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E. Avolio and C. Fanelli contributed equally to this work.

Key Points:

- No significant SST anomalies are found at the early stage of medicanes, except for the winter cases that exhibit a positive anomaly
- SST value is particularly high for the most intense cyclones (September cases)
- The passage of the cyclones over the sea induces a cooling mainly during their mature phase

Supporting Information:

Supporting Information may be found in the online version of this article.

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Unveiling the Relationship Between Mediterranean Tropical-Like Cyclones and Rising Sea Surface Temperature

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Abstract Leveraging the Copernicus high-resolution multi-year Mediterranean Sea Surface Temperature (SST) dataset, 15 selected tropical-like cyclones (TLCs) are analyzed with the objective of elucidating the anomalies of SST at the time of cyclogenesis and the connection between the change in SST during the cyclone lifetime and its characteristics. The long-term SST increase associated with climate change is identified by comparing detrended and original anomalies. Detrending removes the effect of the intensification of SST anomaly over time, revealing that no significant anomalies generally emerge in the early stages of the TLC lifetimes. Conversely, winter events exhibit early-stage positive SST anomalies. Also, high SST values were observed during the intensification of the most intense cyclones. A cold SST anomaly is left after the passage of the cyclones, due to the intense sea surface fluxes extracting heat from the sea.

Plain Language Summary Mediterranean tropical-like cyclones are severe weather events able to produce large socio-economic and environmental impact, as well as considerable damage. On average, 1.5 such events affect the Mediterranean each year. In this study we assess the Sea Surface Temperature conditions related to the events reported in the literature of the past four decades. We use a high-resolution multi-year SST dataset over the Mediterranean Sea, to reveal the potential relationship between the change in SST before and during the cyclone's lifetime and their features. Our results show that SST plays an important role in the intensification phases of the events, while no significant SST anomaly emerges in the early stages for most of the cyclones.

1. Introduction

Mediterranean Tropical-Like Cyclones (TLCs), also known as medicanes (short for MEDIterranean hurriCANES; Emanuel, 2005), are mesoscale low-pressure systems showing visual and physical similarities with tropical cyclones. As tropical cyclones, medicanes develop over the sea and rapidly decay after landfall, showing a deep warm core, a central eye, and spiral-like cloud bands; although TLCs have smaller horizontal scales and weaker intensity than tropical ones, they may be still responsible for severe damage on coastal areas, mainly caused by strong winds, heavy rainfall, storm surges and flooding (Flaounas et al., 2022).

In their initial stage, TLCs develop through baroclinic instability, which is the main mechanism of development of extratropical cyclones. Conversely, in their mature stage, they are mostly or partly driven by strong diabatic processes fed by the transfer of energy from the sea to the atmosphere (air–sea interaction), similarly as tropical cyclones (Emanuel, 2005). A clear difference between the Mediterranean and the Tropics lies in the different values of sea surface temperature (SST): the well-known threshold of 26.5°C, which is not valid for TLCs affecting the subtropics (McTaggart-Cowan et al., 2015), is also not satisfied in the Mediterranean Sea during autumn and winter (e.g., Table 1 in Miglietta et al., 2013), the period favorable to their development.

Few studies have explored the influence of SST on TLCs. Almost all refer to case studies and/or sensitivity experiments with numerical models where the SST is modified to assess cyclone intensity changes (e.g., Miglietta et al., 2011). Also, coupled atmosphere-ocean models have been employed to represent the feedback between the sea and the atmosphere (e.g., Ricchi et al., 2017). These studies suggest that the role of SST on the development of TLCs largely depends on the peculiarities of the individual cases; some of these studies are briefly commented in the Supporting Information S1 (SI hereafter) section.

The objective of the present work is to further investigate the possible relationship between SST and TLCs, considering the most important Mediterranean TLCs identified in the literature in the last 42 years (1982–2023). Our analysis includes original (SSTA) and detrended (DSSTA) SST anomalies, whose comparison allows to account for the impact of climate change (further discussion in Supporting Information S1). Furthermore, we aim to reconsider the outcomes of Cavicchia et al. (2014) (which was based on NCEP/NCAR reanalysis downscaled by CCLM at 10 km resolution in the period 1948–2011) that SST anomaly is not relevant at medicane formation time, using a higher resolution dataset and extending the analysis to recent cyclones.

2. Materials and Methods

2.1. TLCs Detection and Tracking

All the considered TLC tracks are identified adopting a new methodological approach (Flaounas et al., 2023), that combines overlapping tracks from 10 different cyclone detection and tracking methods, originally applied to ERA5 reanalysis (Hersbach et al., 2020) in the 42 year period 1979–2020. These methods consider, for the cyclone center detection, the local maxima of relative vorticity or the local minima of geopotential height or mean sea level pressure (MSLP). For the most recent TLCs (from 2020 onward), not included in the dataset, we considered the ERA5 (Hersbach et al., 2023) local minima of MSLP for the cyclone detection.

To study each cyclone during its lifecycle we have defined two specific times, which correspond respectively to the initial phase (T1) and the mature phase (T2) of each TLC. The former refers to the time of cyclogenesis (i.e., the time at which the cyclone forms), the latter is the time of the minimum value of MSLP during the cyclone lifecycle; each time corresponds to a (different) position.

2.2. SST Data Set

The employed SST dataset is the Mediterranean Sea – High Resolution L4 Reprocessed Sea Surface Temperature product, freely distributed through the Copernicus Marine Service (European Union-Copernicus Marine Service, 2015). This dataset consists of daily (nighttime), multi-sensor optimally interpolated (level-4, L4) estimates of the foundation SST (i.e., the temperature free of diurnal cycle), provided at 0.05° × 0.05° nominal grid resolution and covering the period from 1 January 1982 to present (up to 1 month before real time).

A daily SST climatology, defined as the daily pixel-wise mean over the period 1982–2021, is used to compute daily SST anomalies and detrended SST anomalies. Further information about the dataset and the climatology/anomalies computation are provided in Supporting Information S1.

Following the TLC tracks obtained from the 3 hr ERA5 fields, the corresponding daily SSTs and SST anomalies have been calculated considering the average over squared boxes of 100 km side centered at the points along each track, in order to include the areas where the air–sea interaction is most intense, as well as considering the medicane's dimensions and the typical length scale of relevant mesoscale ocean dynamics. In the cases where a track-point was over land, the nearest track-point over sea was considered.

