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An unprecedented Mediterranean tropical cyclogenesis attempt above extreme sea surface temperatures?

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Abstract

On 3-4 October 2026, a strong and organized mesoscale convective system (MCS) developed over the Balearic Sea in the Western Mediterranean, and produced torrential rainfall in the Barcelona area, with up to 248 mm at Granollers (230 mm in 8 hours; 65 mm in an hour). The event occurred without discernible large-scale forcing from an upper-level cut-off low or trough, while western Mediterranean Sea surface temperatures (SSTs) were about 2.5 °C above the 1991–2020 mean. Satellite imagery showed a compact, quasi-circular cloud shield resembling a tropical disturbance, and Doppler radar showed low-level winds compatible with a cyclonic circulation near the coast. We assess how the MCS and its rotation depended on the SST anomaly with five 1-km convection-permitting HARMONIE-AROME simulations with SST taken respectively from the operational IFS analysis, the ERA5 1991–2020 climatology, and subtracting to the IFS analysis 2.4, 2.6 and 2.9 °C. With the observed SST, the model reproduces an MCS similar to the observed one, with a coherent column of cyclonic vorticity extending from 500 to 925 hPa and accumulated precipitation exceeding 250 mm offshore. With any of the cooler SSTs, neither the MCS nor the vortex forms, and the precipitation in the Barcelona surroundings nearly vanishes. These results are consistent with the hypothesis that tropical cyclogenesis occurred, and suggest that Mediterranean warming may be opening

a new cyclone formation pathway associated with slight to no upper-level forcing that has not been documented in the region before.

Keywords: Medicane; Tropical cyclogenesis; Sea surface temperature; Mesoscale convective vortex; Convection-permitting modeling; Heavy precipitation

1. Introduction

Cyclones with tropical characteristics, commonly known as *medicanes*, occasionally develop over the Mediterranean Sea. Their genesis, however, differs from that of tropical cyclones. A *medicane* almost always originates from a robust upper-level cut-off low or trough that destabilizes the atmosphere and triggers convection; only later, through air–sea enthalpy fluxes and latent heating, does the system acquire tropical features, such as a warm core or a symmetric structure [1]. In the tropics, by contrast, a cyclone can develop without such strong upper-level forcing, from a cluster of highly organized convection that generates its own vortex, for instance through the merger of vortical hot towers (VHTs) that build a surface-concentrated vortex [2]. The latter pathway, which may be termed pure tropical cyclogenesis, has never been documented in the Mediterranean. Climate projections indicate that the hazard posed by medicanes may increase with global warming [3], but whether a warmer sea could also enable this alternative pathway remains an open question.

On 3–4 October 2026, a highly organized and strong MCS formed over the sea off Catalonia and produced torrential rainfall in the Barcelona area: 192.8 mm in the centre of Barcelona (El Raval; 36.1 mm in 30 min), 231.7 mm at Cabrils, about 25 km northeast of the city, 247.9 mm at Granollers, about 25 km north-northeast (68 mm in 30 min), and up to 288.0 mm at Vilassar de Mar, about 20 km northeast, accumulated between 3 October and 08 UTC on 4 October (Fig. 1b). At Barcelona–Can Bruixa, the 213.0 mm recorded in 24 h was the highest daily total in its 39-year record, well above the previous maximum of 132.6 mm (8 October 2002), and no official station in the city had previously exceeded 200 mm in a day; at the Fabra Observatory, the 159.1 mm (07–07 UTC) was the third-highest daily total in its 113-year series [4]. The event occurred without an appreciable large-scale forcing from an upper-level cut-off low or trough (not shown), and with record-warm western Mediterranean SSTs, about 2.5 °C above the 1991–2020 mean over a three-week window centred on 3 October. Off Barcelona (40.84° N, 2.67° E), the SST on 3 October was 25.6 °C, 2.7 °C above normal for the date, and according to the Climate Shift Index: Ocean of Climate Central, based on NOAA OISST,

climate change made this temperature at least 100 times more likely (not shown) [5]. Several signals pointed to an environment favourable to tropical cyclogenesis: the 1.3-km AROME model of Météo-France (operational run starting at 00 UTC on 3 October) developed an intense convective vortex that reached the Barcelona coast with gusts above 100 km h^{-1}, and the NOAA 48-h tropical cyclone formation probability product showed a signal over the same area [6].

