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Is Daniel's Storm 2023 the First of Its Type? What Are the Possibilities of It Occurring Again?

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Abstract

In September 2023, Storm Daniel, a devastating Mediterranean tropical-like cyclone (medicane), caused unprecedented rainfall, particularly in Greece, and catastrophic flooding in Libya, leading to thousands of fatalities and profound environmental changes. This paper examines the meteorological characteristics of Storm Daniel in the context of historical medicanes to determine its novelty. Furthermore, it analyzes the role of climate change in influencing such extreme weather events and assesses the future likelihood of similar occurrences. While medicanes are not a new phenomenon, Storm Daniel represents an unprecedented event in terms of its recorded intensity, extreme precipitation, and devastating socio-economic and geomorphological impacts, including dam failures and significant landscape alteration. Climate projections indicate that while the overall frequency of medicanes may not increase, the intensity of the strongest storms is expected to rise, posing a significant and growing threat to the Mediterranean basin.

Keywords: Storm Daniel, Medicane, Climate Change, Flooding.

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هل عاصفة دانيال 2023 هي الأولى من نوعها؟ ما هي احتمالات تكرار حدوثها؟

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الملخص:
في سبتمبر 2023، تسببت عاصفة دانيال، وهي إعصار مداري مدمر شبيه بالإعصار الاستوائي (ميديكان)، في هطول أمطار غير مسبوقة، لا سيما في اليونان، وفي فيضانات كارثية في ليبيا، مما أدى إلى مقتل الآلاف من الأشخاص وإحداث تغيرات بيئية عميقة. تبحث هذه الورقة الخصائص الجوية لعاصفة دانيال في سياق الأعاصير المتوسطية التاريخية لتحديد مدى جدة هذه العاصفة. علاوة على ذلك، تحلل الورقة دور تغير المناخ في التأثير على مثل هذه الظواهر الجوية المتطرفة وتقيّم احتمالية حدوث ظواهر مماثلة في المستقبل. على الرغم من أن الأعاصير المتوسطية ليست ظاهرة جديدة، فإن عاصفة دانيال تمثل حدثًا غير مسبوق من حيث شدتها المسجلة، وهطول الأمطار الغزيرة، وتأثيراتها الاجتماعية والاقتصادية والجيومورفولوجية المدمرة، بما في ذلك انهيار السدود والتغيرات الكبيرة في المناظر الطبيعية. تشير التوقعات المناخية إلى أنه على الرغم من أن التكرار الإجمالي للأعاصير المتوسطية قد لا يزداد، فمن المتوقع أن تزداد شدة أقوى العواصف، مما يشكل تهديدًا كبيرًا ومتزايدًا لحوض البحر الأبيض المتوسط.

الكلمات المفتاحية: العاصفة دانيال، الأعاصير المتوسطية، تغير المناخ، البحر الأبيض المتوسط، ليبيا، الفيضانات.

1. Introduction

The Mediterranean Sea, a semi-enclosed basin, occasionally gives rise to intense, hurricane-like storms known as "Medicanes" (a portmanteau of Mediterranean and hurricane). These systems exhibit a hybrid structure, sharing characteristics with both tropical and extratropical cyclones (Flaounas et al., 2022). They are

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characterized by a warm core, deep convection, strong winds, and often a distinct eye-like feature, posing significant hazards to coastal communities through extreme rainfall, high winds, and storm surges (Fita et al., 2018).

In early September 2023, Storm Daniel formed and subsequently evolved into a medicane of exceptional intensity. After causing record-breaking rainfall in Greece (Iatrou et al., 2024), the storm made landfall in Libya, triggering the catastrophic failure of two dams in the city of Derna (Qiu et al., 2023) and causing widespread flooding. The death toll was severe, with approximately 11,000 people dead or missing (Ashoor et al., 2024), making this one of the deadliest disasters of the early 21st century. However, casualty estimates vary between sources and may differ by region and reporting methodology, with international assessments providing a broader context on the total humanitarian impact across the Mediterranean. Despite the historical occurrence of Medicanes in the Mediterranean basin, Storm Daniel exhibited unprecedented characteristics in terms of intensity, precipitation volume, and socio-economic impact. This raises a critical research problem: **Does this event signify a fundamental shift in Mediterranean cyclogenesis, or is it an extreme outlier within known meteorological patterns?** Furthermore, the catastrophic failure of infrastructure in Libya highlights a gap in understanding the evolving risks posed by these storms in a warming climate.