3. Results and Discussion

3.1. SST Trend and TLCs

The Mediterranean Sea, known for its high sensitivity to climate variability and change (Giorgi, 2006), is experiencing significant warming in SST. Between 1982 and 2023, the Mediterranean SST has increased at a rate of 0.041 ± 0.001°C/year (Figure 1a) (Pisano et al., 2020), nearly four times faster than the global average SST trend of 0.009 ± 0.0006°C/year for the period 1981–2018 (Bulgin et al., 2020).

The spatial distribution of the Mediterranean SST trend (Figure 1a) makes evidence of an uneven warming pattern across the entire basin, the western basin getting warmer at a slower rate than the eastern one. This analysis leads to the identification of a cumulative average warming in 42 years of about 1.47 ± 0.18°C in the western Mediterranean (i.e., between 5°30′W and 10°E), 1.76 ± 0.19°C in the central Mediterranean (i.e., between 10°E and 22°E), and 2.08 ± 0.18°C in the eastern Mediterranean (Levantine-Aegean seas, namely for longitudes greater than 22°E).

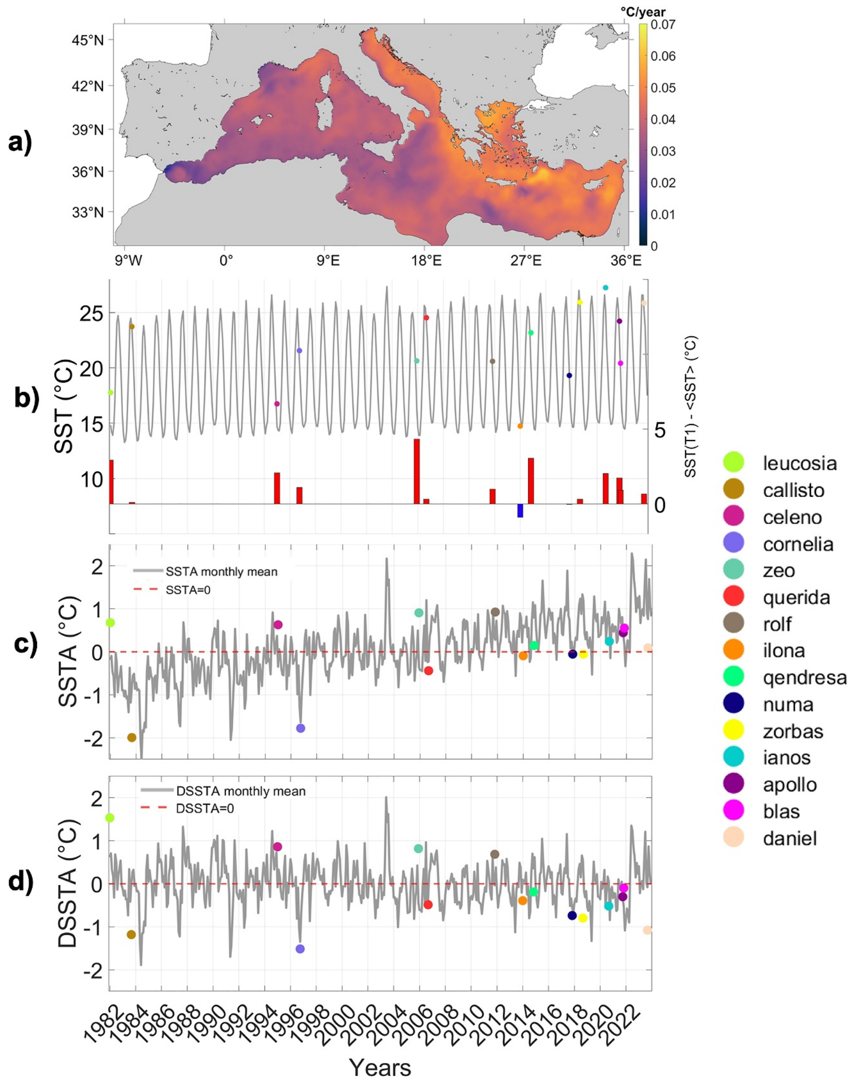

Figure 1. (a) Spatial map of the Mediterranean SST trend (°C/year) over the period 1982–2023; monthly mean time series from 1982 to 2023 spatially averaged between 5°W and 22°E of (b) SST, (c) SSTA and (d) DSSTA. Superimposed on the three time series, 15 points represent the SST (b) and SST anomalies (c), (d) of each medicane at T1. Bar charts in panel (b) indicate, for each TLC, the difference between SST at T1 and the spatially averaged monthly SST; red (blue) colors indicate SSTs warmer (colder) than the monthly average.

Monthly mean SST, SSTA and DSSTA time series are also reported, covering the same period, with 15 points superimposed to represent the absolute (Figure 1b) and anomaly temperature values (Figures 1c and 1d) for each medicane at time T1. This graphical representation provides a global view of the basin-average monthly mean temperatures (computed between 5°W and 22°E, i.e., the region where all the considered TLCs developed), showcasing SST, SSTA and DSSTA values. Obviously, the DSSTA time series (Figure 1d) does not show the linear increase present in the SSTA time series (Figure 1c) owing to the warming trend. The overlaid points allow to highlight the presence of possible patterns of warmer or colder SST (or anomalies in panels c,d) in the TLCs' development areas, compared to the average monthly values calculated on the central and western Mediterranean; vertical bar charts in Figure 1b) further facilitate this assessment.

Most of the cyclones (12 cases) developed with SST values higher than the corresponding basin-average monthly mean SST (Figure 1b). In two cases, SSTs were in line with the average and only one cyclone, Ilona, originated over colder SST compared to the corresponding spatial-averaged monthly mean. A different behavior emerges when detrended anomalies are considered (Figure 1d), with 11 cyclones formed over negative anomalies. It is

