Characterization of medicanes with a minimal number of geopotential levels

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Abstract
Medicanes are tropical-like cyclones that develop in the Mediterranean Sea. Due to their harmful potential, the study of medicanes has captured great attention from the scientific community. In the context of a changing climate, their future climatological characterization can only be achieved using climate model output. A frequently used method to characterize the thermal structure of medicanes is the cyclone phase space (CPS) described by Hart (2003). This requires geopotential data from 300 to 900 hPa every 50 hPa. However, in long, high-resolution climate simulations, model output requires very high storage space and only data from a few geopotential levels are saved. To overcome the lack of geopotential data at some levels, available data are vertically interpolated to obtain data for the 13 levels required. In this work, we use high horizontal resolution data from the ERA-5 reanalysis (1979–2018) to analyse the climatology of medicanes simulated using the 13 vertical levels required according to Hart (2003), as well as different combinations of geopotential data from a few selected levels. Our results allow us to propose, for the first time, a limited set of recommended geopotential levels required for an adequate climatological characterization of medicanes in the perspective of long climate change simulations, taking into account the associated limitations of output data storage.

KEYWORDS
ERA-5 reanalysis, geopotential levels, medicane characterization, Mediterranean cyclones, Mediterranean Sea

INTRODUCTION

Medicanes (MEDIterranean hurriCANES) are mesoscale, warm-core cyclones that occasionally develop in the Mediterranean Sea (Ernst and Matson, 1983; Reale and Atlas, 2001). They are associated with strong precipitation events and heavy winds that can eventually approach hurricane intensities (Emanuel, 2005). Medicanes form from baroclinic cut-off lows, which are very frequent in the Mediterranean Sea since this is one of the three preferred regions in the northern hemisphere for their development (Nieto et al., 2005). These baroclinic cut-off lows evolve into warm-core cyclones through tropical transition (Chaboureau et al., 2012) and are characterized by a convective cloud structure which is symmetric around a cloud-free centre (Fita et al., 2007). This highlights the...
relevance of air-sea interactions and convection in their development and maintenance (Miglietta and Rotunno, 2019). Also, medicane development necessitates enhanced vorticity advection, which forces uplifts and induces further low-level cyclogenesis (e.g., Carrío et al., 2017).

In spite of their small size (with a typical diameter smaller than 300 km), medicanes can drive important socio-economic losses in coastal areas as a result of heavy precipitation and the strength of the associated winds. In the last decades, medicanes have captured the attention from the scientific community as they constitute a serious risk for infrastructures, and, ultimately, can pose a threat to human lives. In Bakkensen (2017), the authors analyse 62 years of historical medicane re-analysed tracks and find that Italy suffers the highest expected damages from medicanes, with an average of $33 million dollars annually. They also show that Mediterranean islands constitute a particularly vulnerable area.

Although medicanes are relatively infrequent, with an annual mean of about 1.6 events per year over the whole Mediterranean basin (Cavicchia et al., 2014a), their harmful potential makes it essential to improve the state-of-the-art knowledge regarding their formation and evolution. Because of their small size and the limited data available over the sea, satellite data has been widely used to study medicanes (Tous and Romero, 2013). In the last decades, the increase in computational power has made it possible to enhance the horizontal resolution of climate models so that model output can be used to characterize medicanes (Akhtar et al., 2014; Gaertner et al., 2018). A potential advantage of the model approach is that it offers the possibility to study medicanes from a climatological point of view (e.g., Cavicchia et al., 2014a), not only for present-day climate, but also in different future climate scenarios. In this context, previous works find small changes (or even a subtle decrease) in medicane frequency, but an increase in their intensity by the end of the 21st century (Romero and Emanuel, 2013; Cavicchia et al., 2014b; Tous et al., 2016; Romera et al., 2017; González-Alemán et al., 2019). This may increase medicane-related hazards for example, strong winds and precipitation that will potentially enhance socio-economic losses and even human casualties by the end of the century.

