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OESCHGER CENTRE
CLIMATE CHANGE RESEARCH

Quasi-stationary Mediterranean Cyclones

MASTER'S THESIS

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HANDED IN BY

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January, 2025

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Abstract

As one of the most active cyclone birth- and transit places in the world, the Mediterranean is frequently affected by (persisting) weather extremes, in which regard quasi-stationary cyclones play an important role. Despite numerous classification schemes, hardly any classifies Mediterranean cyclones according to their stationarity. For this purpose, we apply several stationarity definitions based on propagation speed and spatial distance to composite tracks found in ERA5 of the period 1979-2020. Each definition results in three stationarity classes that are characterized in terms of intensity, duration and spatial distribution.

Firstly, we find that a definition's perspective on the track of a cyclone can have a decisive effect on the results. In our case, considering the full track (FT) reveals the average characteristics of cyclone propagation whereas the inclusion of only 12-hour track sections (AT) captures more of its subtle variations. By the latter (AT), many more cyclones are identified as quasi-stationary instead of their entire tracks (FT). Moreover, quasi-stationary cyclones tend to be shallow rather than deep based on their distances and are detected by all definitions at the most clearly defined hotspots, including the Gulf of Genoa, the eastern Black Sea, the coast of Turkey and Northern Africa. Secondly, our case studies highlight the importance of the context of a cyclone's occurrence in determining which stationarity characteristics can be identified by a certain method. This becomes particularly important regarding the severe weather potential of quasi-stationary cyclones in the Mediterranean. Finally, our findings open the way for investigating the atmospheric large- and small-scale features as well as the surface impacts that are associated with a certain stationarity type of a Mediterranean cyclone.

1 Introduction

The Mediterranean is exceptionally interesting in the field of atmospheric and climate sciences. Located between the mid-latitudes and the tropics, the region is characterized by a highly variable climate. Strong fluctuations in the water balance prevail here, with dry periods interrupted by intense, recurring heavy rains, which occur sporadically in Summer, but most often in Winter (Tuel and Martius, 2023). In fact, heavy rains are so frequent and devastating among the weather extremes, that they are regarded as ”meteorological hazard of highest negative impact” in the region (Mastrantonas et al., 2020).

In this context, cyclones play a decisive role (Lionello et al., 2006; Givon et al., 2024). Locally, Mediterranean cyclones account for over two thirds of the total annual precipitation and are therefore crucial for the region's water supply (Lionello et al., 2006; Michaelides et al., 2018; Flaounas et al., 2022). At the same time, Mediterranean cyclones have a great potential for high-impact weather and trigger the majority of torrential rain, as well as most floods resulting from it (Mastrantonas et al., 2020; Flaounas et al., 2022). Therefore, the region's inhabitants and their living places are both heavily dependent on the occurrence of Mediterranean cyclones and threatened by them.

Previous studies have shown that the severity and frequency of extreme weather brought by a cyclone depends crucially on the latter's temporal and spatial occurrence (Michaelides et al., 2018; Schultz et al., 2019; Mastrantonas et al., 2020; Flaounas et al., 2022). For example, the majority of the Mediterranean cyclonic systems form in winter season, especially deep systems, which is also the time when most of extreme precipitation affects the area (Campins et al., 2011; Mastrantonas et al., 2020).

In addition, the Mediterranean is known worldwide as a hotspot for cyclogenesis, especially lee cyclogenesis (Lionello et al., 2006; Flaounas et al., 2022). Consequently, intense precipitation events triggered by cyclones occur remarkably often in the vicinity of the region's mountain ranges (Campins et al., 2011; Michaelides et al., 2018; Mastrantonas et al., 2020). In this way, the demanding weather phenomena occurring in the Mediterranean not only shape the complex terrain that surrounds the basin, but are themselves also significantly influenced by it.

In recent years, many studies have attempted to classify Mediterranean cyclones on the basis of the above-mentioned characteristics, that is to say seasonality (Lionello et al., 2006; Flaounas et al., 2022; Doiteau et al., 2024, preprint), position Lionello et al. (2006);

Campins et al. (2011); Lionello et al. (2016); Flaounas et al. (2022); Doiteau et al. (2024, preprint) but also intensity Lionello et al. (2006); Campins et al. (2011); Lionello et al. (2016); Flaounas et al. (2022); Doiteau et al. (2024, preprint) and formation mechanisms such as large-scale dynamics (Lionello et al., 2006; Flaounas et al., 2022; Givon et al., 2024). However, direct conclusions from such cyclone characteristics to weather extremes are often misleading. For example, regarding the severity of the weather brought by a cyclone, it is not always just deep cyclones but also shallow ones that can trigger heavy rainfall in the region (Michaelides et al., 2018; Flaounas et al., 2022). The link between extreme weather conditions and the Mediterranean cyclone type that triggers them is therefore still an open question.