This study does not aim to demonstrate that tropical cyclogenesis occurred, but its objective is narrower: to determine to what extent the organized MCS, a possible precursor of such cyclogenesis, and its associated rotation depended on the anomalously warm sea. The key question is whether the mid-level rotation that such systems typically generate, the mesoscale convective vortex (MCV), extended down to low levels, which is the decisive step in tropical cyclogenesis.

2. Observations

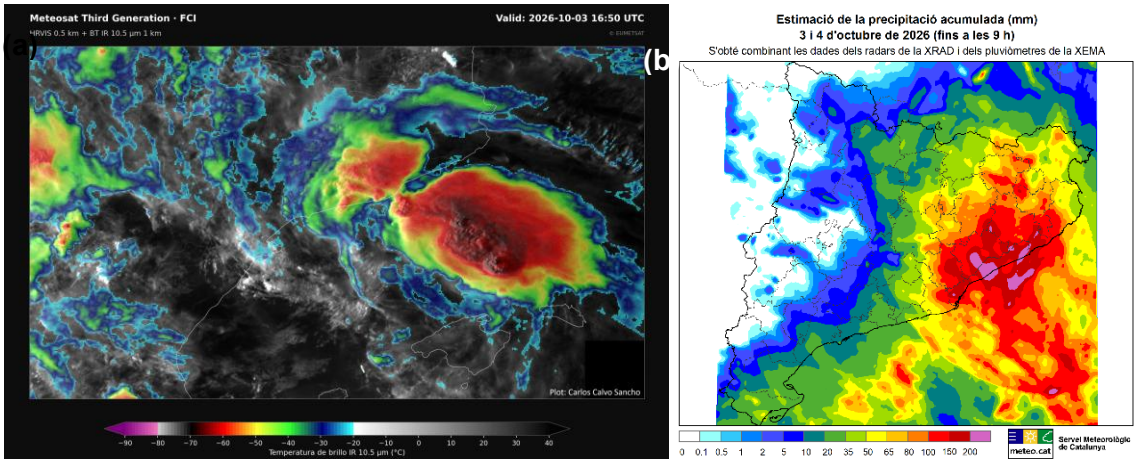


Fig. 1. (a) Meteosat Third Generation (MTG-I1) Flexible Combined Imager (FCI) image at 16:50 UTC on 3 October 2026 over the western Mediterranean: high-resolution visible combined with 10.5 µm infrared brightness temperature (°C, colour scale). © EUMETSAT. (b) Estimated accumulated precipitation (mm) on 3–4 October 2026 up to 09 h, combining Meteocat weather radar (XRAD) and automatic rain-gauge (XEMA) data. Source: Meteocat.

The satellite image of 3 October, 16:50 UTC (Fig. 1a) shows a compact, nearly circular cloud shield between the Catalan coast and Menorca, with very cold cloud tops and several overshooting tops in its central and southern sectors. To the west, a cloud band curves around

the system. Without the coastlines indicating the region, the structure would be difficult to distinguish from that of an early-stage tropical disturbance.