To detect medicanes in climate models, the thermal structure of Mediterranean cyclones (medicanes are a subset of them), must be analysed. The characterization of the thermal structure of cyclones making use of model and/or reanalysis data is frequently performed following Hart (2003). The cyclone phase space (CPS) described in Hart (2003) summarizes the various types of mesoscale to synoptic-scale cyclones into a multidimensional continuum. This method requires the use of geopotential data ranging from 300 to 900 hPa levels every 50 hPa (i.e., 13 levels). However, in long, high horizontal resolution climate simulations model output requires very high storage space and only geopotential data from a few vertical levels is stored. The number of geopotential levels to save is not standardized, neither the specific geopotential levels to store, but it is frequent to save geopotential model output on a few vertical levels like 850, 500 and 300 hPa. To overcome the absence of geopotential data at some levels, available geopotential data can be vertically interpolated in order to get data for the 13 levels mandatory for the CPS calculation. In previous studies, an attempt has been done to simplify the CPS method proposed by Hart (2003) for example, Baatsen et al. (2015); Liu et al. (2017). For instance, in Liu et al. (2017) the upper and lower tropospheric layer definitions of Hart (2003) have been modified in order to adapt to the available levels of the model output: instead of a 900–600 hPa lower layer and a 600–300 hPa upper layer, they use a 850–500 hPa lower layer and a 500–300 hPa upper layer.

In this work we use high horizontal resolution reanalysis data from ERA-5 (Hersbach, 2018) including the entire Mediterranean Sea to examine the climatology of medicanes reproduced by the CPS using geopotential data from (i) the 13 vertical levels required in the original method of Hart (2003), (ii) as well as just using different combinations of data from a few selected geopotential levels and the mean-sea level pressure (MSLP). The frequently available geopotential levels of 850, 500 and 300 hPa are the basis for the different limited groups of levels tested. The MSLP is used, along with the geopotential at 850 hPa, to compute the geopotential at 900 hPa. Specifically, we analyse the capability of the different combinations of geopotential levels to reproduce the medicane climatology of the past years (i.e., 1979–2018). Based on the obtained results we propose, for the first time to our knowledge, a series of recommended, reduced number of geopotential levels that would allow for a proper climatological characterization of medicanes. Though the calculations are done using reanalysis data, this is only a practical way in order to assess the effects of using a small number of geopotential levels (which is the typical situation in long climate change simulations) instead of all 13 geopotential levels indicated in the original CPS method. These 13 levels are available in the reanalysis, not in usual climate change simulations. The final aim is to determine a minimum set of levels that can be recommended for the output in long climate change simulations, where output storage space is limited. This work is structured as follows. In Section 2, the methodology is described. In Section 3, results are presented and discussed. A summary and the conclusions are given in Section 4.
2 | METHODOLOGY

2.1 | Data

To characterize cyclones we use reanalysis data from ERA-5, also recently used in Zhang et al. (2021) to examine precipitation associated with medicanes. In our study we make use of ERA-5 variables with a frequency of 6 hr. One of the major advantages of the new ERA-5 reanalysis is that it offers data with a horizontal resolution of 30 km (i.e., 0.25°) and offers improved tropospheric data and a better representation of tropical cyclones, which is key for this study. In this work we use ERA-5 reanalysis data for several reasons. First, all the geopotential levels required for the original CPS method are available. Second, reanalysis data with enhanced horizontal resolution as ERA-5 provides us good conditions to perform our study, as medicanes are small-size cyclones. The use of reanalysis data is only a functional means for providing practical information, that is, which are the basic geopotential levels to save in order to perform the subsequent CPS calculation and get results comparable to those that would be obtained if all the geopotential levels were available. We consider the period that goes from 1979 until 2018. Variables required for the cyclone tracking are (i) the mean sea level pressure (Pa), (ii) the u and v-components of the wind at 700 hPa (m/s) and (iii) the u and v-components of the 10-m wind (m/s). For the CPS we need geopotential data from the levels specified in Section 2.3.

2.2 | Cyclone tracking

In this work, cyclones are detected and tracked following the methodology presented in Picornell et al. (2001), which has been found to be suitable to detect mesoscale cyclones, such as medicanes (Gaertner et al., 2018). The method can be divided into two steps. First, all pressure minima (i.e., potential cyclones) are computed from 6-hr mean-sea level pressure data. Second, weak cyclones are excluded. To detect weak cyclones, the pressure field along the eight typical directions around the minimum is studied. Only cyclones for which the pressure gradient exceeds 0.005 hPa/km, in at least six of the eight directions, are considered. Another condition intrinsic to the cyclone identification and tracking algorithm is that if two cyclones are not separated by at least four grid points, only the one with the most intense circulation is chosen. More details about the cyclone tracking method can be found in Picornell et al. (2001).

