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Synoptic Analysis of Mediterranean Storm "Daniel" Affecting Northeastern Libya 10-11.9.2023

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Abstract:

In this study, the synoptic conditions accompanying the emergence and development of the Mediterranean storm Daniel were analyzed. The storm hit Greece, Bulgaria and Turkey before developing into a Medicane that struck cities in northeastern Libya on September 10-11. 2023, causing the collapse of two dams in the Derna city and death of thousands of people and massive destruction of buildings and infrastructure.

Surface and upper weather maps were analyzed at several levels to track the elements of the two weather systems, and to identify the vertical sector of the air through thermodynamic charts and the interpretation of satellite images.

The study showed that the increase in the sea surface temperature, which broke observation records in July, and the upper cooling flow associated with the shift of the polar jet stream axis to the southern Mediterranean contributed to the formation of a deep depression, which was characterized after days by the appearance of the features of the Mediterranean storm (Medicane) such as weak wind shear, strong convection activity and the appearance of a semi-closed eye with spiral cloud bands.

As the surface sea water continues to warm, the possibility of such a phenomenon recurring in the future is likely.

Key Words: Synoptic, Storm, Medicane, Mediterranean, Libya, Derna.

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التحليل السينوبتكي للعاصفة المتوسطية "دانيال" التي أثرت على شمال شرق ليبيا، 10-11 سبتمبر 2023

أ.د أنور فتح الله إسماعيل

قسم الجغرافيا/ جامعة درنة- درنة، ليبيا

المستخلص:

في هذه الدراسة، تم تحليل الظروف الجوية المصاحبة لنشأة وتطور العاصفة المتوسطية "دانيال" حيث أثرت العاصفة على اليونان وبلغاريا وتركيا قبل أن تتطور إلى "ميديكين" ضرب مدنًا في شمال شرق ليبيا في 10-11 سبتمبر 2023، مسببةً انهيار سدين في مدينة درنة ومقتل آلاف الأشخاص ودمارًا هائلًا في المباني والبنية التحتية.

تم تحليل خرائط الطقس السطحية والعلوية على عدة مستويات لتتبع عناصر المنظومتين الجويتين، وتحليل القطاع الرأسي للهواء من خلال المخططات الديناميكية الحرارية وتفسير صور الأقمار الصناعية.

أظهرت الدراسة أن ارتفاع درجة حرارة سطح البحر، الذي حطم الأرقام القياسية المسجلة في يوليو، وتدفق التبريد العلوي المرتبط بتحول محور التيار النفاث القطبي إلى جنوب البحر الأبيض المتوسط، ساهم في تكوين منخفض جوي عميق، اتصف بعد أيام بظهور سمات العاصفة المتوسطية (ميديكين) مثل ضعف القص الريحي، ونشاط الحمل الحراري القوي، وظهور عين شبه مغلقة مع نطاقات سحابية حلزونية.

ومع استمرار ارتفاع درجة حرارة مياه البحر السطحية، فمن المرجح تكرار هذه الظاهرة مستقبلًا.

الكلمات المفتاحية: سينوبتيك، عاصفة، ميديكين، البحر الأبيض المتوسط، ليبيا، درنة.

1. INTRODUCTION

Due to the effect of global warming and the accompanying rise in the sea surface temperature of the Mediterranean Sea, which has been increasing rapidly since the mid-nineties of the last century, the Mediterranean basin, especially in its western and central parts, has seen an increase in the intensity of Mediterranean cyclones. Recent studies using regional and global climate simulations agree in representing an increase in the cyclone intensity (Mario, 2019) According to the IPCC report on the Mediterranean region, climate models continue to project regional temperatures to rise at rates about 20% higher than the global average (Ali, 2022).

Medicane is a hybrid phenomenon similar to tropical cyclones, but different in its size, path and intensity. Although this phenomenon is not the result of recent years, it has increased in intensity and changed in its paths, as the eastern Libyan coasts that were struck by Storm Daniel are among the areas least affected by medicines.

More consensus exists about the long-term temporal and spatial distribution of tropical-like cyclones, They form predominantly over the western and central Mediterranean Sea while the area east of Crete is almost devoid it (Nastos et al.,2015).

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On September 10 - 11, 2023, the Mediterranean storm Daniel hit northeastern Libya after developing into a Medicane, causing the biggest natural disaster to hit Libya in its modern history. According to the United Nations Office for the Coordination of Humanitarian Affairs (OCHA) update of November 28th, 2023, 250,000 people (about one third children) have been affected by the disaster and need humanitarian assistance. Of these, 44,800 are internally displaced, 4,352 are deceased and over 8,000 are still missing. losses and damages amounted to $1.6 billion (World Bank, 2023), entire neighborhoods in Derna disappeared, along with their residents swept away by water after two ageing dams collapsed making the situation catastrophic and out of control (WMO, 2023).