To address this, the primary **objectives** of this research are: to contextualize Storm Daniel within the historical climatology of Mediterranean Medicanes; to identify the specific meteorological and environmental factors (e.g., marine heatwaves) that contributed to its exceptional intensity. To evaluate the role of anthropogenic climate change in influencing the frequency and severity of such extreme weather events; and to assess the future likelihood and potential risks of similar Medicanes recurring in the Mediterranean region.

Ultimately, this study seeks to answer the following **key questions**: Was Storm Daniel a fundamentally new type of meteorological phenomenon, or an extreme manifestation of a known storm category? How did the 2023 Mediterranean marine heatwaves specifically fuel the intensification and persistence of Storm Daniel? What do current climate projections indicate regarding the future

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trend of medicane intensity and frequency? And what are the implications of these findings for disaster risk reduction and infrastructure design in vulnerable coastal regions? This paper addresses these questions by (i) contextualizing Storm Daniel within the known climatology of Medicanes, (ii) examining the role of climate change and marine heatwaves in its intensification, and (iii) assessing the projected future frequency and intensity of such storms under different climate change scenarios Figure 1.

Figure 1: The trajectory of Storm Daniel across the Mediterranean Sea in September 2023, illustrating its path from formation in the Ionian Sea, across Greece, and its eventual landfall in Libya.

2. Storm Daniel in the Context of Historical Medicanes

To determine if Storm Daniel was the "first of its type”, it is essential to compare its characteristics with those of previously documented Medicanes.

2.1. The Nature of Medicanes

Medicanes are a known, albeit rare, meteorological phenomenon documented in detail since the advent of routine satellite observations in the late 20th century, with an estimated occurrence of roughly 1- 2 such systems per year across the Mediterranean

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basin. They typically form during the autumn and winter months over the western and central Mediterranean, fueled by latent heat fluxes from relatively warm sea surface temperatures (SSTs) and triggered by upper-level atmospheric disturbances, particularly Potential Vorticity (PV) streamers narrow intrusions of high potential vorticity from the upper troposphere that promote cyclogenesis (Flaounas et al., 2022). Medicanes often develop when cold air intrusions aloft enhance thermodynamic disequilibrium and baroclinic instability, a mechanism analogous to, but dynamically distinct from, tropical cyclone formation (Cavicchia et al., 2014). Historical records and satellite-era observations have identified numerous Medicanes, including notable events such as Qendresa (2014), Zorbas (2018), and Ianos (2020), all of which produced significant regional impacts in terms of wind, rainfall, and coastal hazards (Claud et al., 2018). Understanding this baseline climatology is essential for properly situating Storm Daniel within the broader spectrum of Mediterranean cyclone behavior Figure 2.