2.3 | Cyclone phase space

After the tracking, the CPS described in Hart (2003) is applied to characterize the three-dimensional thermal structure of the cyclones during its life cycle. The CPS considers three parameters, which have been proved to successfully distinguish and describe the structure of tropical and extratropical cyclones. These are:

- The B parameter, which represents the lower tropospheric horizontal thermal asymmetry and provides information regarding the frontal (or non-frontal) nature of the storm on the basis of changes in the thickness between 900 and 600 hPa across the cyclone within a radius of 150 km. The 150-km radius we consider, which has also been used in previous works (e.g., Gaertner et al., 2018), is smaller than the 500-km radius proposed in Hart (2003). The reason for this is that whilst in Hart (2003) larger-scale cyclones are studied, in this work we focus on medicanes, with a typical diameter not larger than 300 km, as shown by Miglietta et al. (2013). As in Hart (2003), we assume that values of B greater than 10 m correspond to frontal systems and values lower than that to non-frontal systems.

- -VTL and -VTU are the lower- (i.e., 600–900 hPa) and the upper-troposphere (i.e., 300–600 hPa) thermal winds, respectively, which provide a measure of the vertical thermal structure. These parameters allow us to determine whether the cyclone has a warm or a cold core. Negative values of thermal wind parameters are indicative of a cold-core cyclone, whilst positive values indicate the opposite.

In this study, we classify as a medicane those cyclones with maximum wind speeds greater than 17.5 m/s within a radius of 400 km from the cyclone centre, values of -VTL and -VTU greater than 0 and B smaller than 10 at least for one time step during the cyclone lifetime. In some previous studies, the vertical limits and extension of the two layers used in the CPS method has been changed for application to medicanes. Picornell et al. (2014) lowered the CPS layer limits (925, 700 and 400 hPa) for detecting medicanes, taking into account the lower tropopause height associated to cut-off lows over the Mediterranean Sea. In contrast to this, Ragone et al. (2018) used higher CPS layer limits (850, 500 and 200 hPa) due to data availability reasons. We have maintained the original limits and extension of the CPS layers, as they were obtained originally without geographical restrictions and for all types of cyclones, and the use of the original layer values favours the comparability with other regions of the world. In the case of medicanes, the original setup of
the CPS layers has been also frequently used (among others, in Gaertner et al. (2007); Chaboureau et al. (2012); Cavicchia et al. (2014a); Miglietta et al. (2015); Pytharoulis (2018); González-Alemán et al. (2019) and Patlakas et al. (2021)). To compute the CPS parameters described in Hart (2003) we use two different methods:

- **Original method (NO-INT):** following Hart (2003), we take geopotential data from 300 to 900 hPa with a vertical spacing of 50 hPa to characterize the thermal characteristics of the cyclone. This allows us to have a reference to compare the results obtained to the different simplified methods explained below.

- **Simplified method (INT):** in this case we use the geopotential of a few selected levels, as well as the MSLP, to compute the CPS. Selected geopotential levels are INT-3 (300, 500 and 850 hPa), INT-4-400 (300, 400, 500 and 850 hPa), INT-4-600 (300, 500, 600 and 850 hPa) and INT-5 (300, 400, 500, 600 and 850 hPa). The geopotential levels taken in the different INT configurations are summarized in Table 1. The geopotential of the missing levels required according to Hart (2003) are computed with a linear vertical interpolation between the available levels. The reason why we use a linear interpolation instead of a more sophisticated one is that we aim to determine whether the most simplistic method can be suitable for medicane characterization. With this simplified method, the MSLP is used to calculate the geopotential at 900 hPa as explained below.

We first compute the geopotential height at 850 hPa (Equation 1).

\[
h_{850} = \frac{z_{850}}{g}
\]  

(1)

where \( h_{850} \) corresponds to the geopotential height at 850 hPa, \( z_{850} \) is the geopotential at 850 hPa and \( g \) the gravitational constant, set to 9.8 m/s².

Then, the pressure change between 850 hPa and the mean sea level pressure is calculated (Equation 2).

\[
DP_{\text{mslp}-850} = \text{MSLP} - 850
\]  

(2)

where \( DP_{\text{mslp}-850} \) corresponds to the pressure change from 850 hPa to the sea level and, as stated above, MSLP is the mean-sea level pressure.

Finally, the geopotential at 900 hPa is computed assuming a linear interpolation as follows (Equation 3):

\[
z_{900} = \left( (h_{850} - (50 * h_{850} / (DP_{\text{mslp}-850}))) * g \right)
\]  

(3)

where \( z_{900} \) is the geopotential at 900 hPa, \( h_{850} \) the geopotential height at 850 hPa, \( DP_{\text{mslp}-850} \) corresponds to the pressure change from 850 hPa to the sea level and \( g \) the gravitational constant, set to 9.8 m/s².