2. DATA AND METHODS

2.1 The study area

The study area is located in the northeastern part of Libya between 32˚56¯20″ N 30˚59¯24″ N and 19˚53¯24″ E 23˚08¯06″ E (Figure 1), It includes weather stations whose data was used in the study, (Table 1). The study area extends from the Gulf of Sirte in the west to the city of Derna in the east for a distance of 300 km. Between them extends a mountainous plateau known locally as Al- Jabal Al-Akhdar. The elevation of the earth's surface ranges from zero on the northern coasts of the Mediterranean Sea to about 883 meters at the third terrace of Al- Jabal Al-Akhdar, with a steep slope towards the sea and a gradual slope towards the south. There are many deep basins and valleys that cut it in different directions, including the Derna valley basin, where two dams collapsed, causing an unprecedented catastrophic flood as a result of Daniel Medicane 10-11/9/2023.

The annual average rainfall in Al-Jabal Al-Akhdar is estimated at about 360 mm, which is a relatively high rate, since about 75% of the country does not have rainfall rates exceeding 100 mm annually (Ismail&Habel.2019).

Due to the variation in topography and elevation, facing the movement of the humid winds, the distance from the sea coast, and the shape of the coastline, rainfall varies spatially, peaking in the high areas close to the coast and facing wind movement, (Shahat and Al-Bayda 500 mm - 600 mm), while the coastal plain has rainfall averages ranging from 250 mm to 350 mm, and decreases significantly on the southern slopes to less than 200 mm (Ismail, 2012).

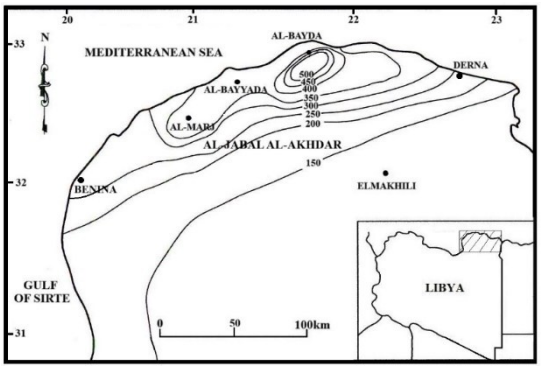

FIGURE 1 location of study area and isohyets.

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TABLE 1 weather stations in the study area

Station	WMO Index	Altitude (m)	Lat	Lon
Benina	62053	125	32.05.38 N	20.15.51E
Al-Marj	62054	282	32.31.20 N	20.52.35 E
Derna	62059	26	32.47.06 N	22.34.46 E
Al-Bayda	-	591	32.45.23 N	21.42.41 E
Al-Bayyada	-	359	32.33.43 N	21.15.02 E

2.2 Methodology

In this study, the synoptic analysis method was used to track the origin and development of the Mediterranean storm "Daniel" by analyzing a set of parameters related to the surface and upper weather systems, which are:

The surface weather system was studied through the atmospheric pressure, cloud cover and water vapor maps in addition to the surface sea temperature maps for the area extending from the Ionian Sea to the Gulf of Sirte.

Important parameters in the upper atmospheric system were tracked at several levels, at 300 hpa, the role of the change in the direction of the axis of the polar jet stream and the relative vorticity and their effect on the activity of convection were highlighted.

The middle layer of the troposphere was important in clarifying the role of upper cooling opposite to surface warming, therefore, through the geopotential height map at 500 hpa, in addition to tracking the amount of atmospheric humidity and temperature in the vertical sector of the atmosphere using the thermodynamic charts (skew t- log p) over the airports of Athens and Heraklion.

To determine the role of wind shear in the development of the depression into a Medicane, wind shear maps were used at the low level and deep layer, and atmospheric instability was calculated through convective available potential energy (CAPE) map and the lifted index that computed as the difference between the observed environmental temperature at 500 mb (Tenv|500) and that of the parcel temperature (Tparcel|500) at the same level. LI is calculated according to the following relation $LI=Tenv,500-Tparcel,500$ (Aorora et al., 2023).

The digital maps required for the study were created using ArcGIS 10.8.