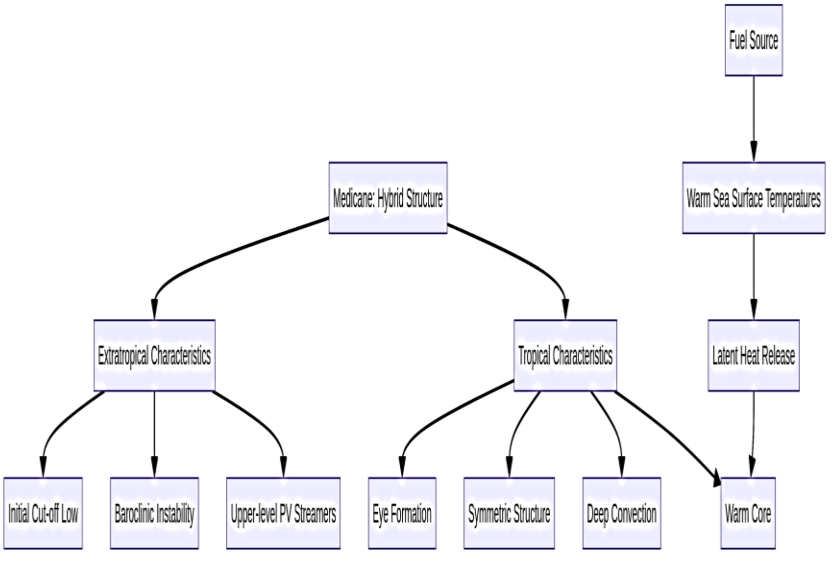

Figure 2: Conceptual diagram illustrating the hybrid nature of a Medicane, combining tropical characteristics (warm core, deep convection) and extratropical characteristics (upper-level PV streamers, baroclinic instability).

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2.2. Was Storm Daniel Unprecedented?

Storm Daniel was **not the first medicane**, but it was unprecedented in several key aspects, setting it apart from its predecessors table 1.

Table 1: Comparison of Storm Daniel with previous Medicanes.

Feature	Storm Daniel (2023)	Ianos (2020)	Zorbas (2018)	Numa (2017)
Fatalities	~11000 dead or missing, (Ashoor et al., 2024)	4 (Lagouvardos et al., 2022).	6 (Jangir et al., 2023).	22 (Marra et al., 2019).
Min Pressure	973 hPa (Hewson et al., 2024).	984 hPa (Lagouvardos et al., 2022).	988 hPa (Jangir et al., 2023).	990 hPa (Marra et al., 2019).
Rainfall	>750 mm in 24 h in Greece (Iatrou, 2024); >414.1 mm (Alkaryani et al., 2025).	>250 mm (Lagouvardos et al., 2022).	>100 mm (Jangir et al., 2023).	>100 mm (Marra et al., 2019).
Intensity	Deepened significantly even after making landfall in Libya (Hewson et al., 2024).	Weakened over Land.	Weakened over Land.	Weakened over Land.
Economic Cost	>$2 billion in Greece alone; catastrophic in Libya (e.g., 3,925 damaged buildings in Derna) (Qiu et al., 2023), (Normand et al., 2024).	Significant.	Significant.	Moderate.
Impact	Dam failure; 20m bank incision (Alkaryani et al., 2025)	Flash floods; Wind damage.	Coastal Flooding.	Severe flash Floods.

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The most striking feature of Storm Daniel was its devastating human and economic toll, making it the **deadliest and costliest medicane in recorded history** (Ashoor et al., 2024; Normand et al., 2024). The extreme rainfall totals, particularly over Greece (Iatrou et al., 2024) and Libya, far exceeded previously observed values for such storms figure 3. In Al Bayda, Libya, 414.1 mm of rain fell, representing approximately 80% of its annual average, and was 55 times higher than the average September rainfall (Alkaryani et al., 2025). Furthermore, its ability to maintain and even intensify its structure after moving over land in Libya was a remarkable and devastating characteristic, directly contributing to the catastrophic dam collapses in Derna (Qiu et al., 2023; Hewson et al., 2024). The storm also caused profound geomorphological changes, including extensive erosion, bank incisions exceeding 20 m, and the formation of temporary water bodies covering over 1,000 km² that persisted for months (Alkaryani et al., 2025).