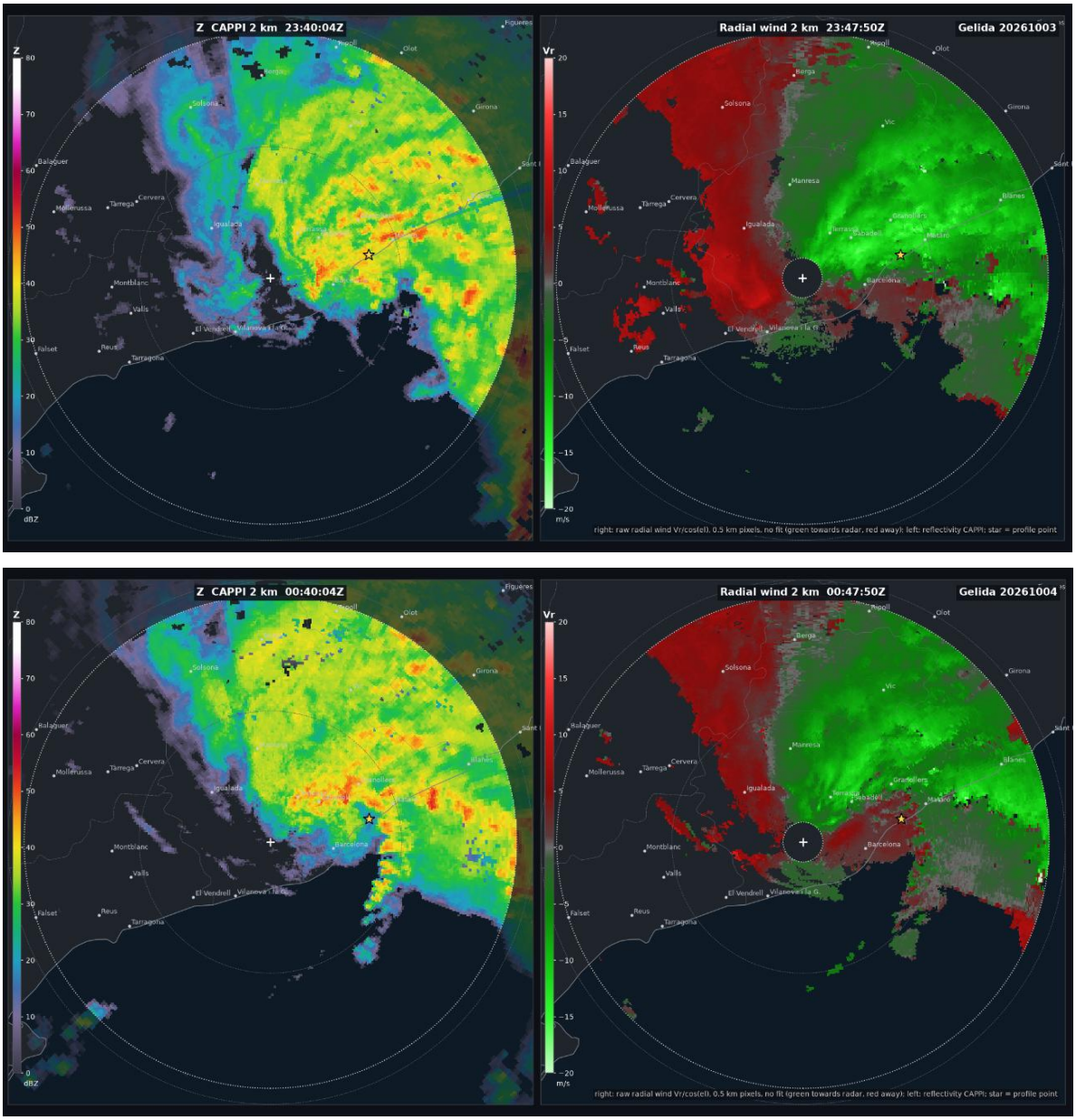


Fig. 2. 2-km CAPPI reflectivity (left, dBZ) and 2-km Doppler radial velocity (right, m s−1; green towards and red away from the radar) from the AEMET Barcelona radar at (top) 23:40 and 23:47 UTC on 3 October and (bottom) 00:40 and 00:47 UTC on 4 October 2026. The cross marks the radar location and the star the location of the wind profile discussed in the text. Source: AEMET.

The 2-km CAPPIs of the Barcelona radar at 23:40 UTC on 3 October and 00:40 UTC on 4 October (Fig. 2), during the peak of the torrential rainfall, show a precipitation band above 50 dBZ that curves from inland areas 20–30 km north of Barcelona to the coast northeast of the

city and wraps around the metropolitan area, and by 00:40 UTC a line of intense cells extends southward offshore from the Barcelona coast. At 2 km, the radial velocity is dominated by inbound easterly flow of 15–20 m s−1 north and northeast of Barcelona. Just south of it, outbound velocities appear along the Barcelona–Mataró coast, more clearly at 00:47 UTC, forming a velocity couplet indicative of cyclonic shear. This low-level wind field is compatible with a cyclonic circulation near the Barcelona coast of 30–50 km in diameter. A radar-derived wind profile around 00 UTC on 4 October, centred on the coast about 15 km northeast of Barcelona (star in Fig. 2), shows the wind speed decreasing with height, from about 17 m s−1 near 1 km to below 5 m s−1 above 6 km (not shown). Through thermal wind balance, a cyclonic circulation that weakens with height is consistent with a warm-core structure.