3. THE FORMATION OF THE DEPRESSION

3.1 Formation of the depression cell

A depression cell began to form on the southwestern coast of Greece on the evening of September 3, 2023, after the collision of two air masses, one warm and dry from the Sahara Desert and the other cold and humid from northern Europe (Figure 2.a). The development of the depression was reinforced by the warming of the surface water of the Mediterranean Sea. the sea surface temperature ranged between 27°C and 28°C in the area extending from the Ionian Sea to the Gulf of Sirte (Figure 2.b) A sea surface temperature (SST) threshold of 26°C to 27°C was

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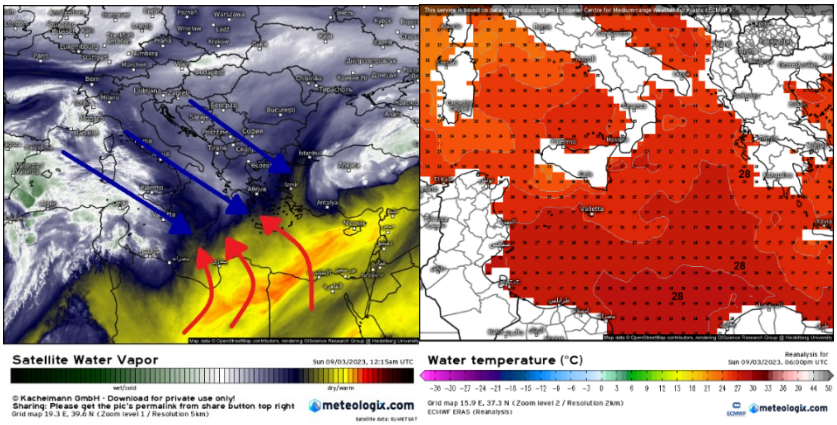
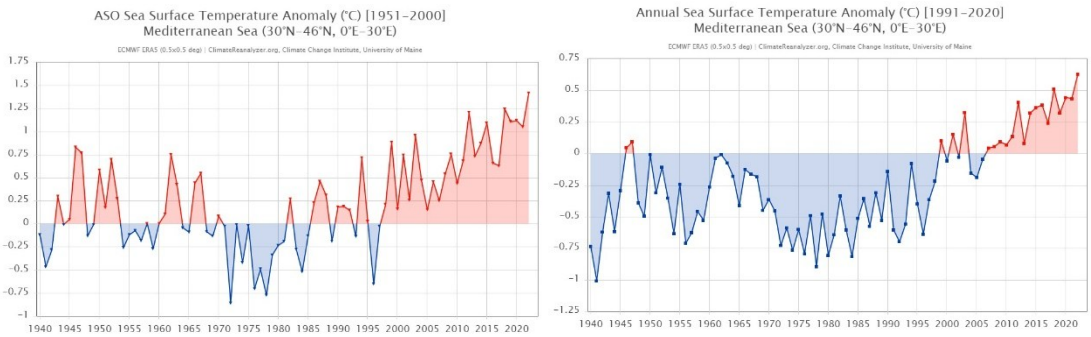
proposed, below which tropical cyclones (TCs) do not form, until a recent study proposed a threshold of 25.5°C (K Tory & R Dare, 2015).



(a) (b)

FIGURE 2 3.9.2023, types of air masses (a) sea surface temperature SST (b)

And it is noted that the sea surface temperature is going through a phase of increasing positive anomalies since the year 1997, especially during the months of August, September and October, which is the period of Medicane activity. This anomaly reached 1.5°C in 2023, (Figure 3).



(a) (b)

FIGURE 3 sea surface temperature anomalies in the Mediterranean Sea, annually (a) ASO (b)

The month of July 2023 was classified as the hottest ever since the beginning of records, as the average global temperature reached 16.96°C according to “Copernicus” (climate change service, 2023).

The global average sea surface temperature on July 31 reached 20.96°C, which is 0.1°C higher than the world record that was recorded. In 2016 it reached 28.7°C in the Mediterranean Sea (Jeannette, 2023).

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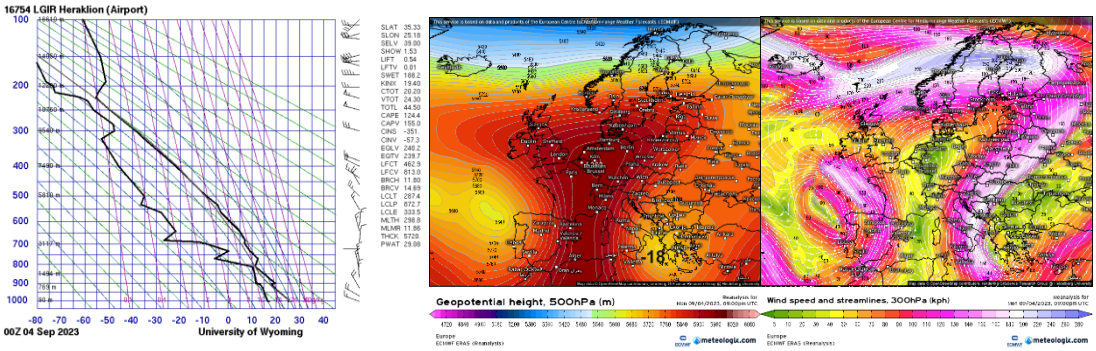
3.2 Upper cooling and convection