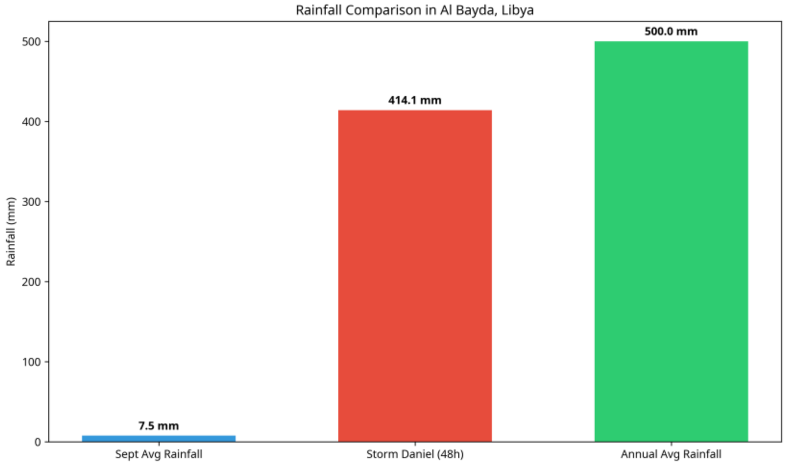

Figure 3: Comparison of rainfall in Al Bayda, Libya, during Storm Daniel (48h) against its typical September average and annual average, highlighting the extreme precipitation event.

Therefore, while storm daniel belongs to the known category of medicanes, its intensity and impact place it in a class of its own. it was not the first of its *type*, but it was the first of its *magnitude* in the observational record *figure 4* .

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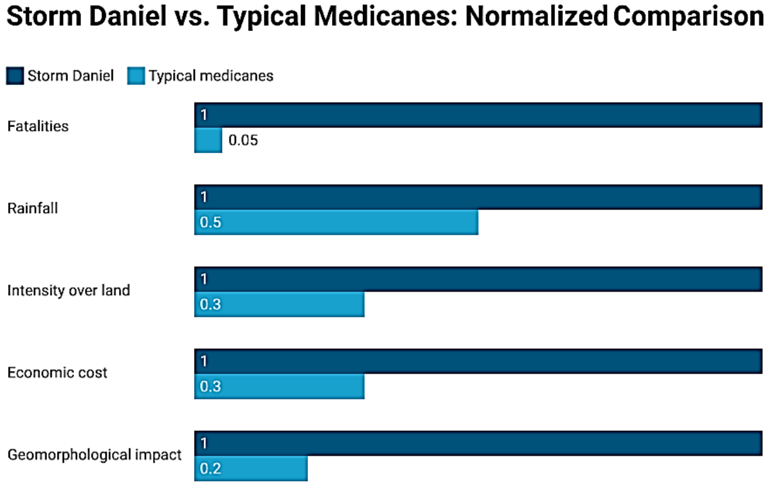

Figure 4: Comparison of Storm Daniel (2023) against typical historical Medicanes across five key impact dimensions. All values normalized to storm Daniel = 1.0. Data highlights the exceptional magnitude of Storm Daniel relative to previous events.

3. The Future of Medicanes in a Changing Climate

The exceptional nature of Storm Daniel is intrinsically linked to the broader context of anthropogenic climate change, particularly the warming of the Mediterranean Sea.

3.1. The Role of Sea Surface Temperature

Storm Daniel developed over Mediterranean waters that were experiencing record-breaking marine heatwaves, which substantially altered the thermodynamic environment for cyclogenesis. In July 2023, sea surface temperatures (SSTs) in the region extending from the Ionian Sea to the North African coast reached anomalies of about +5.5°C above the 1985–2005 climatological average (Qiu et al., 2023), far exceeding typical marine heatwave conditions observed in previous decades. This extreme warming is consistent with long-term Mediterranean SST trends attributed to anthropogenic climate change, with the basin warming faster than the global ocean average, thereby enhancing the energy available for intense cyclones. Medicane intensity is highly sensitive to SSTs, because warmer sea surfaces increase latent and sensible heat fluxes, thereby elevating atmospheric moisture content and convective instability; in line with the Clausius–Clapeyron relationship, an increase aboutb1°C increase in temperature can

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raise the water-holding capacity of the atmosphere by roughly 7%, favoring heavier precipitation (Flaounas et al., 2022)(*Figure 5*). These anomalously high SSTs in summer and early autumn 2023 provided Storm Daniel with exceptional thermodynamic fuel, which, in combination with favorable upper-level dynamics, enabled the storm to produce record-breaking rainfall and to maintain a well-organized structure even after landfall in Libya, directly contributing to the catastrophic dam failures and geomorphological impacts observed in the Derna region.