3. Data and methods

We performed a sensitivity experiment with HARMONIE-AROME [7], a non-hydrostatic limited-area model that explicitly resolves deep convection, which is essential to properly represent an MCS and its vortex. Five simulations were run, identical except for the SST:

- **CTRL:** SST from the ECMWF Integrated Forecasting System (IFS) analysis during the episode.
- **SSTClim:** ERA5 [8] 1991–2020 climatological SST for the same dates (three-week window centred on 3 October), interpolated to the model grid.
- **CTRL−2.4, CTRL−2.6 and CTRL−2.9:** CTRL SST minus a uniform anomaly of 2.4, 2.6 and 2.9 °C, corresponding to the ERA5 SST anomaly in the region in Fig. 3 relative to 1991–2020, 1981–2010 and 1971–2000 ERA5 climatology, respectively. Subtracting a constant preserves the SST gradients of the analysis.

All experiments share initial and boundary conditions from the IFS analysis, a 1500 × 1500 grid-point domain centred on the western Mediterranean, 1-km horizontal grid spacing and 65 vertical levels. They start at 00 UTC on 3 October and are integrated for 36 h with prescribed SST, so that any differences between them should be attributed to the SST. The mean SST over the area shown in Fig. 3 decreases from 25.6 °C in CTRL to 23.2 °C in SSTClim, and to 23.2, 23.0 and 22.7 °C in CTRL−2.4, CTRL−2.6 and CTRL−2.9, respectively.