Interesting is now to look at the frequency of extreme weather events in the Mediterranean. Mastrantonas et al. (2020) discovered, that torrential rainfall at one location in the Mediterranean is often followed by a second event within only a short amount of time. From this, the authors concluded, that such extreme precipitation events may be supported by persistent atmospheric conditions.

Indeed, in November 2001 and September 2023, respectively, two cyclones (the first analyzed in more detail in Section 3.3.1, latter with tropical-like characteristics and named Medicane Daniel) have had devastating effects in the Mediterranean, mainly due to intense and long-lasting precipitation (Tripoli et al., 2005; Flaounas et al., 2024; Hewson et al., 2024). Both cyclones have been particularly notable for being slowly propagating and long-lived (Tripoli et al., 2005; MedCyclones, 2023; Hewson et al., 2024), which in technical jargon is referred to as "weather persistence", more precisely "quasi-stationarity". This term describes the characteristic of an atmospheric system to hardly change its state over a prolonged period of time (Tuel and Martius, 2023).

Such quasi-stationary systems like the cyclones described above increasingly moved into the focus of the scientific community due to their great potential for extreme surface weather (Tripoli et al., 2005; Campins et al., 2011; Flaounas et al., 2024). However, apart from the approach used by Doiteau et al. (2024, preprint) there are hardly any classifications that deal specifically with the stationarity of cyclones.

Therefore, this master's thesis is dedicated to the study of possible methods for identifying the (quasi-) stationarity of Mediterranean cyclones. The aim is to classify the cyclones of the dataset using different stationarity definitions to find the most persistent tracks in time and space. One approach to apply is that of Doiteau et al. (2024, preprint), which analyzed the mobility of Mediterranean cyclones based on the median speed during their whole life cycles. Further, we test alternative stationarity definitions, including those that focus only on sections of the cyclone tracks instead of the whole.

The guiding research questions for this thesis are:

- What are the characteristics of the quasi-stationary tracks found in the dataset (i.e. maximum intensity, total duration and spatial distribution)?
- To what extent do different definitions of stationarity affect the identified tracks?

In the following, Section 2 presents the dataset used in this study to examine the research questions posed above. In addition, the methods for defining and analyzing (quasi-) stationarity are introduced. Section 3 illustrates and discusses the results and summarizes them in Table 2. Finally, Section 4 concludes the study and provides an outlook on future research on the topic.

2 Data and Methods

2.1 Mediterranean Cyclone Tracks

The dataset used in this master's thesis was created by Flaounas et al. (2023). Their aim was to produce reference datasets of extratropical cyclone tracks that combine the results of different climatological studies in the field. As a start, they collected tracks previously found by several individual cyclone detection and tracking methods (CDTMs) applied to ERA5 reanalysis. From the collection of tracks, they kept only those that are the most common or overlap. The result are composite tracks that have a certain level of robustness, the latter being higher the more individual CDTMs agree on the same tracks. However, with a higher robustness or confidence level of the dataset also the number of artifacts (incorrectly identified, i.e. false positive) and wrongly overlooked (false negative) cyclone tracks increases (Flaounas et al., 2023). Therefore, and based on the authors' recommendation for the nature of our study we work with a dataset of confidence level 5 containing 3808 cyclone tracks.

In terms of time and space, our data covers the years 1979-2020 and the Mediterranean region in a 0.25 x 0.25° resolution (longitude, latitude). Table 1 below provides an excerpt of the dataset structure. Each individual track point (row index) of a cyclone (id) represents its center as the pressure minimum (hPa) at a specific step in time (year, month, day, time) and space (lon, lat). Figure 1 shows the resulting spatial distribution of the cyclones tracks contained in the composite.

Table 1: Excerpt of the composite dataset by Flaounas et al. (2023).

	id	lon	lat	year	month	day	time	hPa
0	1	-17.75	48.12	1979	1	3	1	995.45
1	1	-17.45	48.16	1979	1	3	2	993.78
2	1	-16.98	48.14	1979	1	3	3	992.60
3	1	-16.34	48.08	1979	1	3	4	991.93
...	...	...	...	...	...	...	...	...
267343	3808	16.31	28.43	2020	3	19	19	1011.14
267344	3808	16.53	28.22	2020	3	19	20	1012.01

