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RESEARCH ARTICLE

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Examining the precipitation associated with medicanes in the high-resolution ERA-5 reanalysis data

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Abstract
Medicanes, hurricane-like cyclonic systems in the Mediterranean Sea, are becoming an increasingly severe problem for many Mediterranean countries because climate projections suggest a higher risk under anthropogenic forcing even under an intermediate scenario. Due to the small size of these weather systems, high-resolution data are required to better resolve their structure and evolution. Here we investigate medicanes from the perspective of precipitation using the high-resolution (0.25°) ERA-5 reanalysis data released by European Centre for Medium-Range Weather Forecasts. Overall, we identify a total of 59 medicanes from ERA-5 data during 1979–2017, with marked year-to-year variability. These storms tend to occur mostly between September and March. Overall, the intensity of medicanes (i.e., maximum wind) is lower than that of tropical cyclones, and this is also true for precipitation. The composite precipitation of medicanes increases from the centre to ∼0.8° and then decreases. During 1979–2017, many regions along the Mediterranean Sea experienced over 20 extreme precipitation events (i.e., days) which were caused by medicanes, accounting for 2–5% of all the extreme precipitation events.

KEYWORDS
ERA-5 reanalysis, extremes, Medicanes, precipitation

1 | INTRODUCTION

Mediterranean tropical-like cyclones/hurricanes, also known as medicanes, are strong cyclones with tropical features, destructive winds and torrential rainfall, responsible for natural hazards along the heavily populated Mediterranean coast (Emanuel, 2005; Gaertner *et al.*, 2007; Moscatello *et al.*, 2008; Cavicchia *et al.*, 2014*a*). For example, Italy claims the highest damage from medicanes, with annual losses of $33 million dollars (Bakkensen, 2017). Moreover, climate model experiments have projected an increase in the hazards associated with these storms due to their projected higher intensity in a warmer climate (Romero and Emanuel, 2013; Cavicchia *et al.*, 2014*b*; González-Alemán *et al.*, 2019). A better understanding of the features of medicanes is thus crucial for the adaptation, mitigation and resilience to the natural hazards related to these cyclones.

A few studies have examined the genesis, development, and the present and future variability of medicanes through numerical models and reanalysis data (Cavicchia and von Storch, 2012; Romero and Emanuel, 2013; Tous *et al.*, 2016; Flaounas *et al.*, 2018*a*, 2018*b*). For example, different physical mechanisms, including potential vorticity (PV) perspective and Wind Induced Surface Heat Exchange (WISHE) mechanisms, have been proposed to characterize the genesis and development of medicanes (e.g., Homar *et al*., 2003; Moscatello *et al*., 2008; Akhtar *et al*., 2014; Miglietta *et al*., 2017; Miglietta and Rotunno, 2019). Due to the relatively low spatial resolution of the outputs of global climate models (GCMs) and reanalysis data (Cavicchia and von Storch, 2012), dynamical downscaling is commonly used to obtain high-resolution data for tracking medicanes (Gaertner *et al*., 2007; Cavicchia and von Storch, 2012; Miglietta *et al*., 2013; Walsh *et al*., 2014; Pytharoulis, 2018). In addition, Romero and Emanuel (2013) used a statistical–deterministic method to generate synthetic tracks of medicanes and assess their potential future changes. To resolve the structure and evolution of medicanes, a spatial resolution of 25-km or higher may be needed (Cavicchia *et al*., 2014*a*; Tous *et al*., 2016; González-Alemán *et al*., 2019).

In spite of the recent advances made in understanding the feature, genesis and future changes of medicanes, little attention has been paid to precipitation and its extremes associated with medicanes. What role do the precipitation and its extremes associated with medicanes play in the hydrological cycle? To address this question, high-resolution reanalysis data represent a useful resource to investigate medicanes because of their spatial homogeneity and the assimilation of reliable high-frequency observations. This study uses the recently-released high-resolution reanalysis data by the European Centre for Medium-Range Weather Forecasts (ECMWF) to examine the features of medicanes and their precipitation and extremes.

2 | DATA AND METHODS

We use ECMWF ERA-5 data with ~0.25° spatial resolution and 137 vertical levels from the surface up to a height of 80 km (Hersbach, 2018). To identify medicanes, we use sea level pressure, temperature, surface winds, geopotential height. We use precipitation data from both ERA-5 and daily E-OBS v16.0 gridded data with a spatial resolution of 0.25° covering Europe (Cornes *et al*., 2018).