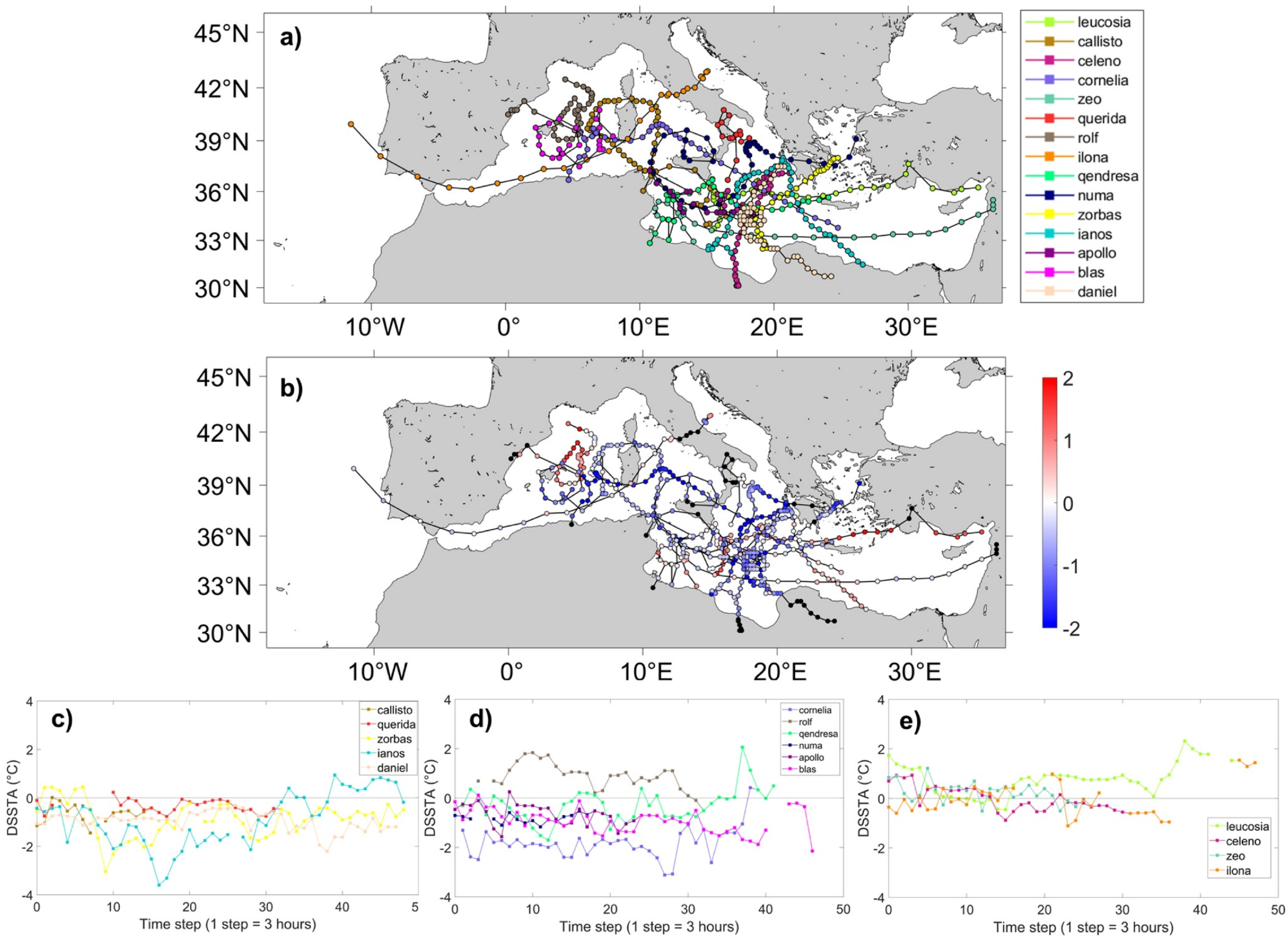

Figure 2. (a) Tracks of the 15 medicanes identified by different colors and (b) DSSTA (°C) along the tracks; black points represent points over land. The three bottom panels show DSSTA track-time series (grouped for months) for TLCs occurring in (c) September, (d) October–November and (e) December–January.

interesting to note the features of some cyclones. Leucosia, Callisto, Celeno, and Cornelia all developed over an area with SST warmer than the basin-average monthly mean (Figure 1b), but the two "autumn" TLCs (Callisto and Cornelia) developed with negative SST anomalies, while the two "winter" TLCs (Leucosia and Celeno) with positive SST anomalies. Ianos and Daniel, two recent TLCs, both developed under very warm sea conditions (Figure 1b) but with slightly negative DSSTA (Figure 1d). This result suggests that, for the development of medicanes, the absolute SST values have a more marked role rather than that of their anomalies.

3.2. TLC Tracks and Along-Track SST Anomaly

The spatial mapping of the 15 tracks shows that almost the whole Mediterranean basin is affected by at least one medicane (Figure 2a) during its lifecycle. Based on the positions at both T1 and T2 times (Table 1, and Figure S1 in Supporting Information S1), it follows that the medicanes considered in this study mainly developed in the central and western Mediterranean basin, with a major concentration in the Ionian Sea (nine events). None of the considered events developed in the Levantine–Aegean Sea or in the Adriatic Sea. Most events occurred in the months of September–October–November (11), while only a small fraction in December–January (4), confirming the marked seasonality of these events known from climatological studies (Cavicchia et al., 2014; Tous & Romero, 2012; Zhang et al., 2021).

Along their path, the medicanes crossed marine areas with predominantly negative DSSTA (predominant bluish colors, Figure 2b); analogous considerations hold when considering SSTA (Figure S2 in Supporting Information S1). Few exceptions refer to the December-January TLCs (Figure 2e), mainly developing in a positive

Table 1
List of the Selected Medicanes

	T1					T2					
Name	Time [dd/mm/yy hh]	LON-LAT [°]	SST [°C]	DSSTA [°C]	SSTA [°C]	Time [dd/mm/yy hh]	LON-LAT [°]	SST [°C]	DSSTA [°C]	SSTA [°C]	△SST [°C]
Leucosia	23/01/82 12	15.52–33.76	17.76	1.53	0.68	25/01/82 03	15.60–35.98	14.67	−0.05	−0.74	−0.43
Callisto	26/09/83 09	17.30–34.96	23.72	−1.18	−1.99	27/09/83 18	10.95–37.09	22.90	−0.55	−1.36	−1.45
Celeno	13/01/95 00	16.56–36.06	16.75	0.86	0.63	14/01/95 15	19.48–36.90	15.67	0.11	−0.19	−0.97
Cornelia	06/10/96 06	4.76–37.22	21.55	−1.51	−1.78	07/10/96 03	5.85–39.17	20.87	−1.79	−2.19	−2.67
Zeo	13/12/05 03	14.02–32.93	20.63	0.82	0.91	14/12/05 03	13.05–34.48	19.09	0.28	0.35	−1.90
Querida	26/09/06 00	16.58–36.68	24.53	−0.49	−0.44	26/09/06 12	16.64–40.47	23.83	−0.37	−0.25	−0.76
Rolf	04/11/11 18	0.19–40.49	20.59	0.69	0.92	04/11/11 18	0.19–40.49	20.59	0.69	0.92	−1.63
Ilona	18/01/14 21	−11.50–39.96	14.74	−0.39	−0.09	19/01/14 09	−2.55–36.15	15.52	−0.15	0.21	−0.27
Qendresa	06/11/14 03	11.16–33.45	23.17	−0.19	0.15	07/11/14 09	12.39–36.00	20.69	−1.22	−0.89	−1.80
Numa	14/11/17 00	13.51–39.62	19.31	−0.74	−0.05	14/11/17 00	13.51–39.62	19.31	−0.74	−0.05	−1.12
Zorbas	27/09/18 00	18.85–33.21	25.93	−0.80	−0.05	28/09/18 03	18.79–33.93	24.17	−2.22	−1.52	−3.09
Ianos	15/09/20 00	16.83–32.22	27.24	−0.52	0.24	17/09/20 03	17.60–36.69	23.66	−2.85	−2.09	−2.40
Apollo	24/10/21 00	13.00–35.00	24.22	−0.30	0.44	28/10/21 06	16.00–34.75	23.64	−0.65	0.10	−1.19
Blas	07/11/21 06	8.00–39.25	20.42	−0.10	0.55	11/11/21 06	3.25–40.00	19.18	−1.08	−0.38	−2.31
Daniel	04/09/23 18	20.75–37.50	25.86	−1.08	0.09	11/09/23 00	23.00–31.00	26.13	−1.29	−0.33	−1.24
MEAN			***21.76***	***−0.23***	***0.01***			***20.66***	***−0.79***	***−0.56***	***−1.55***