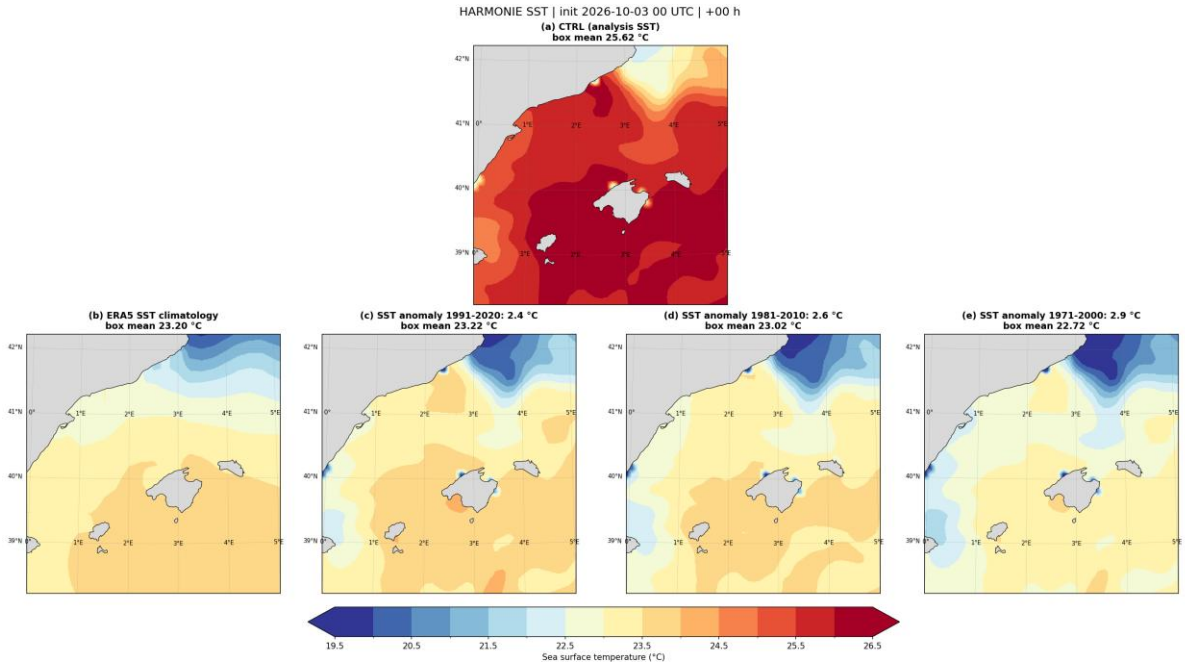


Fig. 3. Initial SST (00 UTC on 3 October) of the experiments. (a) CTRL, analysis SST. (b) SSTClim, ERA5 1991–2020 climatology. (c–e) CTRL SST minus the anomaly relative to 1991–2020 (2.4 °C), 1981–2010 (2.6 °C) and 1971–2000 (2.9 °C). The mean over the area shown is indicated in each panel.

Three diagnostics are used for the sake of comparison: (i) simulated infrared brightness temperature compared with the 10.5 µm channel of the FCI on MTG-I1 to locate deep convection; (ii) relative vorticity at 500, 700 and 925 hPa, smoothed with a 50-km Gaussian filter to damp the noise from individual convective cells; and (iii) accumulated precipitation since initialization, to quantify the impact of the rainfall.

The presence of high SSTs in the days leading up to the event influences the atmospheric conditions at the start of the simulations, whereas sensitivity experiments analyse the effect of SSTs exclusively during the event itself. Consequently, in sensitivity simulations, the role of SSTs is, to some extent, underestimated.

4. Results

4.1. Organized convection

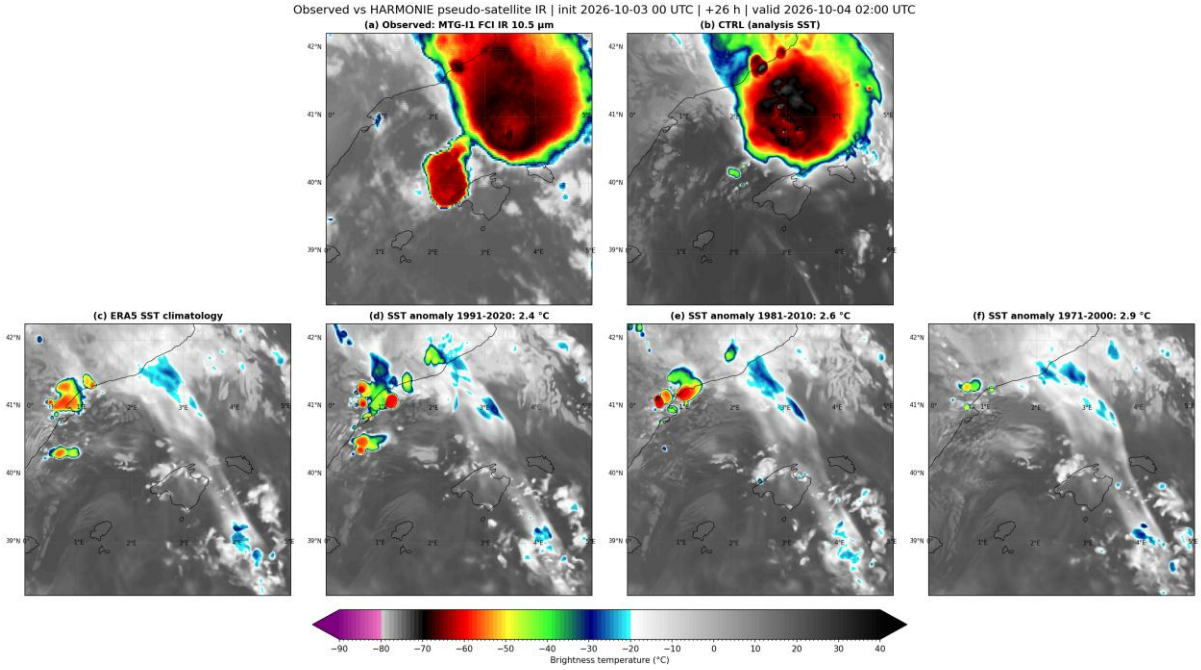


Fig. 4. Infrared brightness temperature at 02 UTC on 4 October (+26 h). (a) Observed by MTG-I1 FCI, 10.5 µm channel. (b–f) HARMONIE-AROME pseudo-satellite: (b) CTRL, (c) SSTClim, (d–f) CTRL minus the SST anomaly relative to 1991–2020 (2.4 °C), 1981–2010 (2.6 °C) and 1971–2000 (2.9 °C).