### RESULTS AND DISCUSSION

In this section we compare results obtained when the CPS is performed following the original methodology proposed in Hart (2003), that is, NO-INT, to those we get with the different simplified interpolated configurations, that is, INT. We start with the climatological study of the annual, seasonal and monthly frequency of reproduced medicanes. Then, we examine the performance of the INT configurations to simulate other relevant aspects such as medicane intensity, regions of medicane formation and the development of spurious medicanes that is, cyclones that actually did not develop the needed tropical characteristics, but which appear as such when the simplified methods are applied to obtain the CPS parameters. Additionally, we also investigate the performance of the INT configurations to reproduce three intense and long-lasting observed medicanes: Rolf, Celeno and Zorbas.

#### 3.1 Frequency of detected medicanes

Figure 1 shows the annual number of medicanes detected from 1979 to 2018 for the case in which the CPS is computed making use of 13 geopotential levels (NO-INT). The corresponding trend (which is not statistically significant in any case, as can be observed in Table 2) is also depicted in the figure. NO-INT reproduces between 0 and 3 medicanes per year, which is in line with former

| Table 1 | Geopotential levels used for the cyclone phase space (CPS) for the different simplified methods here assumed |
|---------|---------------------------------------------------------------|
| Simplified method | Geopotential levels used for the analysis (hPa) |
| | 300 | 400 | 500 | 600 | 850 |
| INT-3 | X | X | | | |
| INT-4-400 | X | X | X | | X |
| INT-4-600 | X | X | X | X | |
| INT-5 | X | X | X | X | X |
climatological studies (e.g., Cavicchia et al., 2014a; Gaertner et al., 2018; Zhang et al., 2021). For the considered time period, we compute an annual mean of 1.17 cyclones and an increasing trend of 0.028 medicanes per year (see Table 2 for details). The NO-INT configuration provides an annual-mean number of medicanes somewhat smaller than ~1.5, the frequency reported in Zhang et al. (2021) using data from ERA-5 for the same time span here examined. In the climatology from Cavicchia et al. (2014a), the time period between 1950 and 2011 is considered. For the time interval common to our work (i.e., 1979–2010), data from Cavicchia et al. (2014a) indicate the occurrence of 1.56 medicanes per year. For that time span we find an average of 1.12 medicanes per year. Also, according to Cavicchia et al. (2014a), an increasing trend of 0.069 medicanes per year from 1979 until 2010 would occur. For that time period we find an increasing trend of 0.046 medicanes per year. It is remarkable that our results are able to capture the increasing trend found in Cavicchia et al. (2014a), which is not reproduced in the climatology from Zhang et al. (2021). With our methodology we are able to capture well-known and intense medicanes such as Rolf (2011), Celeno (1995), Zorbas (2018) or Qendresa (2014), whilst in Zhang et al. (2021) medicanes such as Celeno (1995) are not reproduced.

The differences between the three climatologies, as well as the somewhat smaller frequency we find with respect to Zhang et al. (2021) and Cavicchia et al. (2014a) may be related to several factors. First, the tracking method we use, based on Picornell et al. (2001) is different from that employed in Zhang et al. (2021) and Cavicchia et al. (2014a). In the sensitivity study from Flaounas et al. (2018) six different cyclone tracking methods were applied to regional climate model and reanalysis data and the resulting climatology of Mediterranean cyclones is shown to be highly dependent on the tracking method used. Thus, differences between our climatology and those from Zhang et al. (2021) and Cavicchia et al. (2014a) should be expected. Importantly, the wind criteria we use to define a medicane are different and stricter than that used in those works. In our study, wind speed should attain at least 17.5 m/s within a radius of 400 km by the time the cyclone has a full-tropospheric warm core. Therefore, less medicanes can be expected to develop in our study relative to Zhang et al. (2021) and Cavicchia et al. (2014a). Also, in Zhang et al. (2021) and Cavicchia et al. (2014a) tropical cyclones over land and over the Black Sea are, to our knowledge, considered as medicanes, whilst in our work such cyclones are excluded. Furthermore, in NO-INT, we use the original method of Hart (2003), in which a total of 13 geopotential levels are used (from 300 to 900 hPa every 50 hPa) to characterize the thermal structure of medicanes. As we will see in the next paragraph, the medicane number is highly dependent on the number of geopotential levels used and in the aforementioned works the number of geopotential levels used to perform the CPS is not specified. Furthermore, when the Hart (2003) method is applied, we assume a radius of 150 km, which is different from that in those studies.