Note. The table reports the names, the dates (hours in UTC), the positions (longitude-latitude), the SST values, the SST anomalies (both detrended and not detrended), and the difference in SST (from T2 −5 days to T2 +5 days). All the information is provided for both T1 and T2 times. Last row (bold-italic values) refers to the average values of the corresponding columns.

detrended SST anomaly environment. Recently, Gutierrez-Fernandez et al. (2024) showed that two of these cyclones (Celeno and Leucosia) have peculiar characteristics, with features similar to polar lows (sensible heat fluxes larger than latent heat fluxes). Considering their occurrence in January, we can hypothesize that the SST needs to be somehow above average to determine a vertical temperature gradient with the upper troposphere sufficient to trigger intense convection (Palmen, 1948).

Table 1 reports the list of the TLCs considered in the study. For each cyclone, the SST and anomaly values (SSTA and DSSTA) are calculated at both T1 and T2 times, considering the average in a box of 100 × 100 km centered at the T1/T2 positions. Furthermore, the table reports the SST difference from 5 days before to 5 days after the mature phase (averaged in a 100 km wide box centered at T2). The cyclogenesis occurred, on average, over SSTs of 21.8°C, in agreement with previous findings (Tous et al., 2013), and with a weak negative DSSTA of −0.2°C; in their mature phases the TLCs evolve in the presence of larger negative DSSTAs, on average of −0.8°C, due to the larger extraction of heat from the sea when the cyclone is stronger.

A limited number of cyclones developed over positive DSSTA. These cases are mainly winter events growing in their initial phase over the Ionian Sea (i.e., Leucosia, Celeno, and Zeo), with the only exception of Rolf that developed in November over the Balearic Islands. Two events are characterized by a clearly (early-stage) negative DSSTA: Callisto and Cornelia. Since these events occurred at the beginning of the considered time series, the detrending has a stronger effect and the negative anomaly is even more intense if we consider the SSTA value. Conversely, the most recent cyclone Daniel develops in an environment with a slightly positive SSTA (0.1°C) but, once the trend is removed, it presents a negative DSSTA (−1.1°C). Hence, no positive detrended SST anomalies are needed for the generation of medicanes although, as suggested by previous studies, a higher SST value may be favorable to their intensification (Miglietta et al., 2011; Pytharoulis, 2018).