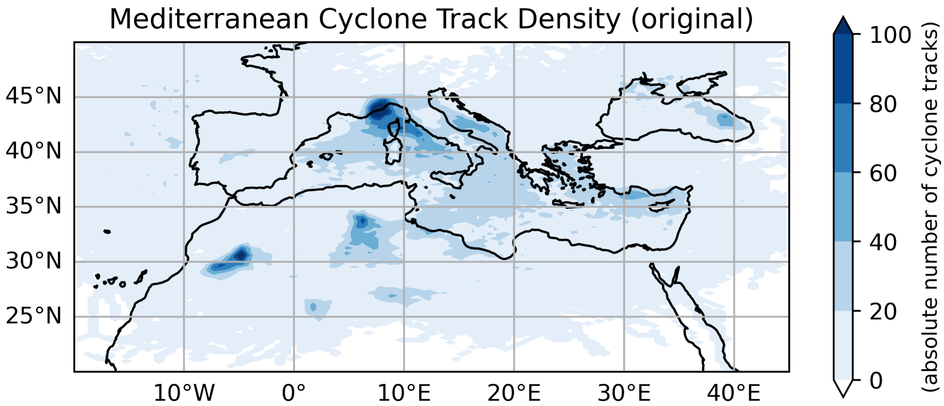

Figure 1: Annual average track density of Mediterranean cyclones per 0.25 x 0.25° resolution grid, based on ERA5 over the period 1979-2020. The color shading accounts for the absolute number of tracks at the respective location.

2.2 Definition(s) of Stationarity

The analysis of stationarity is divided into two parts. In a first step, we define stationarity considering the entire length of a cyclone track, here referred to as full-track stationarity (FT). For this, we use the approaches by Doiteau et al. (2024, preprint) (median velocity) and Aregger (2021) (total distance). The result are three categories, each containing 10% of the cyclones of the dataset, that is to say, the cyclones falling into the percentile 0-10% (quasi-stationary ones, colored blue), the percentile 45-55% (colored orange) and the percentile 90-100% (colored green).

The aim of this procedure is to characterize each category in terms of intensity, duration and spatial distribution, with a more detailed look on quasi-stationary cyclones (see first research question, Section 1).

In a second step, we apply additional stationarity definitions to our data set. This time, we limit the analysis to sections of the track instead of the whole, more precisely 12-hour segments, here referred to as along-track stationarity (AT). For each approach, we again work out three 10%-categories and describe them for the characteristics mentioned above.

The idea behind the AT view is, on the one hand, to identify quasi-stationary cyclones in an alternative way. On the other hand, we want to enable the comparison of a certain track segment's stationarity later on with other (surface) variables along the path, for example precipitation totals or sea surface temperature as done by Avolio et al. (2024).

Finally, all results of the FT and AT definitions are compared among each other and with Doiteau et al. (2024, preprint). Here, we examine how the different stationarity approaches affect the characteristics of the cyclones (see second research question, Section 1).

It should be noted that we concentrate only on the gross similarities and differences between the results, as a detailed comparison proves to be difficult. This is, on the one hand, because the definitions are based on different variables (speed vs. distance) and perspectives on the cyclone tracks (FT vs. AT). On the other hand, the approaches have so far only been applied to datasets different to ours. For example, Doiteau et al. (2024, preprint) worked with cyclones of the period 2001-2021 that have been tracked in the 850 hPa vorticity field and whose spatial distribution is plotted in a style different to ours, given as the "percentage of cyclones having a track point within a radius of 100 km" (see Fig. 7a).

In the following, each stationarity definition is described, with the ones based on distance illustrated in Figure 2.

2.2.1 FT Median Velocity

Following the work of Doiteau et al. (2024, preprint), we classify the cyclones according to their median speed of travel during their whole life cycle. Since each distance between two track points is given in hourly resolution, the median speed is the simple median of all individual distance-per-hour (velocity) values of a cyclone. The quasi-stationary cyclones are defined as the 10% slowest of the dataset.

Note: the use of the mean instead of the median did not lead to a significant change in the spatial pattern of the velocity categories. The corresponding results are shown in Fig. 17 in the Appendix.

2.2.2 FT Total Distance

In Aregger (2021)'s study on stationary convective storms in Switzerland, the author introduces a stationarity metric based on the total distance traveled during a storm's whole life cycle (path stationarity, here renamed to total distance). It is given as the sum of all distances between all track points. The quasi-stationary cyclones are defined as the 10% with the shortest total distances (Fig. 2a).

2.2.3 AT 12-hour Distance

Another type of a distance-based metric is again the total distance traveled by a cyclone but this time within a certain time window only. As described earlier, the analysis is limited to the 13 hours after the reference time. The result constitutes the sum of all track segments that lie between a reference point and the 12 following ones. The calculation is repeated for all track points followed by 12 others, and stopped where fewer follow. The quasi-stationary cyclones are defined as the 10% with the shortest 12-hour distances (Fig. 2b).