Previous studies have used different methods to detect medicanes. Cavicchia *et al*. (2014*a*, 2014*b*) used minimum sea level pressure with a gradient greater than 20 Pa over 3 grid points and the symmetry and warm core criteria of the storm obtained by the phase space variables defined in Hart (2003). Picornell *et al*. (2014) defined a medicane by a relative minimum mean sea level pressure field, with cyclone phase space method used to detect warm-core structure. Meanwhile, González-Alemán *et al*. (2019) used a two-step approach: obtaining cyclone tracks from the sea level pressure field, and the wind field at 700 hPa and filtering out those cyclones with tropical characteristics using the cyclone phase space method (Hart, 2003).

To detect medicanes, we combine the tool "TempestExtremes" (Ullrich and Zarzycki, 2017) and the phase criteria for tropical cyclones proposed in Hart (2003). TempestExtremes is an open-source software for tracking tropical cyclones, extratropical cyclones and tropical easterly waves, which supports a wide range of detecting schemes and criteria (e.g., sea level pressure and maximum sustained wind) (Ullrich and Zarzycki, 2017). We detect medicanes from the $0.25° \times 0.25°$ ERA-5 data at 6-hr temporal resolution within the domain 24–48°N and 10°W–48°E based on the following criteria:

1. Candidates are initially identified by minima in the sea level pressure. The closed contour criterion is applied, requiring an increase in sea level pressure of at least 20 Pa (0.2 hPa) within 1° of the candidates.
2. Warm core: $\Delta T > 0.2$ K at the 300 hPa level within 1° radius.
3. Maximum winds >17 m/s within 1° radius for at least 12 hr with duration of at least 24 hr.
4. Warm-core and vertical symmetry represent tropical-cyclone features of medicanes. The symmetry and warm core criteria using the phase space variables prescribed in Hart (2003) with a radius of 200 km are used to account for the small size of medicanes. Based on Hart (2003), we use the three parameters: B, $-V_T^L$ and $-V_T^U$, which represent the low troposphere thickness asymmetry, structure of the cyclone in the low–middle troposphere, and full-troposphere structure of the cyclone, respectively. A warm-core tropical-cyclone-like system (e.g., medicane) should meet the requirements: $B < 10$ m, $-V_T^L > 0$ and $-V_T^U > 0$. A cyclone is considered as a medicane if it shows vertical symmetry and a warm-core structure for at least 6 hr.

Note that currently there are no objective physical criteria that qualify cyclones as medicanes. After applying the tracking algorithm, we retain the warm core axisymmetric cyclones, the weaker ones of which have been filtered out by applying the criteria of sea level pressure and maximum sustained wind.

When evaluating annual medicane activity, we define a medicane season as the period from August to July of the next year (Cavicchia *et al*., 2014*a*). To characterize the structure of medicanes, we extract and composite precipitation, sea level pressure and 10-m surface winds within a 5° radius of each medicane centre during the entire life cycle of these storms. Although ERA-5 has a higher resolution than ERA-Interim, a spatial resolution of 0.25° in ERA-5 data may still not be fully adequate to resolve the finer scale processes, dynamics and structures of medicanes.

Extreme precipitation in a spatial grid is defined as the precipitation exceeding the 95th percentile of the at-site distribution. Medicane rainfall is defined as the rainfall within 500-km radius of a medicane centre; we also evaluated the sensitivity of the results to different radii (from 400 to 700 km at a 100-km interval), and found similar spatial patterns, albeit the rainfall magnitude is higher for larger radii.

3 | RESULTS

The highest track density is located in eastern Spain, southern France and Italy (Figure 1a), similar to what found in previous studies (Cavicchia and von Storch, 2012; Romero and Emanuel, 2013; Tous *et al.*, 2016; Flaounas *et al.*, 2018*a*, 2018*b*). The tracker identifies a total of 59 medicanes from ERA-5 data during 1979–2017, with ~1.5 events each year; this is consistent with other published studies, such as 1.57 ± 1.3 events·year^{-1} (Cavicchia *et al.*, 2014*a*), 1.5 ± 0.9 events·year^{-1} (Romero and Emanuel, 2013), and 1.4 ± 1.3 events·year^{-1} (Nastos *et al.*, 2018). When we change slightly the criteria (e.g., sea level pressure, maximum sustained wind and warm core), the climatological frequency of medicanes ranges from 0.9 to 2.9 (Table S1).