The warming of sea surface water during the formation of the depression was accompanied by an upper cooling at the level of 500 hpa that reached (-18 C), which caused a high vertical temperature gradient which can be observed through the thermodynamic chart (skew t- log p) over the airport of Heraklion on 4.9.2023 (Figure 4.a) and during the same day, the upper westerlies organized into an Omega Blocking Pattern (Figure 4.b), which led to the incursion of the polar jet stream axis from central Europe to the western Mediterranean before bending north of the Libyan coast, heading to northeastern Europe across the Aegean Sea (Figure 4.c).

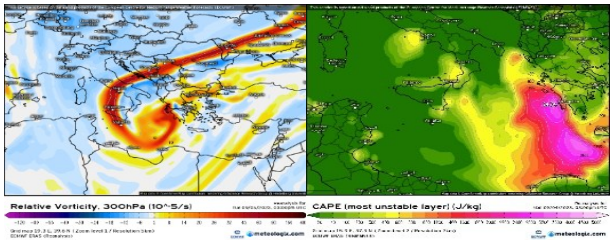


(a) (b) (c)

FIGURE 4 vertical temperature gradient (a) omega pattern 500 hpa (b) jet stream axis 300 hpa (c)

The wind speed at the center of the jet stream (jet streak) reached 193 km/h (at 300 hpa level. 9:00 am U.T.C), and this contributed to the formation of positive vorticity at the level of 300 hpa on 5.9.2023 (Figure 5.a), with high values and an increasing convection located to the north of the jet stream axis. This enhances the transfer of moisture and heat from the sea surface to the atmosphere.

The storm formation stage was characterized by a significant convective activity, which is an important factor in intensification. The activity of air instability during the formation stage can be observed through the values of the convective available potential energy (CAPE) which exceeded 3470 J/kg at the southwestern coast of Greece on 4.9.2023 (Figure 5.b), before the formation of the eye of the storm, in which the stable air and descends towards the surface, and the subsequent relative weakness in convection during mature stage.



(a) (b)

FIGURE 5 relative vorticity at 300 hpa (a) CAPE (b)

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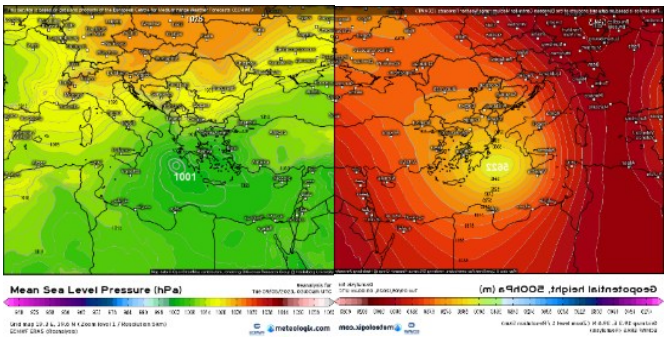
A cut-off low (1001hpa) was separated from the system, accompanied by a cold upper trough center (Figure 6). The depression caused very heavy rain in Greece, Bulgaria, and western Turkey during days 5-6/9/2023, Reports indicated that 754 mm fell within 21 hours at the Greek Village of Zagora station, amounts equivalent to approximately 18 months of rain (Davies, 2023). Storm Daniel was an extreme event, both in terms of rainfall values and duration (more than 72 h) (Dimitriou et al, 2024).



(a) (b)

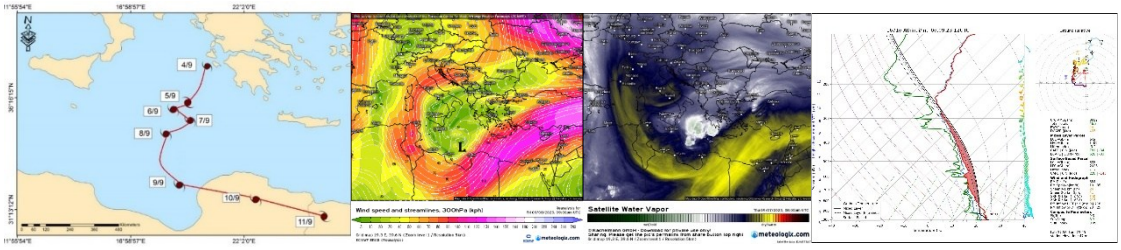
FIGURE 6 cut-off low at surface (a) cold upper trough at 500 hpa (b)

4. THE DEPRESSION DEVELOPED INTO A MEDITERRANEAN STORM (MEDICANE)

4.1 Persisting upper cooling and saturation air

The extreme weather events gradually faded away in Greece by the evening of 6/9/2023, and during the period from the evening of 7/9/2023 to 9/9/2023, the depression moved towards the central basin of the Mediterranean Sea and then moved towards the Gulf of Sirte (Figure 7.a), following the path of the upper trough and the flow of the polar jet stream towards the southern Mediterranean, bringing with it cold upper air and a huge of water vapor mass into the middle troposphere (Figure 7.b, c).