2.2.4 AT Radial Distance

Another way to compute a 12-hour distance is again to sum up 12 individual distances but to calculate each one from the reference point. Again, the whole process is repeated until each track point followed by 12 others has been used as a reference. The quasi-stationary cyclones are defined as the 10% with the shortest radial distances (Fig. 2c).

2.2.5 AT Smallest Circle

A distance-based metric that can also be seen as area-based is that of the "smallest circle". First, 12 individual distances are calculated as in the approach of AT radial distances, but instead of taking the sum in a second step, only the longest segment is selected. This finally forms the radius of the smallest possible circular area, which encloses the 12 track segments covered by a cyclone within the 12-hour window. The quasi-stationary cyclones are the 10% with the smallest radii or circular areas (Fig. 2d).

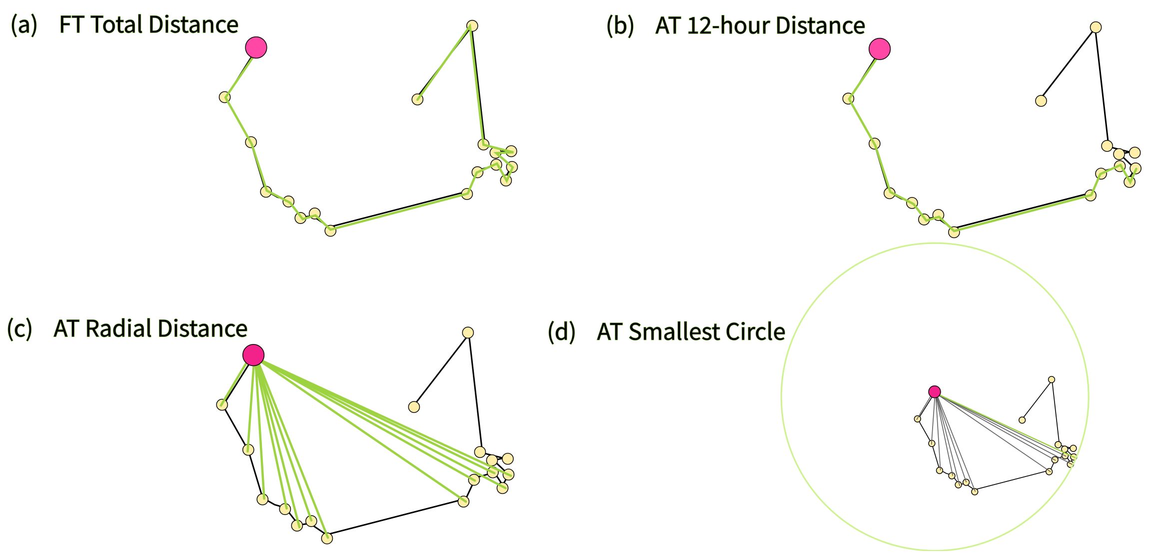

Figure 2: Sketch of distance-based stationarity definitions used in this thesis: (a) FT Total Distance, (b) AT 12-hour Distance, (c) AT Radial Distance and (d) AT Smallest Circle.

2.3 Heat Lows Filter

The spatial density of the cyclone tracks in Figure 1 reveals two hotspots in Northern Africa where cyclone presence is considerably high. A first application of the median-based FT definition to the dataset shows that these locations are particularly prominent in the quasi-stationary cyclone category. We consider most of these apparently stationary tracks to be heat lows, hence low pressure areas that do not form fronts, clouds or precipitation. Their frequent occurrence in the Sahara is supported in the literature (Lionello et al., 2006; Drobinski et al., 2020; Doiteau et al., 2024, preprint; Givon et al., 2024) and described by Flaounas et al. (2022) as: " [...] several shallow cyclones may occur [...] in the Sahara [...]. Although identified as cyclones, these systems do not correspond to organized mesoscale wind vortices [and] should not be confused with active and deeper cyclones."

To prevent those thermal lows from distorting the analysis, we place a condition on the selection of cyclones to keep only those that propagate over the Mediterranean basin. This also makes our results more comparable with Doiteau et al. (2024, preprint), since they also applied a heat low filter in their study, focusing only on cyclones with a minimum mean sea level pressure (MSLP) below 1015 hPa and "entering either the Mediterranean Sea or the Black Sea".

Figure 3a shows that the condition of having at least 1 track point over the sea already leads to the desired outcome: the majority of tracks over land are removed, including the large clusters in the Sahara, and the size of the dataset reduces by 38% to 2377 tracks (Fig. 3b). An increase in the required Mediterranean-crossing track points from 1 to 3 (Fig. 3c), 5 (Fig. 3d) and 12 track points (Fig. 16 in the Appendix) hardly changes the total number of tracks and their spatial distribution, which is why we stick to the first condition.