Overall, the genesis locations of medicanes (Figure 1b) are consistent with previous studies (e.g., Cavicchia *et al.*, 2014*a*; Nastos *et al.*, 2018; González-Alemán *et al.*, 2019). The seasonality of medicanes is characterized by high activity during the early and late parts of a year, with no activity in July and August (Figure 1c). Previous studies also showed weak or no medicane activity during June, July, and August (Romero and Emanuel, 2013; Cavicchia *et al.*, 2014*a*, 2014*b*). The year-to-year variation in medican activity exhibits no linear trend and fluctuates in a range of 0–4 events every year during 1979–2017 (Figure 1d). There seems to be a multi-decadal oscillation in the frequency of medicanes (Figure 1d).

The main structure of medicanes features a warm-core low-pressure and surface cyclonic flow pattern with a deep PV (Figure 2a). The detected medicanes in this study correspond to the strongest warm core/axisymmetric systems of the tracked cyclones. Overall, these systems may probably refer to cyclones undergoing warm seclusion, which also develop within a baroclinic environment as it is the case for all intense Mediterranean cyclones (Flaounas *et al.*, 2015). It appears that there might be some differences between the detected medicanes and tropical cyclones formed in the tropical ocean. For example, a characteristic feature of mid-latitude storms is an

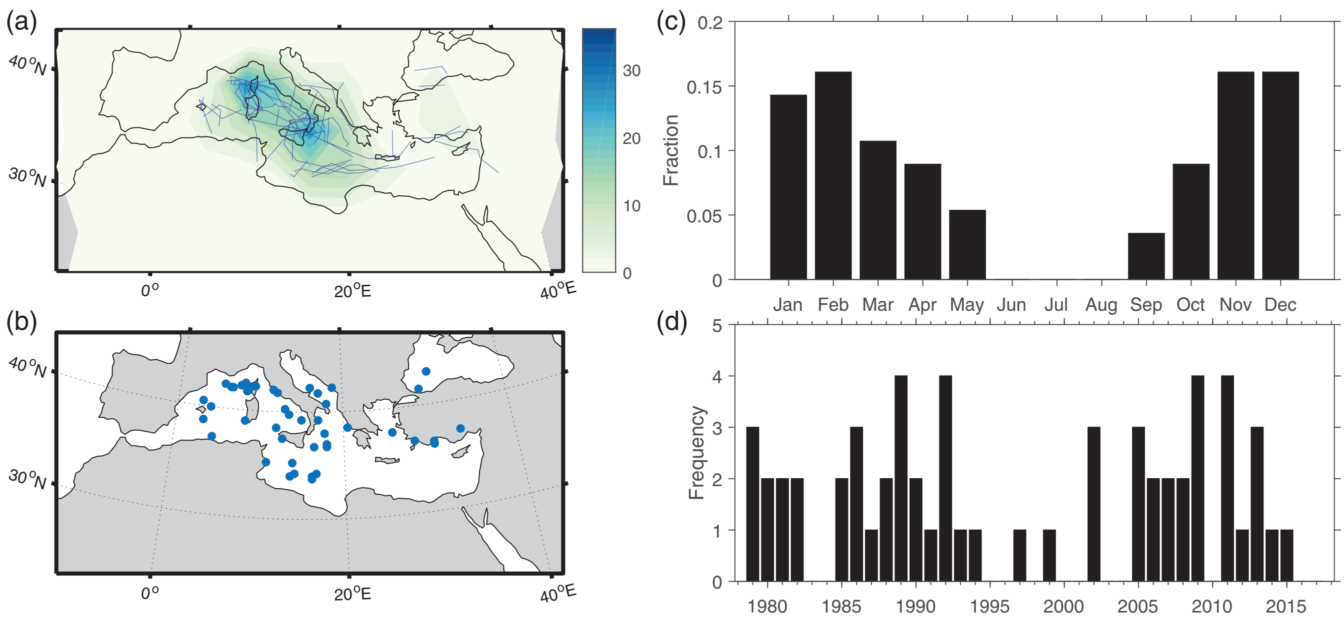

FIGURE 1 (a) Individual tracks (blue lines) and track density (shading) of medicanes by binning the centres of medicanes into 4° × 4° boxes. (b) Geneses of medicanes (blue dots). (c) Seasonality and (d) year-to-year variation of medicanes. A medicane season ranges from August to July of the following year. Results are based on ERA-5 reanalysis data during 1979–2017 [Colour figure can be viewed at wileyonlinelibrary.com]

