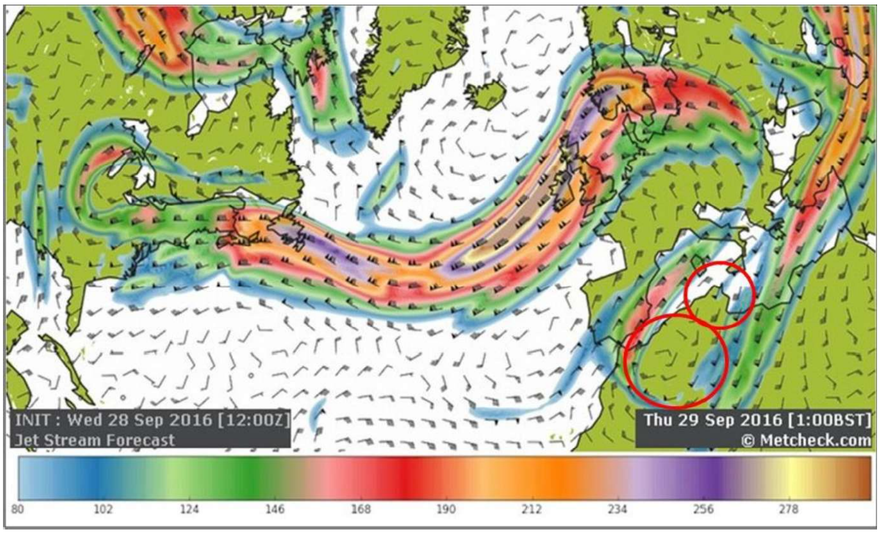

Figure 11. Position of the jet stream on 29/09/2016 at 12:00 GMT

These two cyclonic cells initiated the updrafts/vertical instability that determined the cloud formations observable on satellite images (Fig. 13) from the early hours of 29/09/2016. It should be noted that this high-altitude barometric system had already begun, with the associated cloud cover, in the early hours (00:00) of 28/09/2016 (Fig. 12).

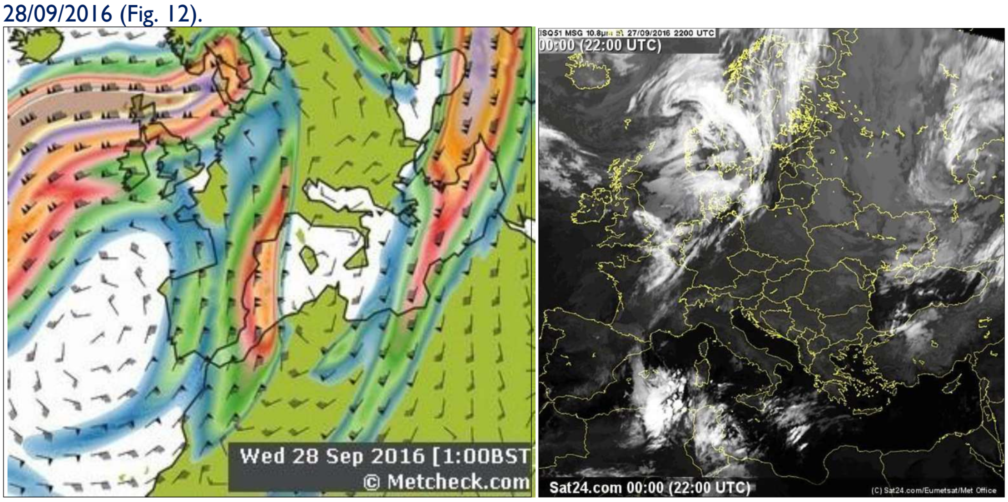

Figure 12. Position of the jet stream on 28/09/2016 at 12:00 GMT (left) and Meteosat satellite image on 28/09/2016 at 00:00 (right).

No radiosonde data is available for Tunis-Carthage for 29/09/2016. The data for 28/09/2016 at 00:00 shows a Ccm-type aerological structure (similar to that described above) but with a lower degree of instability (no IA). An area of Convective and Selective Instability (ICS; less severe than IA) is present in the lower layers, where the CCL (Convective Condensation Level) is located. In this case, the CCL shows the base of a cloud formation (1233 mgp), probably of the cumuliform type. This is very thick: 9,642 mgp. The satellite image (Fig. 13) shows a slightly discontinuous cloud mass on that day, but with very white tops (cold tops: very high: formed of ice). The maximum altitude (10,875 mgp) of the tops of these clouds is slightly above that of the tropopause (10,845 mgp).