Focusing on the other four configurations tested (INT), we note that all of them detect a maximum of 3–4 medicanes per year (Figures 2a–d). All the INT configurations reproduce a similar, but slightly higher, annual-mean number of medicanes than NO-INT (Table 2). Notwithstanding, differences in the annual-mean
The number of medicanes reproduced by the configuration that estimates more medicanes (i.e., INT-4-600) and NO-INT is 0.2. All INT configurations show a significant statistical correlation with NO-INT (p-value < .05; Table 2). The lowest and highest correlations are found for INT-3 and INT-5, respectively, with values greater than 0.7 in all cases with the exception of INT-3. In Table 2 we observe that the addition of more geopotential levels does not have the same impact on the different statistics computed (i.e., mean, trend, standard deviation or correlation with NO-INT). It is remarkable the good performance of INT-4-600 and INT-5, which provide an annual-mean number of 1.37 and 1.35 medicanes, respectively, with correlations close to 0.8 relative to NO-INT. Although INT-5 provides the best results in comparison to NO-INT, for many parameters that is, standard deviation, trend, correlation, INT-4-600 gives a good performance (much better than for INT-3 and INT-4-400). The relevant implication of this is that INT-4-600 is able to provide good results with less geopotential levels than INT-5, which is beneficial to reduce the model output storage (especially important for long climatic model simulations), as well as the computation time of the CPS.

In Figure 3a, the total seasonal number of medicanes simulated for the whole time period of analysis is shown. In all cases, in line with Cavicchia et al. (2014a), the greatest number of medicanes is reproduced in winter, whilst no medicanes develop in summer. The absence of medicanes in the summer matches well with previous studies, since medicane formation requires intrusions of cold air which promote instability which are not active in summer. NO-INT reproduces 23 medicanes in winter, 13 in spring, none in summer and 11 in fall. The fact that 2 more medicanes are found in spring than in fall is
caused by a large number of events in April. A relative maximum in the number of medicanes in April is also found in Cavicchia et al. (2014a) when only the events formed in the main medicane genesis area (the Western Mediterranean; see fig. 6 of Cavicchia et al., 2014a) are considered.

All the INT configurations overestimate the amount of medicanes in winter and tend to underestimate it (although to a lesser extent), in fall. This is shown in more detail in Figure 3b, which is equivalent to Figure 3a, but for the monthly distribution. Figure 3b shows good qualitative agreement with results from Cavicchia et al. (2014a). In view of our results, we can thus state that the overestimation in the annual-mean number of medicanes observed in Table 2 is the result of the development of spurious medicanes with the INT configurations in winter. In winter and fall, INT-3 is the configuration for which results are more biased and INT-5 the one for which results are closer to those obtained with NO-INT. Results reproduced with INT-4-400 and INT-4-600 are quite similar. In summer, all INT configurations are capable to successfully simulate the absence of medicanes from NO-INT.

3.2 Medicane structure and intensity

At this point, it is interesting to analyse the ability of the different configurations to reproduce the wind speed and the warm core distribution of NO-INT. Figure 4 shows the probability density function of the wind speed for NO-INT and the corresponding INT cases. In general, results show that the wind speed distribution of each of the configurations resembles that of NO-INT. Specifically, the differences between the best fit wind distribution of each configuration and NO-INT are not statistically significant according to a Wilcoxon test (not shown). As wind speed increases, the INT configurations tend to provide slightly higher frequencies than NO-INT. All INT configurations are thus able to capture well the wind speed distribution from NO-INT.

Regarding the capability of the different configurations to reproduce the warm core characteristics from NO-INT, Figure 5 shows the probability density function of -VTU (i.e., intensity of the warm core) for each of the configurations tested, respectively, together with that from NO-INT. In this respect, high values of -VTU correspond to intense, tropical cyclones with a well-developed upper level warm core. In turn, the intensification of the cyclone entails high wind speeds, intense precipitation etc. Different from results from Figure 4, results now show that the specific distribution obtained is very dependent on the configuration selected, although the differences between the NO-INT and corresponding INT configurations are not statistically significant (p-value >.05). We note that configurations with an additional upper level (i.e., 400 or 600 hPa), represent better the warm core of medicanes than INT-3. Also, INT-5 gives the best performance regarding -VTU.