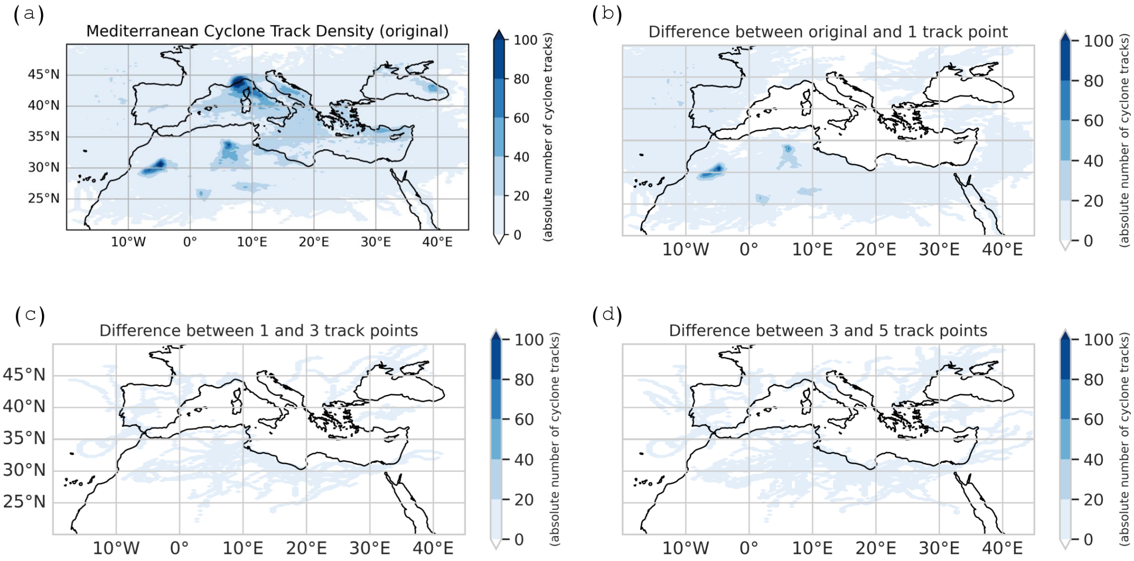

Figure 3: (a) Track density of Mediterranean cyclones with at least 1 track point over the sea. The remaining subplots show the tracks that disappear (b) relative to the original, and when the number of required Mediterranean-crossing track points is increased (c) from 1 to 3 and (d) from 3 to 5 track points over the sea.

3 Results and Discussion

3.1 Full-track Stationarity

The cyclones in the dataset propagate through the Mediterranean region at highly variable speeds. Their median velocities cover a range from 3 to 56 km/h, which is somewhat larger than that found by Doiteau et al. (2024, preprint) (17 to 30 km/h), but the median of the spread is about the same (21 km/h vs. 25 km/h). Figure 4a shows a clearly right-skewed distribution, with the 10%, 45%, 55% and 90% percentiles of median velocity values at 11, 20, 22 and 35 km/h, respectively. A total of 148 are classified as quasi-stationary cyclones.

Like the speed, the total length of the cyclone tracks also vary greatly. During their whole life cycles, the cyclones cover distances between 187 and 6569 km, with a median of the spread of around 1582 km. Here again but more pronounced, the distribution is right-skewed, with the 10%, 45%, 55% and 90% percentiles of total distance values at 752, 1476, 1686 and 3032 km, respectively (Fig. 4b). 144 cyclones belong to the quasi-stationary ones.