At 02 UTC on 4 October, CTRL develops a large, compact, nearly circular MCS, with a diameter of about 250 km, south of the coasts of Barcelona and Girona and centred in the Balearic Sea (Fig. 4b). Cloud tops are colder than −70 °C, with cores below −75 °C in the central sector, consistent with the presence of overshooting tops. Its structure and position closely resemble those observed at the same time (Fig. 4a), although CTRL misses the secondary cell observed northwest of Mallorca.

In all the SST sensitivity experiments the MCS does not form (Fig. 4c–f). Only isolated cells appear near the coast of Tarragona and off the Ebro Delta, with tops of −50 to −65 °C, together with a northwest–southeast band of warmer-topped cloud crossing Mallorca. Convection is slightly more abundant in CTRL−2.4 (Fig. 4d) and nearly disappears in CTRL−2.9 (Fig. 4f). An SST reduction of only 2.4 °C (but preserving the observed SST gradients), is thus sufficient to prevent the system from forming.

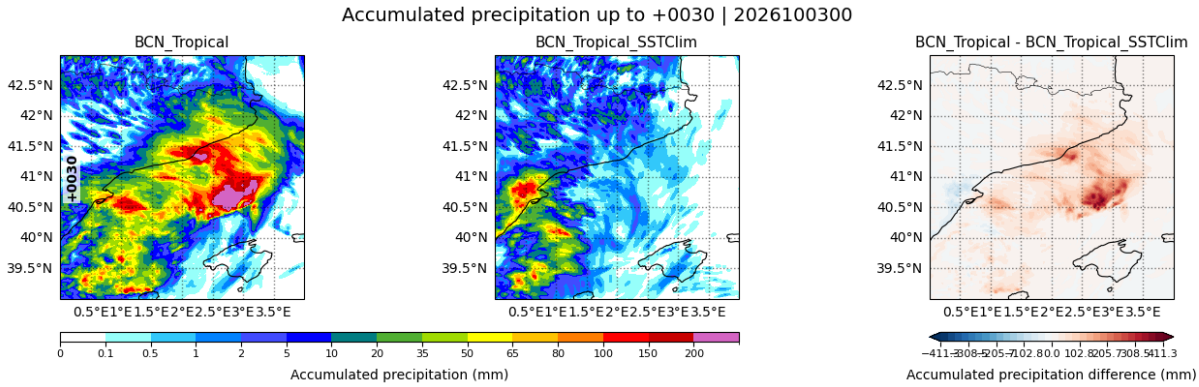


Fig. 5. HARMONIE-AROME 30-h accumulated precipitation (mm) between 00 UTC on 3 October and 06 UTC on 4 October. Left: CTRL. Centre: SSTClim. Right: CTRL − SSTClim difference.

Accumulated precipitation reflects the same sensitivity (Fig. 5). In CTRL, rainfall is concentrated in a broad southwest–northeast band off the northeastern Spanish coast, exceeding 50 mm but with local maxima above 250 mm in the middle of the Balearic Sea where the MCS developed. A second maximum of 150–250 mm appears along the Barcelona coast, comparable to the amount observed in the metropolitan area. In SSTClim, precipitation is largely confined to the southwestern corner, in the area between the Castellón coast and the Ebro Delta, with maxima of 75–150 mm. The CTRL − SSTClim difference exceeds 300 mm over the MCS area and is only slightly negative around the Ebro Delta, where SSTClim concentrates its convection.