Figure 6 shows annual time series of the total number of hours during which the medicanes have tropical characteristics (symmetric, warm-core cyclones), as well as the corresponding trend. A very interesting result from NO-INT is the observed increasing trend of the duration of tropical characteristics during the last decades. This
**FIGURE 4** Probability density function of the wind speed (m/s) for NO-INT (red bars) and the corresponding interpolated case (green bars; a: INT; b: INT-4-400; c: INT-4-600; d: INT-5). The best fit of the probability density functions for NO-INT (red line) and the different interpolated cases (blue line) are also shown [Colour figure can be viewed at wileyonlinelibrary.com]

**FIGURE 5** As for Figure 4, but taking into account -VTU (m) [Colour figure can be viewed at wileyonlinelibrary.com]
may be related to an increase of the Mediterranean sea-surface temperature (Gaertner et al., 2018), which favours the maintenance of the tropical structure (Miglietta et al., 2011), and is fully consistent with the results obtained by González-Alemán et al. (2019) for a future climate scenario. All INT configurations coincide in an increase of the number of hours with tropical characteristics over time. This progressive tropicalization of medicanes is better captured with INT-4-600 and INT-5. The INT-4-600 configuration, once more, appears to be a suitable candidate since it provides a similar representation as INT-5 but with less geopotential data. It is interesting to note that all configurations (i.e., NO-INT and INT) also show an increase in medicane lifetime. This trend, which is statistically significant in all cases (not shown), indicates a progressive increase in the period during which medicanes have a fully tropical structure.

3.3 | Areas of preferential formation of medicanes

Different studies conclude that medicane genesis is more common at several locations of the Western and Eastern Mediterranean Sea (e.g., Tous et al., 2013; Cavicchia et al., 2014a). The preferred areas for cyclone formation are roughly coincident with regions of enhanced vorticity advection (de la Torre et al., 2008). Medicines form more frequently in the Western Mediterranean Sea, in particular, within the area located between the Balearic Islands and the coast of Spain, the south of France and the western coast of Corsica and Sardinia. A secondary area of medicane formation is between Sicily and Greece, covering the Ionian Sea until the Libyan coast. In Figure 7 we observe the track density for the tropical phase for the studied time period for the different configurations. We note that with NO-INT (Figure 7a), in agreement with literature, medicanes are primarily formed in the mentioned regions. First, near the western coast of Corsica and the north of Sardinia (Figure 7a). Second, between the south of Italy and Greece. The two areas of enhanced medicane formation we find are qualitatively similar to those found in Cavicchia et al. (2014a) and are in line with the regions proposed in Zhang et al. (2021) using ERA-5 data as well. Only the configurations INT-4-600 and INT-5 capture a similar density of medicanes formed in those two areas. With INT-3 and INT-4-400 the frequency of medicanes is underestimated in both the Eastern and Western Mediterranean basin, especially with INT-4-400. This highlights that the incorporation of the 600 hPa geopotential level is key to reproduce observed genesis areas. These results underline, once more, that
INT-4-600 is able to provide a good performance and thus may constitute, in many cases, a good alternative for INT-5.

3.4 | Concurrence

The duration of the fully tropical phase of medicanes obtained with NO-INT and INT configurations, respectively, is presented in Figure 8. In agreement with what found so far, the INT configurations reproduce more medicanes than NO-INT. This therefore implies that also, a variable number of spurious medicanes is reproduced with the interpolated configurations. It is also important to realize that, in general, the fully tropical phase of medicanes lasts more in the INT cases. In more detail, with INT-5 and INT-4-600, differences in the duration of each of the individual medicanes relative to NO-INT are smaller than with INT-3 or INT-4-400. Also, spurious medicanes have a shorter duration with INT-4-600 and INT-5. Therefore, INT-5 and INT-4-600 are clearly the best options once more. Although with INT-5 differences with respect to NO-INT are slightly smaller than with INT-4-600, results are quite similar and the choice of INT-4-600 could be a good one since it involves less data to compute the CPS. The lack of concurrence between NO-INT and INT-3 is quite remarkable, making this configuration the least recommended one.