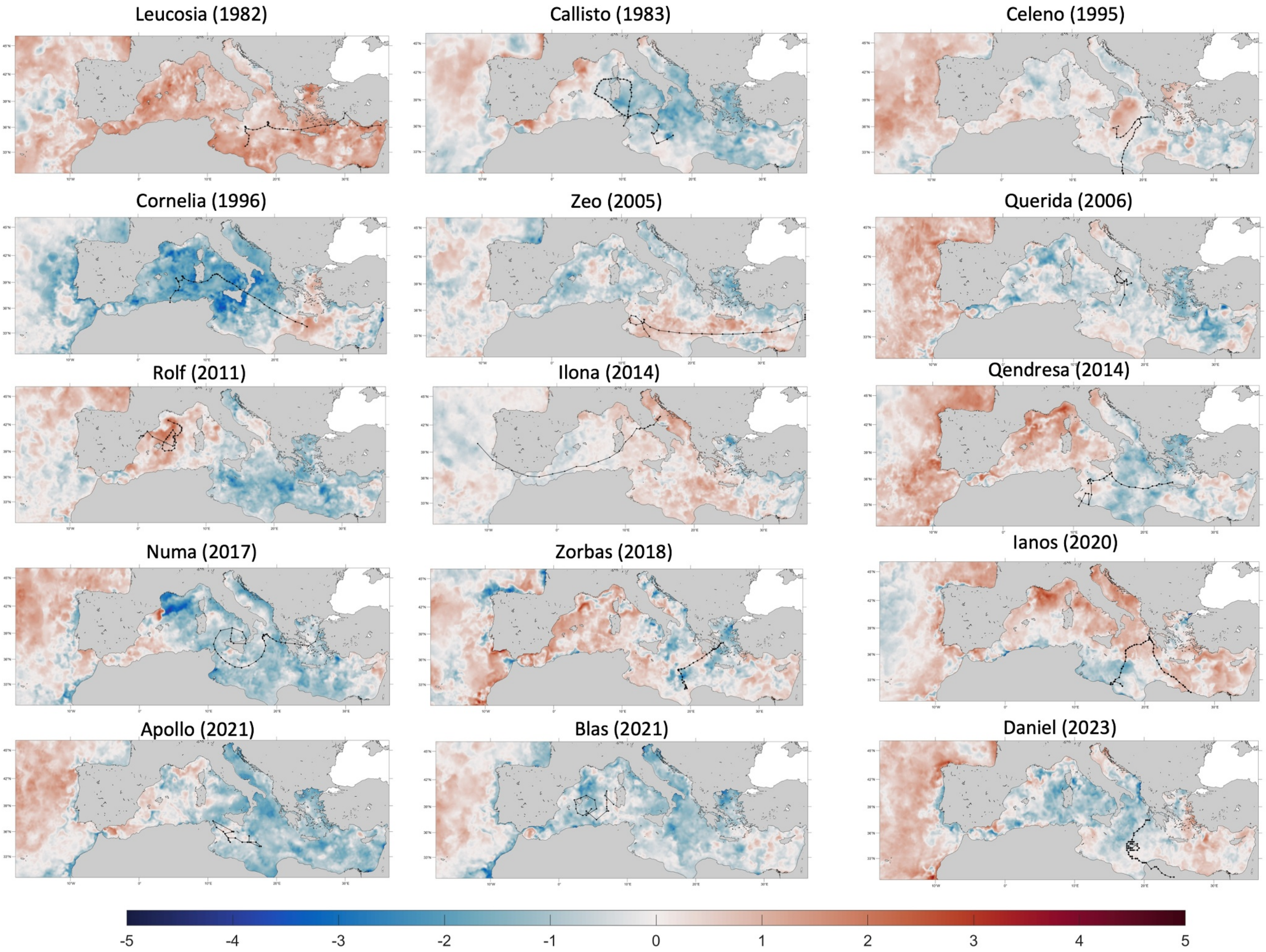

Figure 3. Spatial map of DSSTA (°C) at time T1 for each medicane with its (time-varying) trajectory overlaid on each map.

3.3. TLCs in the Early Stage

A comprehensive view of the spatial anomaly distribution over which all TLCs developed is depicted in Figure 3. While the DSSTA fields are shown for a fixed time (T1), the overlaid cyclone trajectory occurs over a time-evolving SST; however, this representation allows us to assess:

1. the prevailing presence of small negative DSSTA in the cyclone triggering phases (in agreement with Table 1).
2. a moderate positive DSSTA for the winter TLCs.

For completeness, we report a similar figure for SSTA (Figure S3 in Supporting Information S1), from which a more pronounced positive anomaly can be seen for many events.

Particular attention should be paid to three very intense cyclones: Ianos (Lagouvardos et al., 2022), Rolf (Ricchi et al., 2017), and Zorbas (Portmann et al., 2020). Only Rolf developed on positive detrended SST anomalies, while for Ianos and Zorbas the values were slightly negative at T1; however, anomalies for Ianos and Zorbas became strongly negative at T2 (Table 1). Our interpretation is that Zorbas and Ianos extracted a lot of energy from the Mediterranean Sea during their intensification phase; these cyclones developed over the far south Mediterranean Sea in September, when the SST beneath them was still high, even if the anomaly was negative; by their mature stage, they have already cooled down the sea (thus the anomalies at T2 were strongly negative; see Figure S4 in Supporting Information S1). Apparently, for these intense TLCs, the high SST values were favorable for their strong intensification and no positive anomaly was needed. Our results do not contradict the presence of a positive SST anomaly in Ianos (near Greece, as mentioned in Lagouvardos et al., 2022), since this was present at

T1 (Figure 3). However, when the cyclone moved toward Greece and reached its mature stage (T2), the SST anomaly below the cyclone was negative.

3.4. TLCs in the Mature Phase: Cooling Effect

In this section we discuss the SST cooling from 5 days before to 5 days later, centered at each T2 time/position for all TLCs (thus covering the longest-lasting cyclone lifetime). The time series in Figure S4 (Supporting Information S1) represents the change in SST due to the extraction of energy from the sea surface by the cyclone, also favored by the increase of vorticity and wind speed in the mature stage. The curves confirm, for Zorbas and Ianos, the most evident cooling in the areas of maximum cyclone intensity, both considering DSSTA and SSTA. A cooling of the upper-ocean layers has been observed and simulated in several medicanes (Bouin & Lebeaupin Brossier, 2020; Ricchi et al., 2017; Varlas et al., 2020). The synergistic combination of intense water evaporation, vertical mixing mechanisms, and mixed layer uplift induced by the intense wind associated with TLCs, may determine a SST cooling along the TLC's trajectories (Kassis & Varlas, 2021; Menna et al., 2023). Scardino et al. (2024) have assessed that the thermal drops of some medicanes at different water depths may occur already before the time of cyclogenesis. As discussed in Miglietta et al. (2021), some medicanes, like Zorbas or Cornelia, show strong sea surface fluxes not directly related to the cyclonic circulation, but associated with mesoscale wind outbreaks over the Mediterranean induced by topographic features, that contribute to create a favorable environment for the intensification of the cyclones already before their development. Finally, a short discussion about the possible relationship between the cooling and the (monthly) mixed layer depth (MLD) is provided in Supporting Information S1.

Figure 4 permits evaluating the cooling effects associated with TLCs considering the whole Mediterranean basin. Each panel shows the 10-day difference in SST centered at time T2. On average, the medicane-induced cooling effect (at T2 time/position) is −1.6°C (Table 1); some "autumn" cases (Callisto, Cornelia, Qendresa, Zorbas, Ianos, Daniel and Blas) exhibiting an even more pronounced cooling (on average −2.1°C). This is not unexpected, considering that these cyclones are among the most intense, developing over warmer SST, and therefore the ones that drain more energy from the sea to the atmosphere.

It is interesting to note some analogies and differences between three cyclones (Zorbas, Ianos and Daniel) all occurring in September and affecting the same area. In particular, these cyclones exhibit the highest (similar) early-stage SST: 25.9°C (at T1) for Zorbas and Daniel, 27.2°C (at T1) for Ianos, and a similar early-stage negative DSSTA (about −0.8°C, on average). At the same time, the SST pattern and cooling are different: for the Daniel case, a prevailing negative SST anomaly at T1 is visible over the whole basin, while in the other two cases the anomaly is negative near the development area, but positive in the rest of the basin (Figure 3); also, the cooling at T2 over the sea affects the whole basin for Zorbas (this abrupt surface cooling was also studied by Kassis & Varlas, 2021), while for the other two TLCs, the cooling is confined in the area crossed by the cyclones (Figure 4).

4. Conclusions

Results suggest that the SST anomaly does not play a significant role in the development of Mediterranean cyclones. In fact, the SST anomaly at the early stage is on average nearly zero. This result aligns with Cavicchia et al. (2014), who found no significant SST anomalies where the cyclones developed. Also, the most intense (Autumn) cases developed over high SST values, with small (often negative) SST anomaly; this result is consistent with the results of several sensitivity studies (e.g., Bouin & Lebeaupin Brossier, 2020; Miglietta et al., 2011; Varlas et al., 2023) which shows that a higher SST values (though not necessarily anomalous) favor the development of the most intense cyclones.