Satellite images from 29/09/2016 (Fig. 14) at different times of the day (06:00 to 22:00) show convective clouds with very high tops. No spiral pattern is visible.
From a genetic and physiognomic point of view, the probability of a "Medicane" can be ruled out. In the first instance, the formation of the latter requires the prior presence of an ordinary Mediterranean cyclone, which is completely absent. The geopotential is very high, and the barometric field is completely dominated by a powerful anticyclone. Physically, satellite imagery (4 p.m. and 8 p.m.) shows well-developed convective (stormy) cells over north-eastern Tunisia.

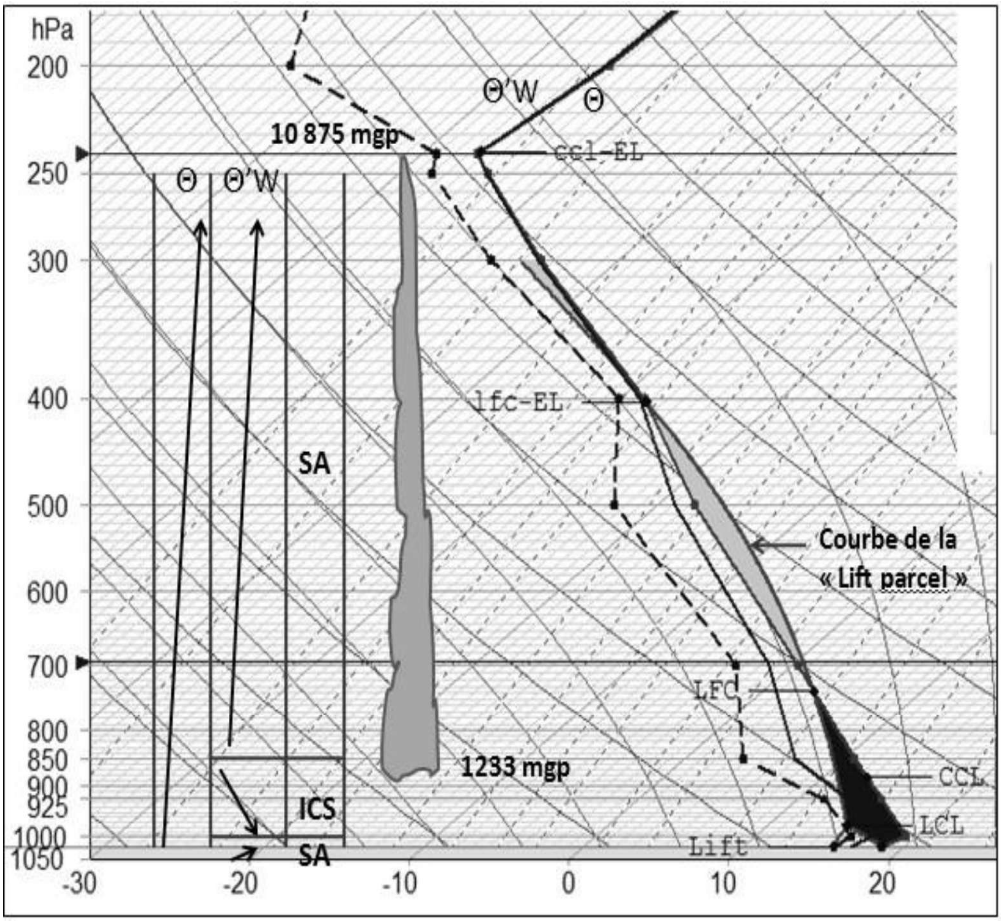

Figure 13. Radiosonde from Tunis-Carthage on 28 September 2016 at 00:00.