In this context, it is of interest to examine the seasonal pattern of the concurrence, specifically, for winter and fall, in which medicanes are prone to develop. In winter, in line with what has been stated in the previous paragraph, all INT configurations reproduce more medicanes than NO-INT (Figure 9). We note that medicanes common to NO-INT and INT tend to last more in the INT cases. In more detail, 11 spurious medicanes develop with INT-3. Also, 2 of the medicanes from NO-INT are not captured by INT-3. With INT-4-600, 1 of the medicanes found with NO-INT is not detected, and 8 spurious medicanes are found. With both configurations, INT-3 and INT-4-400, differences between NO-INT and the corresponding INT configuration can reach up to two time steps (12 hr). With INT-4-600, 9 spurious medicanes are found but these have a maximum duration of a single time step. With this configuration, one observed medicane is not captured. Differences in the amount of time steps between INT-4-600 and NO-INT only attain a value of 2 time steps once. With INT-5 only 6 spurious medicanes have been simulated. The differences in the duration of medicanes from NO-INT and INT-5 never exceed 1 time step.

In fall, less medicanes are reproduced in all INT configurations with respect to NO-INT (Figure 10). Interestingly, all medicanes common to NO-INT and the corresponding INT configuration have the same duration. In this season, INT-4-600 and INT-5 provide a representation which is better than that from INT-3 to INT-4-400. With INT-4-600, 3 observed medicanes are not represented and 1 spurious medicane arises. With INT-5, only 1 observed medicane is missing and one false medicane develops. It is important to spell out that none of the
spurious medicanes or the reported medicanes that are not captured by the INT configurations have a fully-tropical phase longer than one time step.

3.5 Study cases

Here we show the differences in the results obtained with the NO-INT and the INT configurations for three study cases. We concentrate on results for the calculated CPS, in which -VTL, -VTU and B (i.e., lower- and upper-tropospheric thermal wind parameter and symmetry parameter) are represented. This analysis allows us to gain additional insight into the performance of the different INT configurations with respect to NO-INT. To this end, we select three intense and long-lasting medicanes that have been reported in previous studies. We choose medicanes ‘Rolf’ (6–9th November, 2011; Ricchi et al., 2017; Dafis et al., 2018), ‘Celeno’ (14–17th January, 1995; Pytharoulis et al., 2006) and ‘Zorbas’ (27 September–1st October 2018; Statopoulos et al., 2020). These medicanes present, according to previous data and also in our analysis, a deep warm core over more than 24 hr (as seen in Figure 11). The tracking of the medicanes is shown in Figure 1S.
3.5.1 Medicane Rolf

This medicane occurred from 6th to 9th November, 2011 and affected the Balearic Islands and the south of France. On 6th November, 2011, at the surface, a low-pressure system evolved in a baroclinic environment near the Balearic Islands, where the formation of a convective structure close to the centre of the cyclone occurred. On seventh of November the system acquired tropical characteristics with a symmetric warm core structure and convective bands, which were especially developed on 8th November. On November 9th, Rolf made landfall in the southeast of France. Its weakening was rapid and it quickly lost its structure (see Dafis et al., 2018 for details). In line with this, we observe that NO-INT starts with an asymmetric, deep cold core which evolves into a symmetric, deep warm core cyclone the 7th and 8th of November after briefly going through a shallow warm core phase (Figure 11a,b). Focusing on the other configurations we note that, qualitatively, all configurations capture the phases reproduced with NO-INT. In more detail, it can be appreciated that the CPS from INT-3 and INT-4-400 are almost identical (Figure 11a,b). In both cases the intensity of the warm core is slightly lower in INT-3 and INT-4-400 than in NO-INT, and the deep cold core phase for these two INT configurations shows also some differences to NO-INT. The other two configurations, INT-4-600 and INT-5 provide a very similar CPS evolution, which is almost identical to that from NO-INT.

3.5.2 Medicane Celeno

According to literature, after its formation during the late hours of the 14th January 1995, the low intensifies.
During the 15th of January a symmetric, intense cyclone with a warm core is clearly developed to the east of Sicily. The lifetime of this long-lasting medicane was 78 hr according to satellite archives (see more details for example, Tous et al., 2013). We observe that with NO-INT, there is a transition from a deep cold core towards a shallow warm core, and, afterwards, towards a deep warm core (Figure 11c,d). The development of a deep warm core on the 15th of January finally evolves into a shallow warm core cyclone. As for Rolf, all the INT configurations capture the same phases as NO-INT. Also in line with that, INT-4-600 and INT-5 are the ones that capture best the intensity and timing of the different phases, while INT-4-400 and INT-3 deviate more from NO-INT.