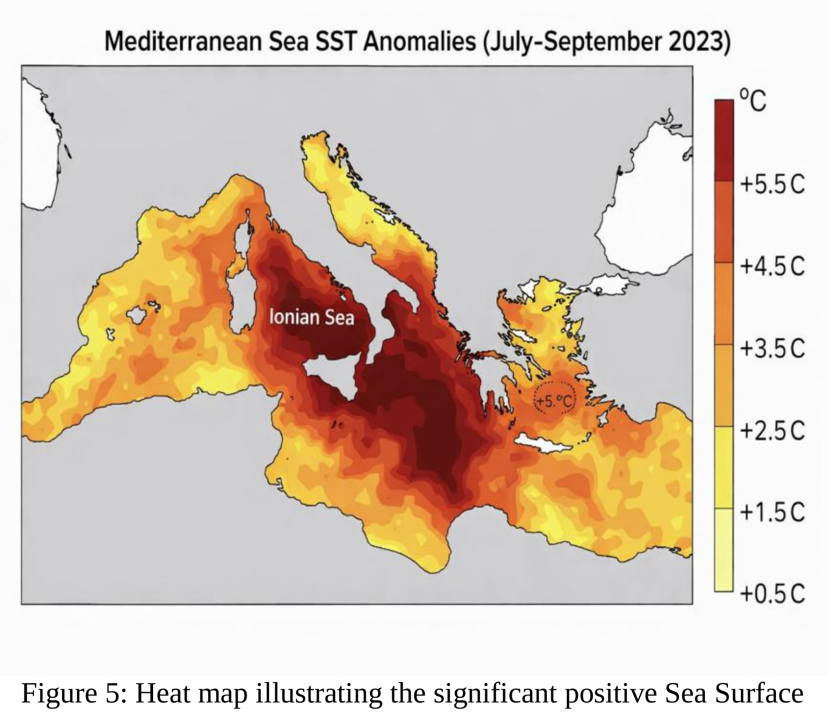

Figure 5: Heat map illustrating the significant positive Sea Surface Temperature anomalies across the Mediterranean Sea during the summer of 2023, with a notable +5.5°C anomaly in the Ionian Sea and North African coast region, contributing to Storm Daniel\'s intensification.

3.2. Climate Model Projections

To assess the likelihood of similar events occurring in the future, we turn to climate model projections, including those cited in the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6). Climate model projections for the 21st century suggest a dual evolution of Mediterranean Medicanes, characterized by changes in both frequency and intensity, though

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with differing levels of confidence. Regarding frequency, multi-model ensembles and regional climate simulations indicate that the overall number of Medicanes per year may remain approximately stable or decrease slightly under medium- to high-emission scenarios (Cavicchia et al., 2014; Romera et al., 2017) figure 6. such as those comparable to RCP 4.5 and RCP 8.5, particularly toward the late 21st century. This projected reduction is linked to large-scale circulation changes, including modifications in baroclinicity and upper-tropospheric dynamics, which may become less favorable for cyclone initiation in some seasons and subregions, although substantial inter-model and regional variability persists. In contrast, there is high confidence that the Medicanes that do form will have the potential to become more intense. Climate projections consistently indicate increases in maximum wind speeds and extreme precipitation rates under high emission scenarios, with intensity increases of 10- 25% and rainfall extreme increases of 20-40% projected by mid- to late century (Cavicchia et al., 2014) figure 7. This intensification is driven primarily by warmer SSTs and a moister atmosphere, which shift the distribution of storm severity toward more extreme events, implying a future climate characterized by fewer but potentially more destructive Medicanes, similar in magnitude to or exceeding Storm Daniel (Khodayar et al., 2025). Therefore, the future climate is likely to be one with fewer, but more powerful, Medicanes. The risk of "super-charged" storms like Daniel is projected to increase, shifting the entire distribution of medicane intensity towards more extreme outcomes figures 6, 7.