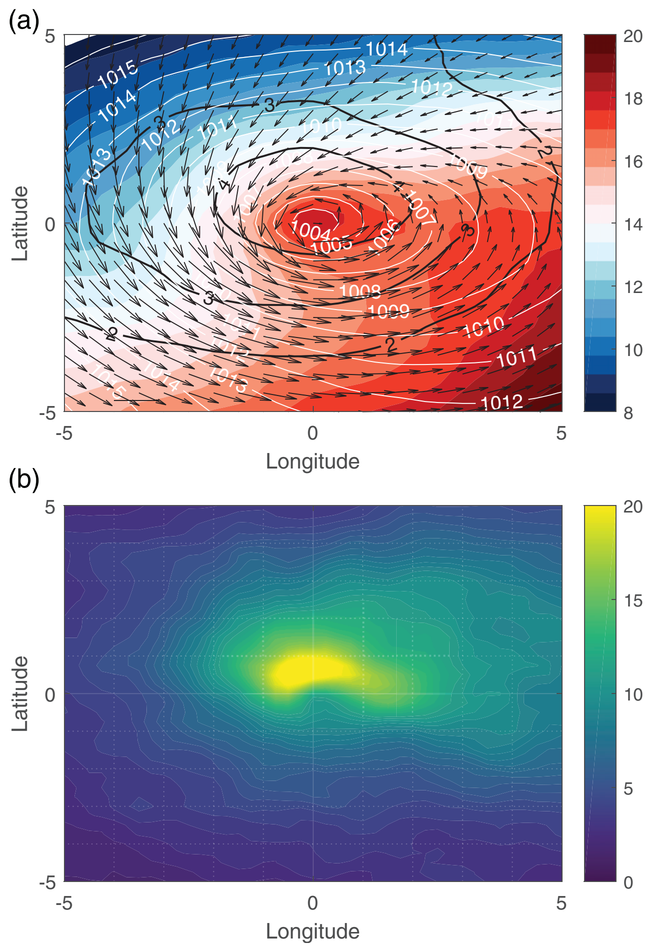

FIGURE 2 (a) Composite surface winds (vector; unit: m·s^{-1}), 850-hPa equivalent potential temperature (shading; unit: °C), 300-hPa PV (black contours; $\times10^{-6}$ m^2·s^{-1} K·kg^{-1}) and sea level pressure (white contours; unit: hPa) of medicanes. (b) Composite precipitation of medicanes (unit: mm). The composites are calculated over all instances of the medicanes at 6-hourly intervals [Colour figure can be viewed at wileyonlinelibrary.com]

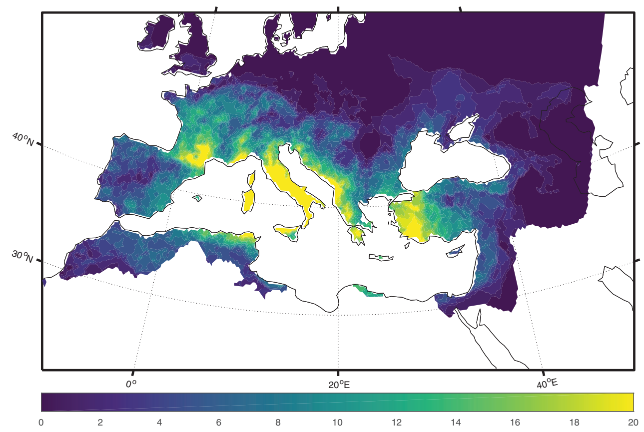

FIGURE 3 Number of days (shading, unit: days) with extreme precipitation caused by medicanes based on EOBS data during 1979–2017. Missing values on land are coloured in white [Colour figure can be viewed at wileyonlinelibrary.com]

upper tropospheric forcing to all known medicane cases (e.g., Nastos *et al.*, 2018) and deep convection associated with tropical cyclones is not always expected to be present at the centre of many known medicane cases (Fita and Flaounas, 2018).

The composite precipitation pattern of these storms exhibits a lower magnitude than tropical cyclones (Figure 2b). Medicanes produce a composite precipitation of ∼6 mm/6-hr close to the centre of circulation (Figure 2b). This precipitation structure is similar to what is observed in tropical cyclones (e.g., Villarini *et al.*, 2014; Rios Gaona *et al.*, 2018; Zhang *et al.*, 2019). Moreover, there are similarities in the composite rainfall structures between medicanes in this study and those for Mediterranean cyclones (Flaounas *et al.*, 2018*a*, 2018*b*). However, the rainfall structure in this study is concentrated in the northwest side of the cyclone centre, while Flaounas *et al.* (2018*a*, 2018*b*) found that most precipitation associated with Mediterranean cyclones was concentrated to the northeast side of the cyclone centre due to warm conveyor belts. The highly phenomenological difference in rainfall between this study and Flaounas *et al.* (2018*a*, 2018*b*) may be due to the following reasons: (a) the two composite rainfall is not obtained from the same cyclones and based on different rainfall datasets; (b) the association of cyclones with rainfall does not follow the same methodology; and (c) Flaounas *et al.* (2018*a*, 2018*b*) objectively identifies warm conveyor belts (WCB) and their rainfall while we directly composite rainfall without identifying WCB.