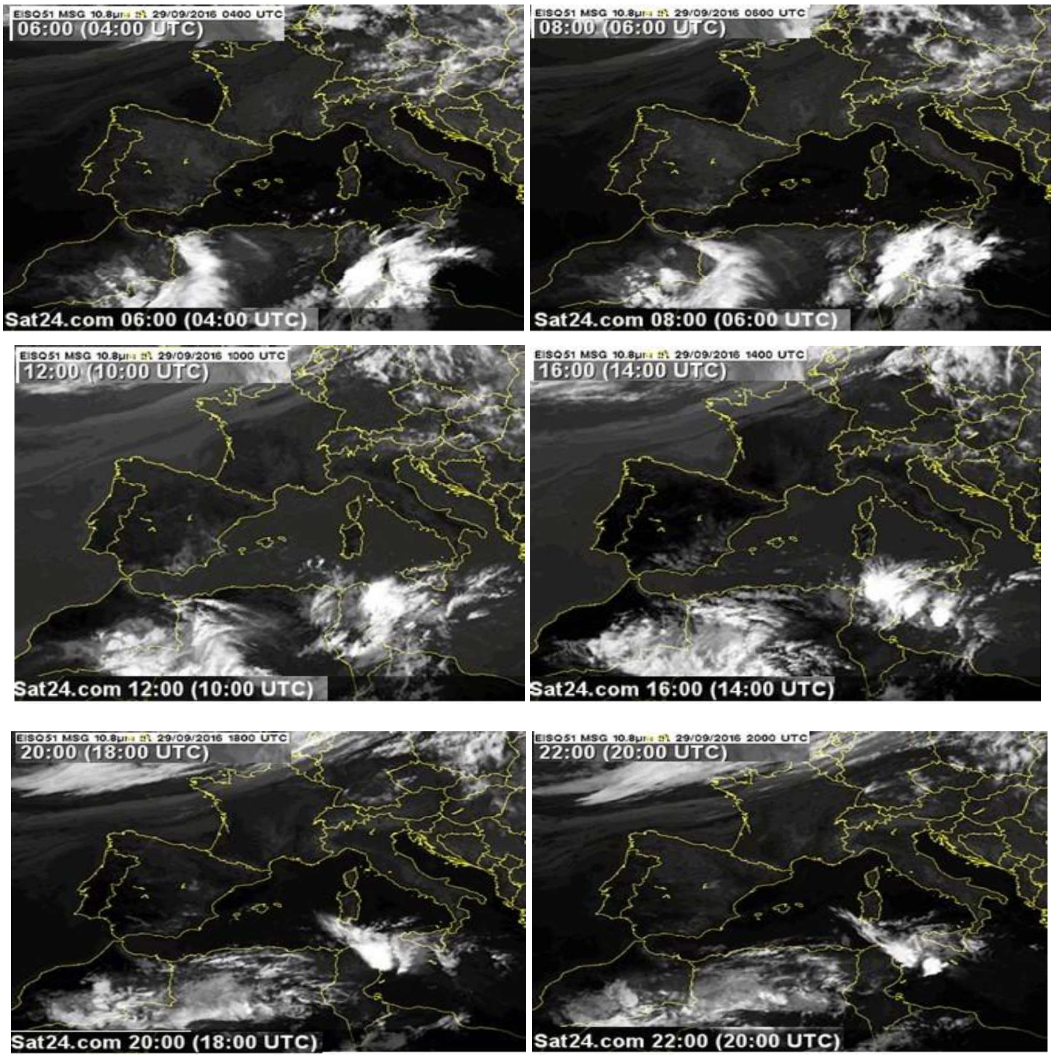

Figure 14. Meteosat satellite images from 29/09/2016: evolution of cloud cover in north-eastern Tunisia between 06:00 and 22:00.

The rainfall that occurred in the Sahel region of Sousse on 29/09/2016 (Fig. 8) was very unevenly distributed beneath the cloud cover that caused it. This issue, which goes beyond the scope of this study and relates to cloud microphysics, provides valuable insight into the interlocking spatial and temporal scales that determine atmospheric phenomena. Taking this fact into account certainly helps to better characterise the different states of the atmosphere.