On average, the medicanes analyzed are distributed in the whole basin, but with a major concentration in the Ionian Sea. They most frequently occur in the months of September–October–November (11 cases out of 15). Along their path, the TLCs cross marine areas with predominantly negative SST anomalies; this means that a positive SST anomaly is not necessary for the development of medicanes. In particular: the TLCs develop, on average, over SSTs of 21.8°C and with a (weak) negative detrended SST anomaly of −0.2°C. For a few winter cases, local positive SST anomalies of a few °C are observed, thus they contribute to the instability and the intensification of these cyclones, which show characteristics similar to polar lows.

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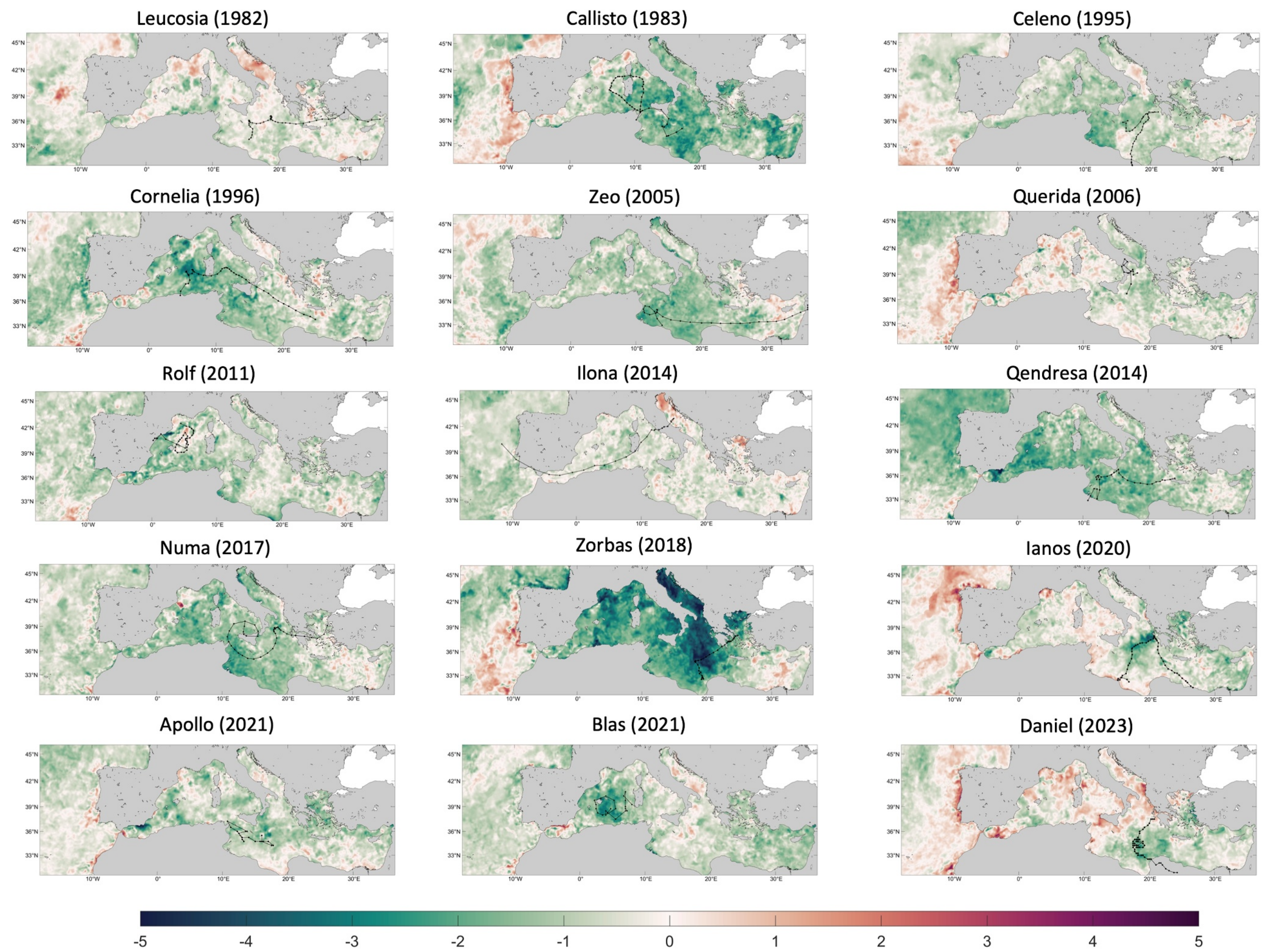

Figure 4. Spatial map of difference (from T2 −5 days to T2 +5 days) in SST (°C) for each medicane with its (time-varying) trajectory overlaid on each map.

The cyclones extract energy from the sea, so that a cold anomaly is left after their passage. A general cooling is present for each TLC (on average an SST difference of −1.6°C is observed between the cyclogenesis and after the mature stage).

During cyclone formation, DSSTA is predominantly negative for most of the medicanes studied (11 out of 15). In contrast, SSTA shows an increasing trend from negative to positive over the 1982–2023 period, reflecting the influence of the warming trend, which is eliminated upon detrending (Figures 1c and 1d). The occurrence of the most intense cyclones over warmer SST (early Fall) suggests that their intensification may be enhanced under climate change conditions; this assessment aligns with prior research findings (e.g., Gonzalez-Aleman et al., 2019; Koseki et al., 2021).

While detrending separates the impact of climate change on SST, a comprehensive analysis of climate variability should include the possible contributions of leading climate modes influencing the Mediterranean region, such as the North Atlantic Oscillation (NAO) and the Atlantic Multidecadal Oscillation (AMO) (see, e.g., Criado-Aldeanueva & Soto-Navarro, 2020), to the detrended SST signal. This topic could be covered by future investigation.

Data Availability Statement

The considered dataset for the ERA5 reanalysis is the "ERA5 hourly data on single levels from 1940 to present" (Hersbach et al., 2023).

Composite cyclone tracks are derived by Flaounas et al. (2023). Data are provided as a Supplement in ASCII format (Supplement of Weather Clim. Dynam., 4, 639–661, 2023, https://doi.org/10.5194/wcd-4-639-2023-supplement).

The Mediterranean Sea L4 Sea Surface Temperature Reprocessed dataset is publicly available through the Copernicus Marine Service (European Union-Copernicus Marine Service, 2015) with product name SST_MED_SST_L4_REP_OBSERVATIONS_010_021.