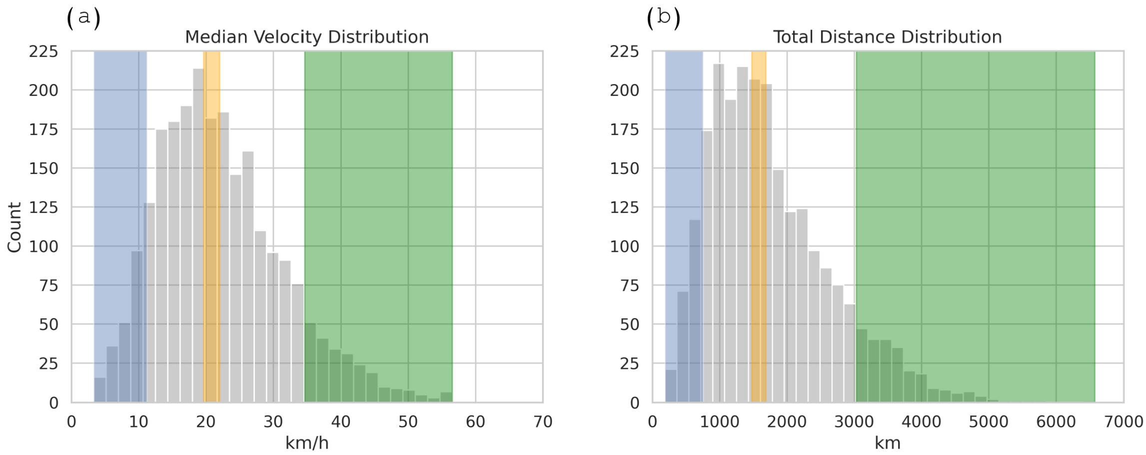

Figure 4: Distribution of the (a) median velocities and (b) total distances of the cyclones of the dataset. The full-track categories of the percentiles 0-10%, 45-55% and 90-100% are colored in blue, orange and green, respectively.

Figure 5 shows that there is a weak positive correlation between the speed of a cyclone and its total track length. In other words, the faster a cyclone moves, the farther it tends to travel which seems rather intuitive. However, as the velocity and distance values increase, so does their spread. It is therefore more likely for a fast cyclone to cover a short distance than for a slow one to cover a long distance.

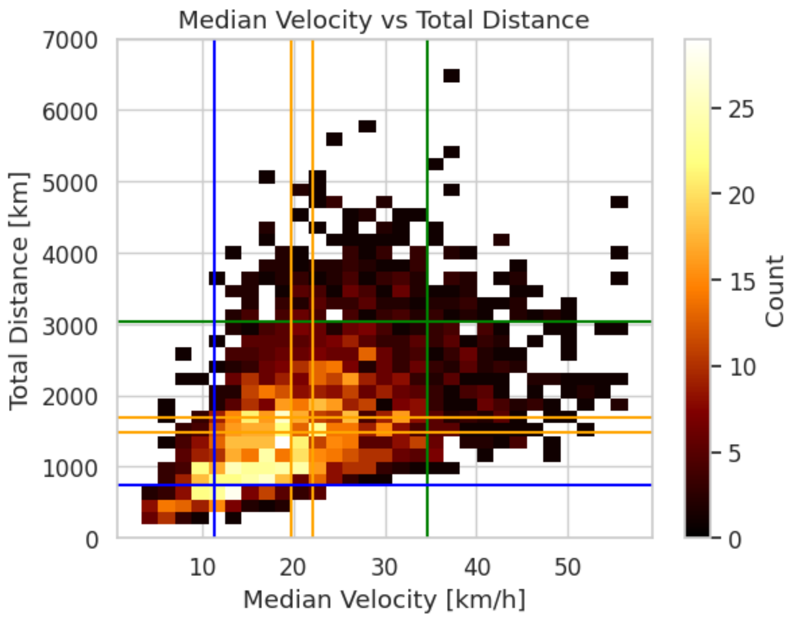

Figure 5: Comparison of the median speed (x-axis) and the total track length (y-axis) of the Mediterranean cyclones.

3.1.1 Intensity and Duration

How fast or how far a cyclone travels does not directly indicate how intense it is, nor are the farthest-traveled cyclones necessarily the longest-lasting ones. Shallow, medium and deep cyclones are found among all cyclone categories of both FT definitions and in roughly equal numbers (Fig. 6, top row). The intensities range from 968 hPa (FT median velocity) and 981 hPa (FT total distance) to 1018 hPa, with most of the cyclones reaching their maximum strength at a pressure of 1001-1003 hPa. However, there is less overlap between the categories of the FT total distance method with regard to the deepest cyclones (Fig. 6b, top): those with a minimum pressure below 990 hPa tend to cover long (green and orange) rather than short distances (blue), apart from an outlier at 968 hPa belonging to the quasi-stationary cyclones.

In terms of total duration, there are negligible differences among the FT categories (Fig. 6c and d). In general, cyclones living for more or less 3 days are the most common, regardless of how fast or far they travel. While some cyclones undergo lysis already after 29 hours, the cyclones can last as long as 9 days in rare cases regardless of their propagation speed or distance traveled.