The Skew-T thermodynamic chart for the Athens station on September 6, 2023 (Figure 7.d), it indicates a very humid environment and the values of precipitable water (PWAT) reach 44 mm, the CIN (Mixed Layer) value -34 j/kg is weak and it is easily penetrated, with a large extension of the convection energy zone CAPE indicates air instability in the layer extending from 850 hpa to 300 hpa, which supports the development of the storm.



(a) (b) (c) (d)

FIGURE 7 Storm track (a) jet stream axis penetration (b) water vapor mass (c) Skew-T thermodynamic chart 6.9.2023(Athens station)

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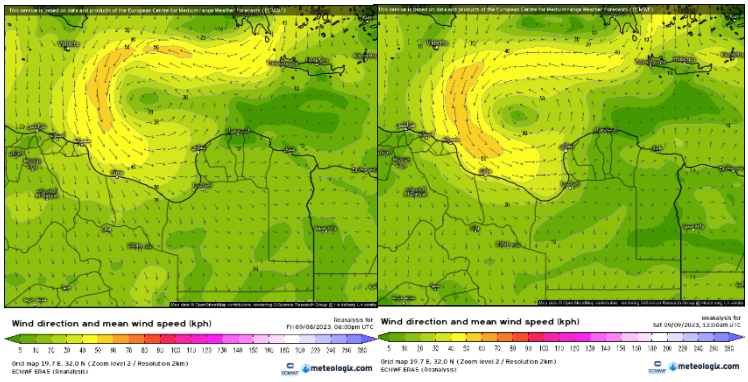
4.2 Evolution of tropical characteristics

Tropical features become more evident on 8/9/2023, the system can be classified as Medicane as the rotational movement of the winds became clear and a semi-closed eye of the system appeared characterized by a warm not fully symmetrical core, in which the temperature in the center is higher than the margins between 4-8°C, with spiral cloud belts and a relative decrease in atmospheric pressure (1001 hpa) and an increase in the speed of sustained surface winds. Some studies indicate that the formation of Medicane requires wind speed of at least 17 m/s (61 kph), lasting at least 6 hours (EUMETRAIN, 2023). Wind speed reached (62-71 kph) in the northern and western storm wall (Figure 8) with gusts reaching 89 kph and lightning and thunder activity.



(a) (b)

FIGURE 8 wind speed (kph) 8.9.2023 06:00 pm U.T.C (a) 9.9.2023 12:00 am U.T.C (b)

Convection started to be more active close to the cyclone center (COST, 2023) The convective available potential energy index "CAPE" exceeded (2500 J/Kg) off Al- Jabal Al-Akhdar and reached (3251 J/Kg) in the northeastern Mediterranean Sea (Figure 9.a), which is a very high value indicating the presence of strong convective energy, in addition to the lifted index reached (-7) which means the occurrence of severe air instability and very turbulent weather accompanied by violent thunderstorms that contributed to the storm developing into an isolated warm subtropical system with its arrival in the Gulf of Sirte on the evening of 9/9/2023.

With the activity of the atmospheric instability, high values of theta are a parameter of active baroclinicity, as appeared in Al- Jabal Al-Akhdar and the Gulf of Sirte on 9.9.2023. (Figure 9.b)

The wind shear values in the shallow (0-0.6 mi) and deep layers were less than 5 knots (Figure 9.c,d) Some studies indicate that weak wind shear is generally more suitable for the formation and intensification of the storm, as strong vertical shear disrupts the organization of the Medicane and prevents its development.