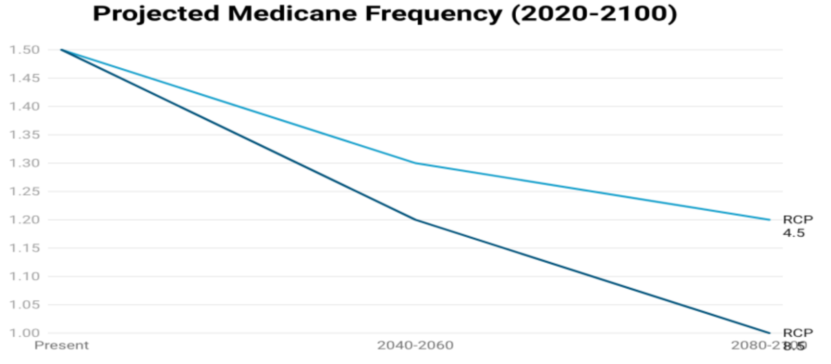

Figure 6: Multi-model projections showing stable or slightly declining Medicanes frequency under medium (RCP 4.5) and high (RCP 8.5) emission scenarios through the end of the 21st century.

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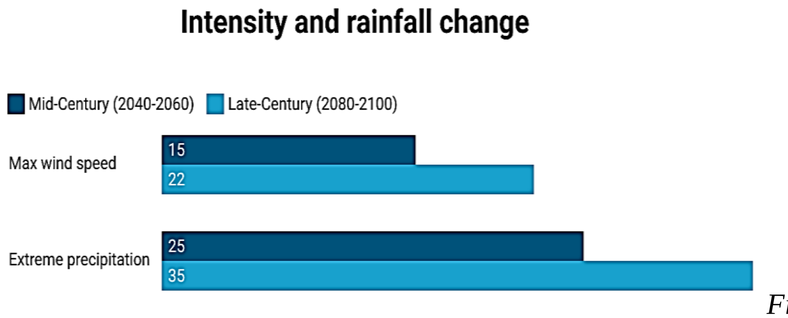

Figure 7: projected percentage increases in medicane maximum wind speed and extreme precipitation intensity relative to the present climate, under high-emission scenario (RCP8.5) based on multi-model projections.

4. Conclusion

Storm Daniel was not a meteorological anomaly in the sense of being a new type of storm. It was a medicane, a phenomenon well-documented in the Mediterranean. However, its record-shattering intensity, rainfall, and devastating impact make it a watershed event, a stark manifestation of the potential for extreme weather in a warming climate. It serves as a grim benchmark for the destructive power that these hybrid storms can achieve when fueled by anomalously warm ocean waters. The event was also the most severe flash flood to impact the Derna region in over 80 years, underscoring the long-term vulnerability of the area (World Bank, 2024).

The analysis presented in this paper indicates that events comparable in magnitude to Storm Daniel can recur in the Mediterranean region, even if their exact frequency and timing remain uncertain. While the overall number of Medicanes may not increase and could even decline slightly, the environmental conditions that allow individual storms to reach catastrophic intensity, particularly anomalously warm SSTs and a more moisture-laden atmosphere are becoming more prevalent in a warming climate. This emerging risk profile necessitates a fundamental shift in how coastal and riverine communities across the Mediterranean approach disaster risk reduction, moving beyond reliance on historical records toward proactive planning for unprecedented extremes. Key priorities include strengthening early warning systems for rapidly intensifying storms, revising design

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standards for critical infrastructure such as dams, reservoirs, and urban drainage networks to account for projected 21st-century precipitation extremes, and developing integrated monitoring frameworks that combine oceanographic observations, hydrological data, and high-resolution meteorological forecasts. Given the scale of damage observed in Derna and other affected areas during Storm Daniel, building long-term resilience will require coordinated investments in structural defenses, nature-based solutions, land-use planning, and emergency preparedness, informed by evolving scientific understanding of Medicanes in a changing climate.

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