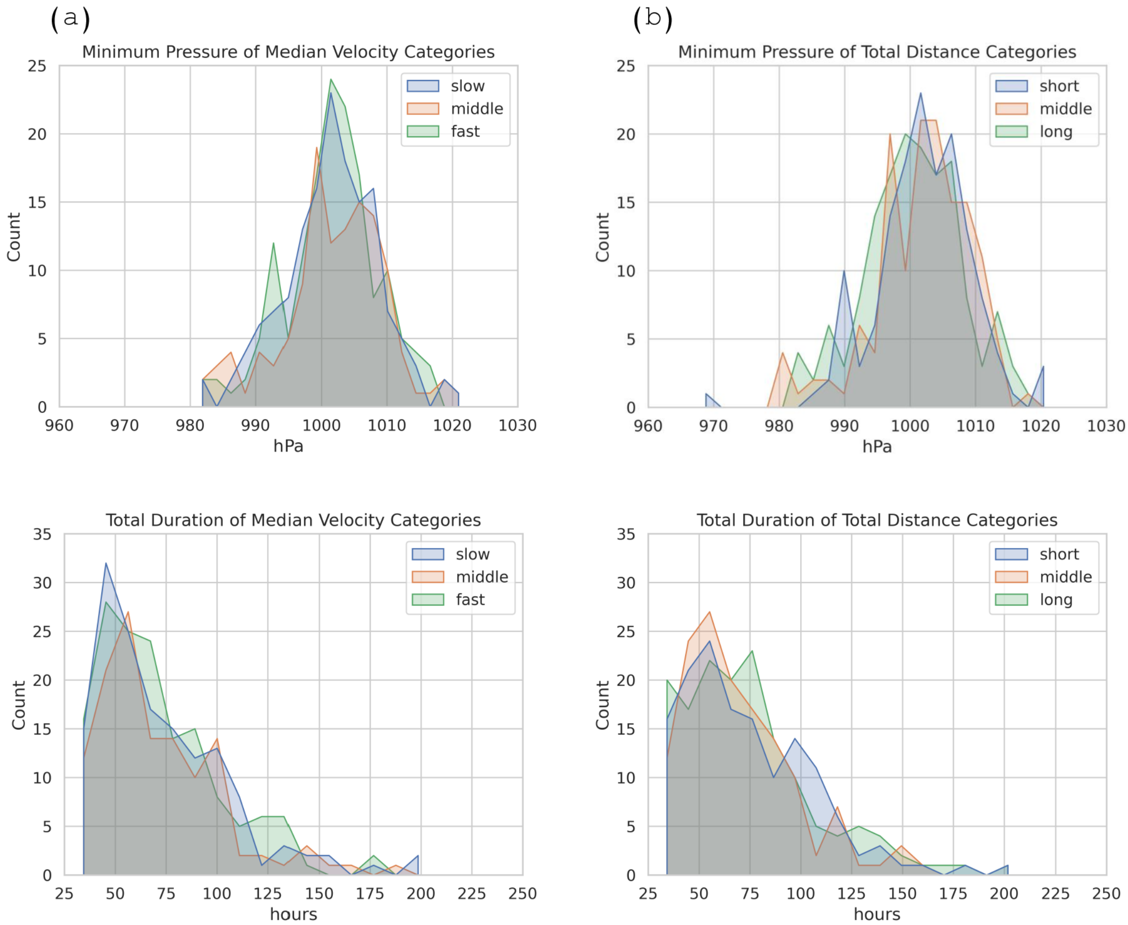

Figure 6: Comparison of the maximum intensities (top row) and total durations (bottom row) of the cyclones according to the (a) FT median velocity and (b) FT total distance. The categories of the percentiles 0-10%, 45-55% and 90-100% are colored in blue, orange and green, respectively.

3.1.2 Spatial Distribution

Figure 7 shows the spatial distribution of the analyzed cyclones falling into the percentiles 90-100% (top row), 45-55% (middle row) and 0-10% (bottom row) of each FT method. Doiteau et al. (2024, preprint)'s findings are in the panels in the left most column.

The first thing to note is that the median velocity approach shows a very similar spatial pattern in all categories (Fig. 7b). For each, we find the bulk of the cyclones being concentrated in the Gulf of Genoa, with it the most pronounced in the quasi-stationary category. In the latter, two more, slightly fainter hotspots appear in the eastern Mediterranean Sea and the Black Sea.

Classifying the cyclones according to the total length of their track yields comparable findings (Fig. 7c). The spatial pattern of the long-distance traveling cyclones hardly differs from that of the middle or short-distance travelers. The most frequented location is the Gulf of Genoa again, but in this case most pronounced in the middle category, together with the hotspot in the Black Sea.

These results are in contrast to Doiteau et al. (2024, preprint) who found category-specific hotspots using the median velocity approach (Fig. 7a). In addition, we find the cyclone hotspots slightly offset to the (North-/South-) East. However, our findings agree on the spatial distribution of the quasi-stationary cyclones.