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References

Bouin, M.-N., & Lebeaupin Brossier, C. (2020). Impact of a medicane on the oceanic surface layer from a coupled, kilometre-scale simulation. *Ocean Science*, *16*(5), 1125–1142. https://doi.org/10.5194/os-16-1125-2020

Bulgin, C. E., Merchant, C. J., & Ferreira, D. (2020). Tendencies, variability and persistence of sea surface temperature anomalies. *Scientific Reports*, *10*(1), 7986. https://doi.org/10.1038/s41598-020-64785-9

Cavicchia, L., von Storch, H., & Gualdi, S. (2014). A long-term climatology of medicanes. *Climate Dynamics*, *43*(5–6), 1183–1195. https://doi.org/10.1007/S00382-013-1893-7/FIGURES/13

Criado-Aldeanueva, F., & Soto-Navarro, J. (2020). Climatic indices over the Mediterranean Sea: A review. *Applied Sciences*, *10*(17), 5790. https://doi.org/10.3390/app10175790

Emanuel, K. (2005). Genesis and maintenance of Mediterranean hurricanes. *Advances in Geosciences*, *2*, 217–220. https://doi.org/10.5194/adgeo-2-217-2005

European Union-Copernicus Marine Service. (2015). Mediterranean Sea - high resolution L4 Sea Surface temperature reprocessed. *Mercator Ocean International*. [Dataset]. https://doi.org/10.48670/MOI-00173

Flaounas, E., Aragão, L., Bernini, L., Dafis, S., Doiteau, B., Flocas, H., et al. (2023). A composite approach to produce reference datasets for extratropical cyclone tracks: Application to mediterranean cyclones. *Weather and Climate Dynamics*, *4*(3), 639–661. https://doi.org/10.5194/wcd-4-639-2023

Flaounas, E., Davolio, S., Raveh-Rubin, S., Pantillon, F., Miglietta, M. M., Gaertner, M. A., et al. (2022). Mediterranean cyclones: Current knowledge and open questions on dynamics, prediction, climatology and impacts. *Weather and Climate Dynamics*, *3*(1), 173–208. https://doi.org/10.5194/wcd-3-173-2022

Giorgi, F. (2006). Climate change hot-spots. *Geophysical Research Letters*, *33*, 8. https://doi.org/10.1029/2006GL025734

González-Alemán, J. J., Pascale, S., Gutierrez-Fernandez, J., Murakami, H., Gaertner, M. A., & Vecchi, G. A. (2019). Potential increase in hazard from mediterranean Huriicane activity with global warming. *Geophysical Research Letters*, *46*(3), 1754–1764. https://doi.org/10.1029/2018GL081253

Gutiérrez-Fernández, J., Miglietta, M. M., González-Alemán, J. J., & Gaertner, M. A. (2024). A new refinement of Mediterranean tropical-like cyclones characteristics. *Geophysical Research Letters*, *51*(8), e2023GL106429. https://doi.org/10.1029/2023GL106429

Hersbach, H., Bell, B., Berrisford, P., Biavati, G., Horányi, A., Muñoz Sabater, J., et al. (2023). ERA5 hourly data on single levels from 1940 to present. *Copernicus Climate Change Service (C3S) Climate Data Store (CDS)*. [Dataset]. https://doi.org/10.24381/cds.adbb2d47

Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., et al. (2020). The ERA5 global reanalysis. *The Quarterly Journal of the Royal Meteorological Society*, *146*(730), 1999–2049. https://doi.org/10.1002/qj.3803

Kassis, D., & Varlas, G. (2021). Hydrographic effects of an intense "medicane" over the central-eastern Mediterranean Sea in 2018. *Dynamics of Atmospheres and Oceans*, *93*, 101185. https://doi.org/10.1016/j.dynatmoce.2020.101185

Koseki, S., Mooney, P. A., Cabos, W., Gaertner, M. Á., de la Vara, A., & González-Alemán, J. J. (2021). Modelling a tropical-like cyclone in the Mediterranean Sea under present and warmer climate. *Natural Hazards and Earth System Sciences*, *21*(1), 53–71. https://doi.org/10.5194/nhess-21-53-2021

Lagouvardos, K., Karagiannidis, A., Dafis, S., Kalimeris, A., & Kotroni, V. (2022). Ianos – a hurricane in the mediterranean. *Bulletin of the American Meteorological Society*, *103*(6), E1621–E1636. https://doi.org/10.1175/BAMS-D-20-0274.1

McTaggart-Cowan, R., Davies, E. L., Fairman, J. G., Galarneau, T. J., & Schultz, D. M. (2015). Revisiting the 26.5°C sea surface temperature threshold for tropical cyclone development. *Bulletin of the American Meteorological Society*, *96*(11), 1929–1943. https://doi.org/10.1175/bams-d-13-00254.1

Menna, M., Martellucci, R., Reale, M., Cossarini, G., Salon, S., Notarstefano, G., et al. (2023). A case study of impacts of an extreme weather system on the Mediterranean Sea circulation features: Medicane Apollo (2021). *Scientific Reports*, *13*(1), 3870. https://doi.org/10.1038/s41598-023-29942-w

Miglietta, M. M., Carnevale, D., Levizzani, V., & Rotunno, R. (2021). Role of moist and dry air advection in the development of Mediterranean tropical-like cyclones (medicanes). *Quarterly Journal of the Royal Meteorological Society*, *147*(735), 876–899. https://doi.org/10.1038/s41598-024-58335-w

Miglietta, M. M., Laviola, S., Malvaldi, A., Conte, D., Levizzani, V., & Price, C. (2013). Analysis of tropical-like cyclones over the Mediterranean Sea through a combined modeling and satellite approach. *Geophysical Research Letters*, *40*(10), 2400–2405. https://doi.org/10.1002/grl.50432

Miglietta, M. M., Moscatello, A., Conte, D., Mannarini, G., Lacorata, G., & Rotunno, R. (2011). Numerical analysis of a Mediterranean 'hurricane' over South-Eastern Italy: Sensitivity experiments to sea surface temperature. *Atmospheric Research*, *101*(1–2), 412–426. https://doi.org/10.1016/J.ATMOSRES.2011.04.006

Palmen, E. (1948). On the formation and structure of tropical cyclones. *Geophysica*, *3*, 26–38.