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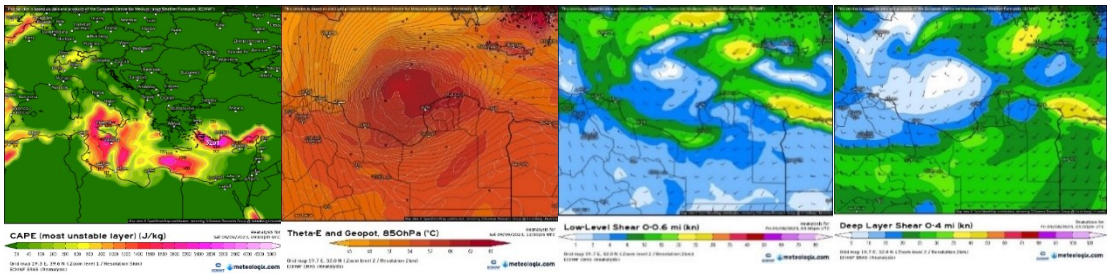

(a) (b) (c) (d)

FIGURE 9 8.9.2023, CAPE map (a) Theta-E (b) 9.9.2023 wind shear, low level (c) deep layer (d)

Daniel was distinguished by its slow horizontal movement which provided more time for the storm to intensify (Figure 10), as the average speed of its movement over the waters of the Mediterranean Sea reached 10 kph, and it increased to 15.5 kph during the days 9-10/9/2023. when storms move slower, their attendant hazards (like heavy precipitation) last longer for the areas they impact (Alex et al.,2023) this movement was within the air circulation over Europe and the Mediterranean, in which the meridional flow pattern prevailed at the surface level and in the upper atmosphere (Figure 11.a, b), meridional flows tend to move slowly and are stronger. this supports the power of extreme weather events.