### 3.5.3 Medicane Zorbas

This storm developed over warm waters in the Eastern Mediterranean Sea during the 27th of September 2018 (Portmann et al., 2020; Stathopoulos et al., 2020). The day after, it gradually intensified and acquired tropical-like characteristics on its way to the NE. The cyclone reached its maximum intensity as it approached, and hit, the SW of Greece on September 29th. Then, it continued to the NE, towards the Aegean, and dissipated over Turkey the day after. We observe that with NO-INT, there is a transition from a deep, cold core towards a shallow warm core (Figure 11e,f). This is followed by the development of a deep, symmetric warm core on the 28th of September 2018. As for the previously studied medicanes, all INT

![Figure 10](image-url)
FIGURE 11  First column: CPS parameter diagrams that show -VT(m) and -VTU(m). Second column: CPS diagrams in which -VTU(m) and B(m) are represented. Medicane Rolf (2011) is shown in a and b, Celeno (1995) in c and d and Zorbas (2018) in e and f. In each panel, a represents the situation at the beginning of the medicane and Z corresponds to the state at its end. The initial and final dates are shown [Colour figure can be viewed at wileyonlinelibrary.com]
configurations are able to reproduce the same phases as NO-INT and INT-4-600 and INT-5 are the configurations in which intensity and timing of the phases are better reproduced. Results from INT-4-400 and INT-3 deviate more from NO-INT.

Results found for the studied medicanes support the selection of INT-4-600 and INT-5 as the configurations providing an adequate representation of the medicanes, which is much better than that from INT-3 and INT-4-400. We can conclude that, as stated in above sections, INT-4-600 allows us for a proper characterization of medicanes with less data than INT-5 (i.e., one geopotential level less).

4 | SUMMARY AND CONCLUSIONS

In this work we use data from the high horizontal resolution ERA-5 reanalysis to investigate the effect of reducing the amount of geopotential levels on the characterization of the medicane climatology from 1979 to 2018. Information provided here sheds light on the minimum number of geopotential levels that should be used for the CPS calculation (i.e., stored from climate simulations) in order to attain an adequate representation of the medicane thermal structure. The main findings from this analysis can be summarized as follows:

- A very interesting result that emerges from the climatology is the observed increasing trend of the duration of tropical characteristics during the last decades, which is consistent with the results for future climate projections obtained by González-Alemán et al. (2019).
- All INT configurations reproduce quite well the wind speed distribution from NO-INT. As wind speed increases, the INT configurations tend to provide higher frequencies than NO-INT.
- All INT configurations reproduce well, qualitatively, the seasonal and monthly cycles of the total number of medicanes in the studied time period. They capture a maximum in winter and do not reproduce medicanes in summer. In all INT cases, however, the total number of medicanes is overestimated (underestimated) in winter (fall). INT-3 is the configuration in which winter and fall biases attain a greater magnitude, whilst INT-5 is the one in which biases are smaller. INT-4-400 and INT-4-600 show a similar performance.
- Warm core intensity, determined by the -VTU parameter, is better captured by INT-5. INT-4-400 and INT-4-600 provide better results than INT-3. This highlights that the addition of an additional geopotential level is important to get a good representation of the medicane warm core.
- Regarding the areas of preferential medicane formation, NO-INT captures well the main genesis areas of the Eastern and Western Mediterranean Sea. These are only captured, with a similar medicane formation rate, by INT-5 and INT-4-600. Although the performance of INT-5 is slightly better, these results underline that INT-4-600 is able to provide good results and thus constitutes a good alternative for INT-5.
- With INT-5 and INT-4-600, differences in the duration of the fully tropical phase of each of the individual medicanes relative to NO-INT are smaller than with INT-3 or INT-4-400. Also, spurious medicanes have a shorter duration with INT-4-600 and INT-5. Whilst INT-5 and INT-4-600 are the best options, the lack of concurrence between NO-INT and INT-3 is quite large.
- Regarding the study cases (Rolf, Celeno and Zorbas), all configurations reproduce the main phases described in literature. INT-4-600 and INT-5 provide a very similar CPS evolution, which is almost identical to that depicted from NO-INT. The other two configurations deviate more from the NO-INT results.

We can thus conclude that from all INT configurations tested, INT-5 and INT-4-600 are the ones that provide results closer to those from the full original method (NO-INT). In many cases, however, the performance of INT-5 and INT-4-600 is so similar that we highly recommend the use of INT-4-600 (that is, saving geopotential at 850, 600, 500 and 300 hPa), since this can alleviate the data storage required for the analysis, particularly for long climate simulations where the constraints on model output are larger. In addition to that, INT-3 (using geopotential data only at 850, 500 and 300 hPa) constitutes the configuration which provides more deficient results and its usage is therefore not recommended.

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