4.2. Vertical extent of the rotation

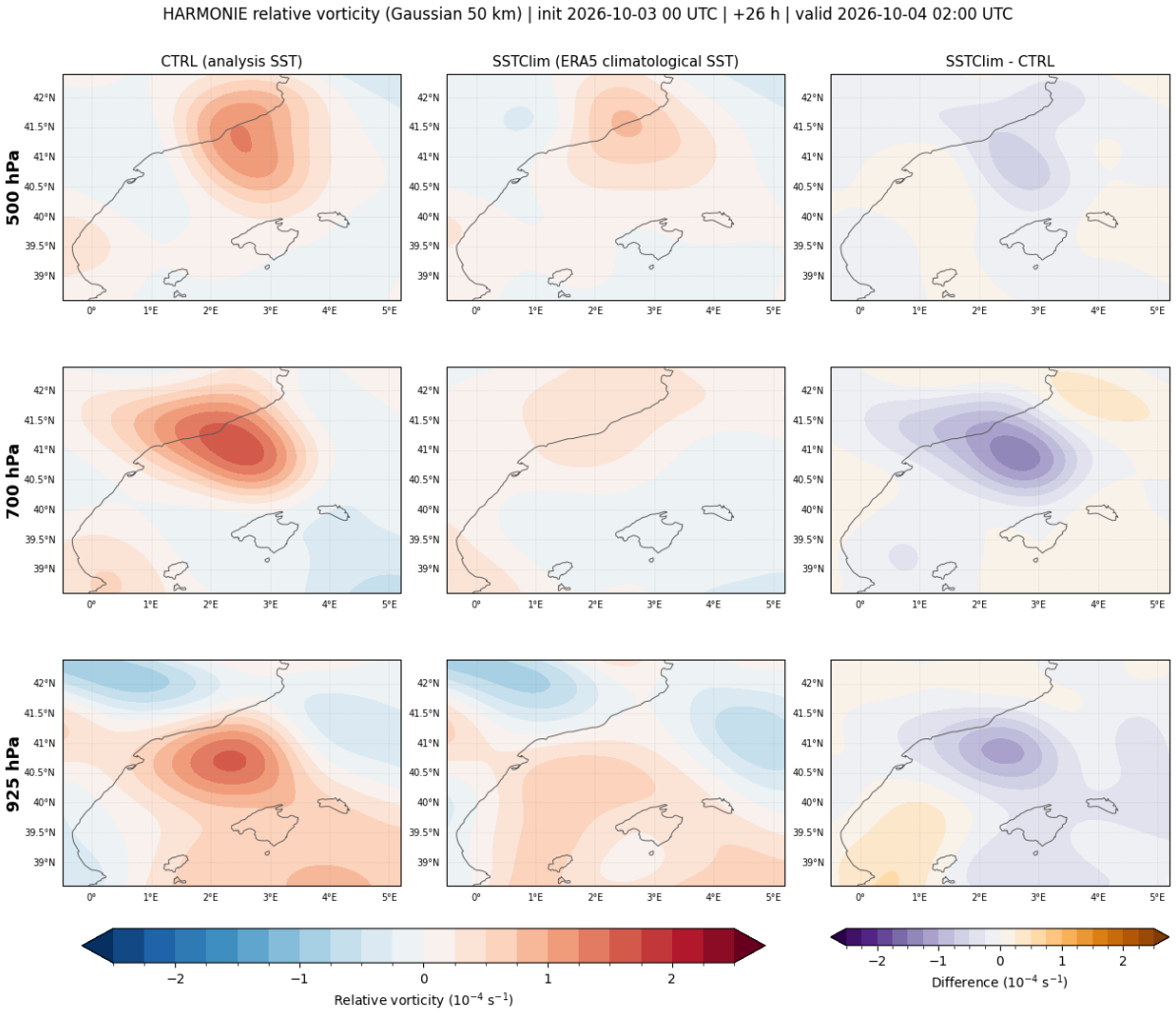


Fig. 6. HARMONIE-AROME relative vorticity (50-km Gaussian smoothing) at 02 UTC on 4 October (+26 h) at 500 hPa (top), 700 hPa (middle) and 925 hPa (bottom). Left: CTRL. Centre: SSTClim. Right: SSTClim − CTRL difference. Zoom inside Fig. 5.