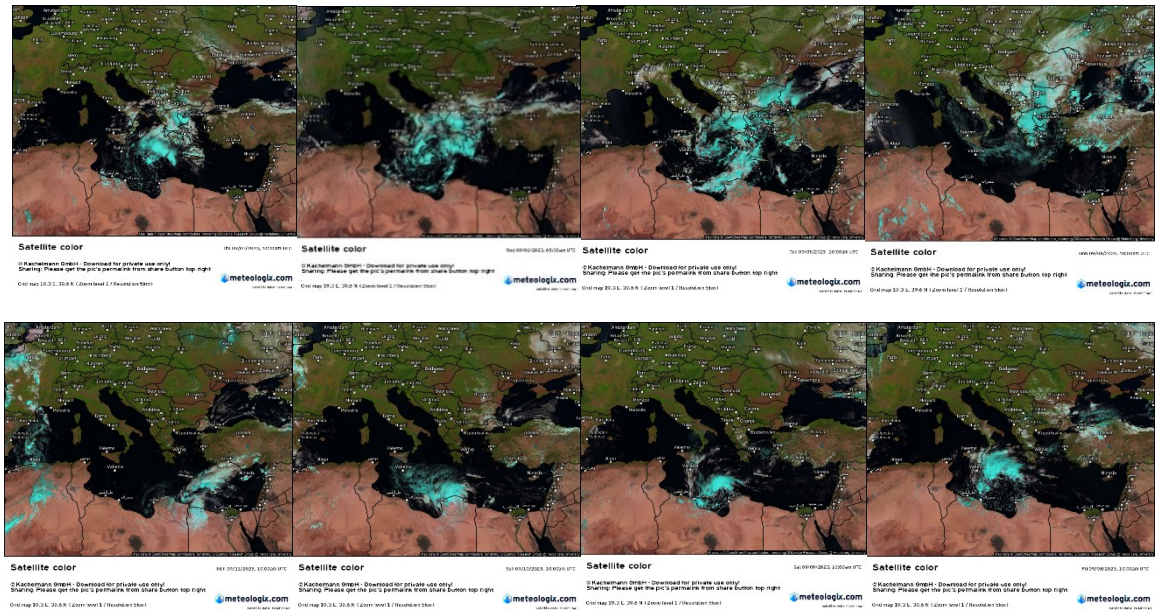

FIGURE 10 Storm movement during 4 – 11.9.2023

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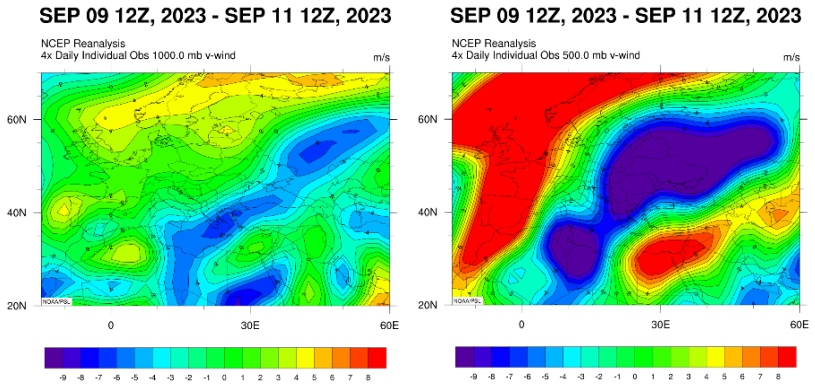
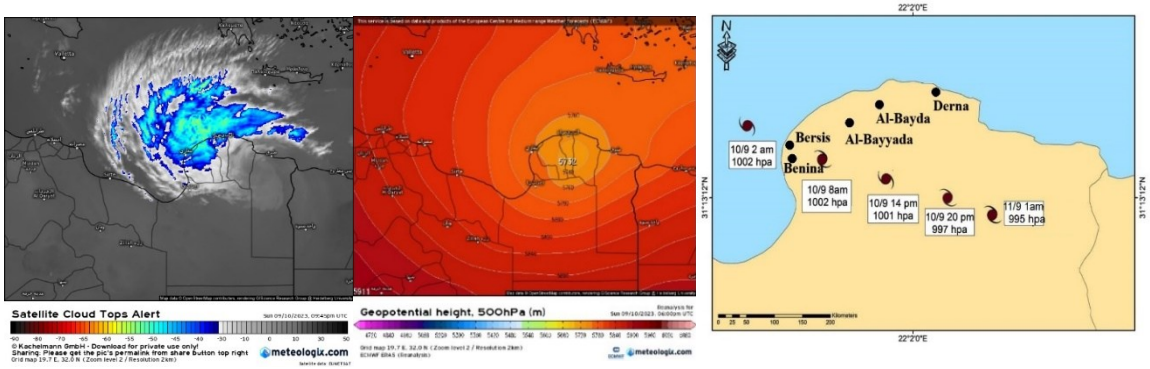


(a) (b)

FIGURE 11 The meridional wind zone v-wind at 1000 hpa (a) at 500 hpa (b)

5. STORM DANIEL ARRIVES IN EASTERN LIBYA

The path along which the storm moved contributed to providing it with the potential energy necessary to continue and support its development, as air laden with huge amounts of water vapor flowed over the warm waters of the Gulf of Sirte, rushing across the southern slopes of Al- Jabal Al-Akhdar (about 880 meters) which strengthened the air instability and the development of cumulus and cumulonimbus clouds that covered an area exceeding 230,000 km2, and the cloud formations penetrated south of Al- Jabal Al-Akhdar for more than 200 km (NASA. WorldView, 2023) (Figure 12).



(a) (b) (c)

FIGURE 12 10.9.2023. Cloud cover over northeastern Libya (a) gph 500 hpa (b)

Storm motion and decreasing air pressure (c)

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The center of the storm reached the northeast of Benghazi (Bersis village) at 5:00 U.T.C on 9/10/2023, taking a path towards the southeast of Al- Jabal Al-Akhdar with upper trough and the gradual decrease in air pressure at the storm center (1002 hpa - 995 hpa) Figure (12.b,c) while it ranged from 1002.4 to 1004 at the time of its passage through the weather stations, temperature ranged (20 c˚ - 25.2 c˚) and relative humidity average was high (93% - 100%) with strong sustained winds exceeding 74 kph in Derna at the peak of the storm (Table 2).

TABLE 2 Weather elements values at synoptic stations in the study area

Station	Day	Time (U.T.C)	Press S.L	Prec (mm)	Tem (c)	HR (%)	Nt (oktas)	W.S (Kph)
Benina	10/09/2023	6.00	1002.4	15	24.3	86	7	51.9
	10/09/2023	12.00	1007	20	21.6	90	8	59.3
	10/09/2023	18.00	1009.5	22	22	93	8	55.6
	11/09/2023	0.00	1010	7	22.9	81	8	33.4
	11/09/2023	6.00	1010.8	0	23.2	77	7	27.8
Al-Marj	10/09/2023	6.00	1004.1	10	21	90	8	29
	10/09/2023	12.00	1003	33	21	100	8	41
	10/09/2023	18.00	1006.2	99.2	20	100	8	41
	11/09/2023	0.00	1010	25.7	21	80	8	46
	11/09/2023	6.00	1009.1	1	21	70	8	37
Derna	10/09/2023	6.00	1008.2	0	25.2	87	6	18.5
	10/09/2023	12.00	1007.1	7	24.2	94	8	27.8
	10/09/2023	18.00	1003	15	25	93	8	55.6
	11/09/2023	0.00	1004	184.6	23	95	8	74.1
	11/09/2023	6.00	1005.3	39.2	22	90	8	27

National Meteorological Center.

https://www.ogimet.com.

This was accompanied by exceptional rainfall. However, the cloud convection was not exactly over the city of Derna where the most devastating flooding occurred; instead, it was around this area and especially along the hydrographic network of this area (Stavros and Niki, 2024). As the maximum rainfall was concentrated in the area extending from Al-Bayyada to Al-Bayda at 3:00 U.T.C, the accumulated rainfall over 24 hours exceeded 325 mm (Figure 13.a) and 414.1 mm was recorded at Al-Bayda station (Omar Al-Mukhtar University) at 6:00 U.T.C (Figure 13.b) which is an amount almost equivalent to the total annual rainfall.