Pisano, A., Marullo, S., Artale, V., Falcini, F., Yang, C., Leonelli, F. E., et al. (2020). New evidence of mediterranean climate change and variability from Sea Surface temperature observations. *Remote Sensing*, *12*(1), 132. https://doi.org/10.3390/rs12010132

Portmann, R., González-Alemán, J. J., Sprenger, M., & Wernli, H. (2020). How an uncertain short-wave perturbation on the North Atlantic wave guide affects the forecast of an intense Mediterranean cyclone (Medicane Zorbas). *Weather and Climate Dynamics*, *1*(2), 597–615. https://doi.org/10.5194/wcd-1-597-2020

Pytharoulis, I. (2018). Analysis of a Mediterranean tropical-like cyclone and its sensitivity to the sea surface temperatures. *Atmospheric Research*, *208*, 167–179. https://doi.org/10.1016/J.ATMOSRES.2017.08.009

Ricchi, A., Miglietta, M. M., Barbariol, F., Benetazzo, A., Bergamasco, A., Bonaldo, D., et al. (2017). Sensitivity of a Mediterranean tropical-like cyclone to different model configurations and coupling strategies. *Atmosphere*, *8*(5), 92. https://doi.org/10.3390/ATMOS8050092

Scardino, G., Miglietta, M. M., Kushabaha, A., Casella, E., Rovere, A., Besio, G., et al. (2024). Fingerprinting Mediterranean hurricanes using pre-event thermal drops in seawater temperature. *Scientific Reports*, *14*(1), 8014. https://doi.org/10.1038/s41598-024-58335-w

Tous, M., & Romero, R. (2012). Meteorological environments associated with medicane development. *International Journal of Climatology*, *33*(1), 1–14. https://doi.org/10.1002/joc.3428

Tous, M., Romero, R., & Ramis, C. (2013). Surface heat fluxes influence on medicane trajectories and intensification. *Atmospheric Research*, *123*, 400–411. https://doi.org/10.1016/J.ATMOSRES.2012.05.022

Varlas, G., Pytharoulis, I., Steeneveld, G.-J., Katsafados, P., & Papadopoulos, A. (2023). Investigating the impact of sea surface temperature on the development of the Mediterranean tropical-like cyclone "Ianos" in 2020. *Atmospheric Research*, *291*, 106827. https://doi.org/10.1016/j.atmosres.2023.106827

Varlas, G., Vervatis, V., Spyrou, C., Papadopoulou, E., Papadopoulos, A., & Katsafados, P. (2020). Investigating the impact of atmosphere–wave–ocean interactions on a Mediterranean tropical-like cyclone. *Ocean Modelling*, *153*, 101675. https://doi.org/10.1016/j.ocemod.2020.101675

Zhang, W., Villarini, G., Scoccimarro, E., & Napolitano, F. (2021). Examining the precipitation associated with medicanes in the high-resolution ERA-5 reanalysis data. *International Journal of Climatology*, *41*(S1), E126–E132. https://doi.org/10.1002/JOC.6669

References From the Supporting Information

Amaya, D. J., Jacox, M. G., Fewings, M. R., Saba, V. S., Stuecker, M. F., Rykaczewski, R. R., et al. (2023). Marine heatwaves need clear definitions so coastal communities can adapt. *Nature*, *616*(7955), 29–32. https://doi.org/10.1038/d41586-023-00924-2

Boyer, M. C. (2024). *Mixed layer depth over the global ocean: A climatology computed with a density threshold criterion of 0.03 kg/m3 from the value at the reference depth of 5 m*. SEANOE. https://doi.org/10.17882/98226

Dunn, R. J., & Morice, C. P. (2022). On the effect of reference periods on trends in percentile-based extreme temperature indices. *Environmental Research Letters*, *17*(3), 034026. https://doi.org/10.1088/1748-9326/ac52c8

Fita, L., Romero, R., Luque, A., Emanuel, K., & Ramis, C. (2007). Analysis of the environments of seven Mediterranean tropical-like storms using an axisymmetric, nonhydrostatic, cloud resolving model. *Natural Hazards and Earth System Sciences*, *7*(1), 41–56. https://doi.org/10.5194/NHESS-7-41-2007

Homar, V., Romero, R., Stensrud, D. J., Ramis, C., & Alonso, S. (2003). Numerical diagnosis of a small, quasi-tropical cyclone over the western Mediterranean: Dynamical vs. boundary factors. *Quarterly Journal of the Royal Meteorological Society*, *129*(590), 1469–1490. https://doi.org/10.1256/QJ.01.91

Houpert, L., Testor, P., De Madron, X. D., Somot, S., D'ortenzio, F., Estournel, C., & Lavigne, H. (2015). Seasonal cycle of the mixed layer, the seasonal thermocline and the upper-ocean heat storage rate in the Mediterranean Sea derived from observations. *Progress in Oceanography*, *132*, 333–352. https://doi.org/10.1016/j.pocean.2014.11.004

Lim, Y. K., Schubert, S. D., Kovach, R., Molod, A. M., & Pawson, S. (2018). The roles of climate change and climate variability in the 2017 Atlantic hurricane season. *Scientific Reports*, *8*(1), 16172. https://doi.org/10.1038/s41598-018-34343-5

Martínez, J., Leonelli, F. E., García-Ladona, E., Garrabou, J., Kersting, D. K., Bensoussan, N., & Pisano, A. (2023). Evolution of marine heatwaves in warming seas: The Mediterranean Sea case study. *Frontiers in Marine Science*, *10*, 1193164. https://doi.org/10.3389/fmars.2023.1193164

Merchant, C. J., Embury, O., Bulgin, C. E., Block, T., Corlett, G. K., Fiedler, E., et al. (2019). Satellite-based time-series of sea-surface temperature since 1981 for climate applications. *Scientific Data*, *6*(1), 223. https://doi.org/10.1038/s41597-019-0236-x

Reed, R. J., Kuo, Y. H., Albright, M. D., Gao, K., Guo, Y. R., & Huang, W. (2001). Analysis and modeling of a tropical-like cyclone in the Mediterranean Sea. *Meteorog. Atmos. Phys.*, *76*(1–4), 183–202. https://doi.org/10.1007/S007030170029/METRICS

Sanchez, C., Gray, S., Volonte, A., Pantillon, F., Berthou, S., & Davolio, S. (2023). How a warmer Mediterranean preconditions the upper-level environment for the development of Medicane Ianos. *EGUsphere*. [preprint]. https://doi.org/10.5194/egusphere-2023-2431

Stathopoulos, C., Patlakas, P., Tsalis, C., & Kallos, G. (2020). The role of sea surface temperature forcing in the life-cycle of mediterranean cyclones. *Remote Sensing*, *12*(5), 825. https://doi.org/10.3390/RS12050825