CTRL shows a column of cyclonic vorticity offshore, about 50–80 km south-southeastward Barcelona (Fig. 6), extending from about 925 to 500 hPa in the western half of the MCS (Fig. 4b). It is consistently present at all three levels shown in Fig. 6, with a maximum of about 2 × 10^{-4} s^{-1} at 700 hPa, extending down to 925 hPa (about 1.5 × 10^{-4} s^{-1}). With 50-km smoothing, these values are 1.5–2 times higher than the Coriolis parameter at that latitude. At 700 hPa, and to a lesser extent at 925 hPa, positive vorticity also extends along the coast of Barcelona and southwest of the city, consistent with the cyclonic circulation suggested by the radar at a nearby time (Fig. 2).

SSTClim exhibits no organized vorticity, with widespread positive values below 1×10^{-4} s^{-1}. The SSTClim − CTRL difference is negative over the vortex area at all levels, with a peak of about -1.5×10^{-4} s^{-1} at 700 hPa. In CTRL, therefore, the rotation is not confined to the mid-levels, as is the case in a classical MCV, but instead forms a coherent column that extends down to 925 hPa, as in the VHT route to tropical cyclogenesis [2]. The 700-hPa maximum is consistent with a vortex that forms at mid-levels and propagates downward.

5. Discussion and conclusions

With the observed SST, the HARMONIE-AROME model generates an organized MCS off the northeastern Spanish coast, structurally similar to the observed one, with a cyclonic vortex extending from mid-levels down to near the surface. Moreover, the accumulated precipitation exceeds 250 mm offshore and 150–250 mm along the Catalonian coast. With the 1991–2020 climatological SST, or reducing uniformly the SST by 2.4–2.9 °C, neither the MCS nor the vortex forms. The response in the SST experiments goes beyond a weakening, displacement or delay of the system. According to the simulations, the heavy rainfall in the provinces of Barcelona and Girona was tied to the MCS and its surface vortex suggest a tropical cyclogenesis attempt and both would not have occurred without the anomalously warm sea.

These results do not demonstrate that tropical cyclogenesis occurred, but they are consistent with that hypothesis. Observations showed a tropical-like cloud structure and a low-level wind field compatible with the early stage of a tropical cyclone. In the model runs, the low-level rotation, the element that distinguishes a convective system from incipient tropical cyclogenesis, appears only with the warm sea. If further analysis confirms this interpretation, Mediterranean warming may be opening a cyclone formation pathway not previously considered in the region. A possible tropical-like genesis pathway for medicane Ianos [9] has recently been hypothesized; however, QG forcing from both the Trenberth–Sutcliffe approximation and the Q-vector based diagnostics [10] indicates that, during the initial stages of Ianos, large-scale dynamical forcing played a non-negligible role with the existence of a previous low-pressure system (not shown), where it is nearly 10 times weaker and less persistent in the case under examination and no low-pressure centre was present. This would place Ianos more in the tropical transition context [11].

Several limitations should be noted in the present study. First, convection is highly sensitive to small perturbations, and part of the difference could reflect intrinsic variability. Therefore,

ensembles that account for this uncertainty, as well as data assimilation, are required for a more comprehensive investigation. Second, the ERA5 climatology is not only cooler but also smoother than the operational IFS analysis, lacking mesoscale fronts and filaments that can favour low-level convergence and convective initiation. The uniform-anomaly experiments, which preserve those gradients, partly take into account both effects: with a mean SST nearly equal to that of SSTClim (23.2 °C; Fig. 3), the system still does not form, indicating that the SST magnitude, rather than its gradients, is decisive. Third, the vortex dynamics remain to be analysed in greater detail, including its temporal evolution in the vertical, the existence of a closed circulation and a surface pressure minimum, the presence of a warm core and the intensity of air–sea latent heat fluxes, in order to establish whether tropical cyclogenesis really took place in the CTRL simulation.

CRediT authorship contribution statement

Juan Jesús González-Alemán: Conceptualization, Methodology, Formal analysis, Investigation, Visualization, Writing– original draft, Supervision. **Carlos Calvo-Sancho:** Methodology, Formal analysis, Investigation, Visualization, Writing – Review & Editing. **Mario Marcello Miglietta**: Formal Analysis, Investigation, Writing – Review & Editing

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work the authors used Claude (Anthropic) to assist with grammar and phrasing checks during manuscript preparation.

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Data availability

Data will be made available on request.

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