Following the analysis of the composite rainfall pattern of medicanes, we quantify the contribution of these storms to precipitation across Europe. During 1979–2017, the regions along the Mediterranean Sea experienced a large number of extreme precipitation events associated with medicanes. Italy experienced over 20 extreme precipitation events (i.e., days), followed by France, Croatia, Serbia, Greece and Turkey (Figure 3). In addition, medicanes account for 2–5% of all the extreme precipitation events, with the highest fraction located in Italy. Overall, the spatial pattern of days with extreme precipitation (Figure 3) is consistent with the track density of these storms (Figure 1). For the first time, we quantify the contribution of medicanes to total rainfall and extremes in Europe using the ERA-5 data.

We also examine the rainfall caused by the cyclones which are tracked but are excluded due to the criteria applied to identify medicanes (Table S2 and Figure S1). Figure S1 shows that rainfall produced by medicane candidates filtered out by maximum sustained wind is much greater than those filtered out by warm core and symmetry because many medicane candidates are filtered out by the criterion maximum sustained wind >17 m·s^{-1} (Table S2).

4 | DISCUSSION AND CONCLUSIONS

Medicanes, hurricane-like cyclonic systems in the Mediterranean Sea, are becoming an increasingly severe problem for the coastal Mediterranean countries. Due to their small size, high-resolution data are required to better resolve structure and evolution of these storms. We have investigated medicanes from the perspective of precipitation and climatology using the high-resolution (0.25°) ERA-5 reanalysis data by ECMWF.

We identified 59 medicanes during 1979–2017, with marked year-to-year variability. These storms tend to occur mostly between September and March, with a secondary peak in May and little to no activity during July and August. Overall, the intensity of medicanes (i.e., maximum wind) is lower than what observed in tropical cyclones, and this is also true for precipitation. During 1979–2017, many regions along the Mediterranean Sea experienced over 20 extreme precipitation events (i.e., days) associated with medicanes, accounting for 2–5% of all the extreme precipitation events. The composite medicane rainfall exhibited the highest value in Italy.

The Genoa Gulf is one of the most cyclogenetic regions of the Mediterranean (Trigo *et al.*, 2002). Given the uncertainties in the tracker and a spatial resolution of 0.25° in the ERA-5 data, the tracker may capture a few nonmedicane cyclones in this study. However, the overall conclusion of this study should hold even with the existence of such cyclones. Moreover, Ragone *et al.* (2018) compared the statistics of medicanes in 1979–1998 between runs forced by ERA-Interim with a resolution of 11 km and different convective parameterizations and microphysics schemes and runs at a resolution of 4 km with explicitly resolved convection, exhibiting quite different statistics of medicanes. Because the ERA-5 reanalysis is based on a specific IFS model setup, their results indicate that different physical setup in ERA-5 may lead to different results in the climatology of medicanes.

Compared to tropical cyclones, these contributions are generally smaller (both in terms of extremes and total amounts; for example, Khouakhi *et al.*, 2017); nonetheless, they are capable of causing significant damage and disruptions due to flooding and landslides. While these results focus on the 1979–2017 period, future studies should examine the response of the rainfall associated with these storms to the projected changes in the climate system, similar to what has been done for tropical cyclones (e.g., Scoccimarro *et al.*, 2014; Villarini *et al.*, 2014). González-Alemán *et al.* (2019) have already examined the future change of the rainfall associated with medicanes using a fully coupled climate model. This can now be accomplished thank to the availability of the new high-resolution model runs part of the High Resolution Model Intercomparison Project (Haarsma *et al.*, 2016).

There are still uncertainties and dependence on data sets in the tracking algorithm of medicanes. For example, there are missing medicane cases compared with Miglietta *et al.* (2013) in which they simulated well known cases of Mediterranean cyclones qualified as medicanes due to their spiral cloud coverage. Currently, there are no objective physical criteria that qualify cyclones as medicanes and the detection of medicanes is based on subjective criteria and does not necessarily represent the strongest cases in the Mediterranean (Flaounas *et al.*, 2015). The number of medicanes after applying the criteria of sea level pressure and maximum sustained wind highly depends on model and model resolution (Gaertner *et al.*, 2018). In this study, we have focused on the warm core axisymmetric cyclones. We do not attempt to evaluate all the tracking algorithms for medicanes in this study. Rather, our objective is to identify the climatological feature of medicanes in the recently available ERA-5 reanalysis data with a 0.25° spatial resolution.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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