3. DISCUSSION

3.1 Comparative analysis of the two extreme events

The two extreme rainfall events studied – the Medicane of 4 October 1996 in Kelibia and the convective event of 29 September 2016 in the Sahel region of Sousse are prime examples of the complexity of the atmospheric processes that govern intense precipitation in Tunisia. Although they generated exceptional daily rainfall totals, these events resulted from very different dynamic configurations, showing that distinct mechanisms can lead to comparable hydrometeorological impacts. The 1996 episode was distinguished by the formation of a Medicane, characterised by a compact spiral morphology, a cloud-free centre, strong deep convection and barotropic forcing linked to the passage of an upper-level jet stream. The identified genetic conditions (low vertical wind variation, high atmospheric humidity and high vorticity) were all present, while the superimposition of surface and altitude depressions, combined with the strengthening of the subtropical jet stream, allowed the development of explosive instability leading to a cyclonic system similar to tropical cyclones. Kelibia's location in the immediate vicinity of the Medicane's eye explains the very high spatial concentration of precipitation (179.8 mm/24 hours), while neighbouring stations received only a few millimetres, highlighting the highly localised and non-linear nature of this type of phenomenon. Conversely, the episode of 29 September 2016 shows no morphological or dynamic evidence of the presence of a Medicane. At that time, the country was dominated by a powerful anticyclonic field, with high geopotentials and moderate temperatures, which did not favour the usual thermo-convective storms. The extreme rainfall was caused by an atypical jet stream configuration, forming a tight meander that generated two independent cyclonic cells, responsible for localised and persistent updrafts that gave rise to intense convective cells. This case perfectly illustrates that an anticyclonic situation at the surface does not guarantee the absence of severe convection when synoptic and planetary forcings occur at altitude.

3.2 Role of the jet stream and spatial variability of precipitation

Both episodes highlight the decisive role of the subtropical jet stream, a factor that is still largely unexplored in Tunisian climate studies. In both cases, the jet stream structures the updrafts, reinforces vertical thermal contrasts, frames the low-pressure systems as in 1996 or generates high-altitude vortices as in 2016and directly contributes to the deep instabilities responsible for intense precipitation. This observation is essential, as most local studies tend to focus on surface mechanisms or simple thermal contrasts, neglecting this fundamental dynamic driver (El Melki, 2007, 2014). Furthermore, observations reveal extreme spatial variability in precipitation in both episodes: in 1996, the contrast between Kelibia (179 mm) and neighbouring stations, which did not exceed 12 mm, was particularly significant, while in 2016, intense rainfall was limited to a few localities in the Sahel. This heterogeneity highlights the importance of cloud microphysics, showing that even under continuous cloud cover – as in 2016 – precipitation can remain highly localised due to local mechanisms that are difficult to detect. All of these elements demonstrate that explaining extreme rainfall in Tunisia requires an integrated approach, taking into account local, synoptic and global scales simultaneously.

CONCLUSION

In recent decades, climatological research has moved towards an applied approach that is increasingly focused on finer spatial scales (local and microclimatic) and shorter temporal scales.

Several factors have contributed to this trend, which seems to be gaining widespread acceptance. The countless technological innovations in the field of microclimatic measurement techniques and tools – particularly portable devices – are among the most important of these factors. By allowing researchers to build their own databases, they are suddenly freed from all the constraints of using conventional databases and the tedious processing of large amounts of information: climate norms. Thus, it seems that the interlocking of the spatial and temporal scales governing atmospheric phenomena is increasingly being neglected, which in some cases can be a major shortcoming.

The atmospheric circumstances surrounding the intense rainfall events of 4 October 1996 in Kelibia and 29 September 2016 in the Sahel region of Sousse demonstrate the complexity of rainfall processes and the intertwining of multiple factors of varying spatial and temporal scales that determine the genesis of these events. The influence of the subtropical jet stream, a zonal scale factor that is often overlooked among the factors contributing to intense rainfall, proved to be decisive in both events.

This high-altitude current is closely interdependent with the major centres of action (the Azores High and the Icelandic Low (which govern atmospheric circulation in the synoptic zone where Tunisia is located: North Africa and the Sahara, the North Atlantic, Europe and the Mediterranean. In this context, temperate atmospheric circulation is far from being disconnected from that of hot and cold regions. In this context, the increase in global climate variability (various IPCC reports, for example) induced by global warming must inevitably have repercussions on the jet stream patterns. In-depth investigations into the interactions of these factors with intense rainfall in Tunisia are certainly of great interest in terms of short- and medium-term forecasting of such rainfall.

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