As the storm center moved towards the southeast of Derna, winds blew from the eastern sector as a result of the air circulation in a cyclonic motion accompanied by dense formations of cumulonimbus clouds that caused 245.8 mm of rainfall at Derna station within 24 hours, including 184.6 within 6 hours (annual average of 265 mm) causing a massive flood that led to the destruction of a great part of the city and the death of thousands of lives.

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سبتمبر 2025

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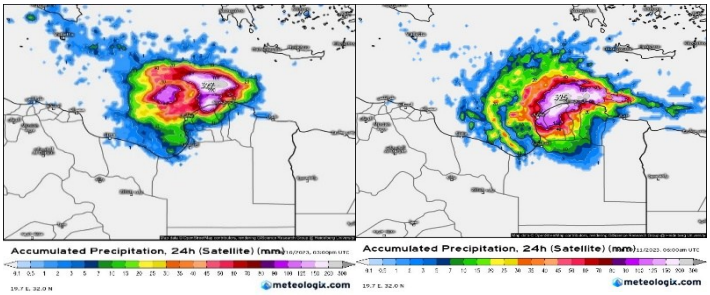
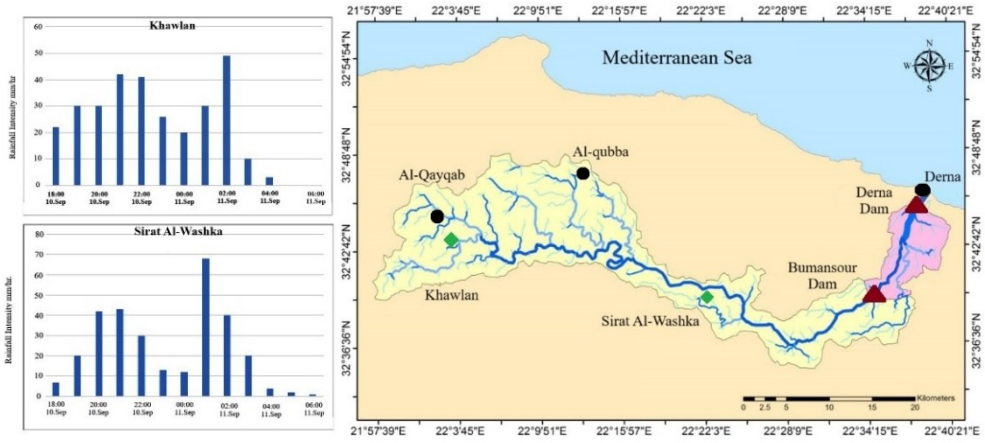


(a) (b)

FIGURE 13 Accumulated precipitation 24/h. at 3:00 U.T.C (a) at 6:00 U.T.C (b)



Global Precipitation Measuring (GPM) satellites and Integrated Multi-satellite Retrievals for GPM (IMERG) algorithms. *https://gpm.nasa.gov/data/imerg*

FIGURE 14 Precipitation intensity (mm/h) at two points in the Wadi Derna basin

(10.9.2023 18:00 pm – 11.9.2023 06:00 am).

The peak of the precipitation was concentrated in the Sirat Al-Washka area (southwest of Derna) (Figure 14), the precipitation intensity reached 68 mm/hour at 1:00 am on September 11, about an hour and a half before the collapse of the Derna Dam, then the collapse of the Boumansour Dam. According to WMO, precipitation is classified as being violent if the rate exceeds 50 mm per hour (WMO, 2020). Where the runoff volume for the watershed was 160 million cubic meters (Ayman et al,.2024), exceeding the capacity of the dams (Boumansour 22.5 million cubic meters, Derna1.5 million cubic meters), and causing a disaster that killed thousands of people in the city of Derna.

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6. CONCLUSION

The results of the study showed the importance of the surface warming of the Mediterranean Sea in the area extending from the Ionian Sea to the Gulf of Sirte as a major factor in the formation of Storm Daniel, with the combination of important weather factors, including upper cooling as a result of the shift of the polar jet stream axis with the cold upper trough wave to the southern Mediterranean Sea. With the increase in relative vorticity values, a cut-off low separated from the weather system to later develop into a Medicane characterized by spiral cloud bands and a warm eye.

The storm took an unusual path towards northeastern Libya, while continuing to be fed by latent heat and convective activity, which extended the life of the storm, which was accompanied by exceptional rainfall, causing catastrophic floods.

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