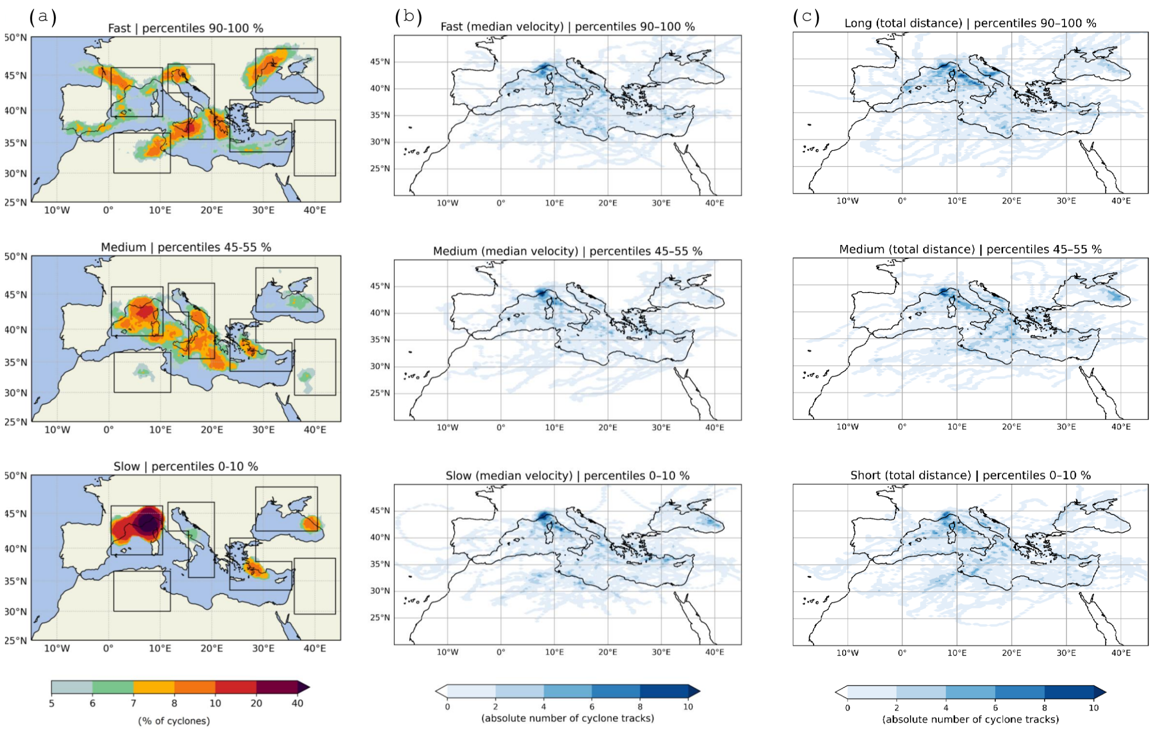

Figure 7: Mediterranean cyclone track density according to (a), (b) FT median velocity and (c) FT total distance. In each column, the percentile 0-10% is shown on the bottom, the percentile 45-55% in the middle and the percentile 90-100% on the top. Doiteau et al. (2024, preprint)'s findings are shown in the left most column.

According to both FT definitions, the cyclones in our data set all have very similar (spatial) stationarity characteristics. The fact that Doiteau et al. (2024, preprint), instead, found clear differences among the cyclone of their dataset may be due to the different style of visualizing the results: While Doiteau et al. (2024, preprint) represent the Mediterranean track density as the "percentage of cyclones having a track point within a radius of 100 km", we represent it as the absolute number of tracks at the respective location.

In addition, the slight offset of our hotspots with respect to Doiteau et al. (2024, preprint)'s could result from the fact that they used the relative vorticity field at 850 hPa for tracking the cyclones. This would lead to a cyclone center that is further upstream compared to one calculated using MSLP, as in the case of our study (Schultz et al., 2019).

3.2 Along-track Stationarity

Each AT measure covers an equally wide range as the total track distances in Section 3.1. For example, a 12-hour distance classified as long can extend up to 1600 km which roughly equals the beeline from Bern, Switzerland to Athens, Greece (Fig. 8a, green). In contrast, the quasi-stationary cyclones with the shortest track segments travel only 10 km within the same amount of time, which is about the distance from Bern to Worb, BE (Fig. 8a, blue). Regarding the radii of the smallest circles, they vary between 4 and 1600 km (Fig. 8b) and the radial distances between 30 and 12 300 km (Fig. 8c).

Like those of the FT, the distributions of the AT measures are right-skewed. The 10%, 45%, 55% and 90% percentiles of 12-hour distance values are at 105, 237, 278 and 513 km, of radial distance values at 500, 1383, 1663 and 3261 km, and of smallest circle values at 74, 208, 250 and 484 km, respectively. A total of 991 (AT 12-hour distance), 1199 (AT radial distance) and 1197 cyclones (AT smallest circle) have quasi-stationary 12-hour sections along their track.

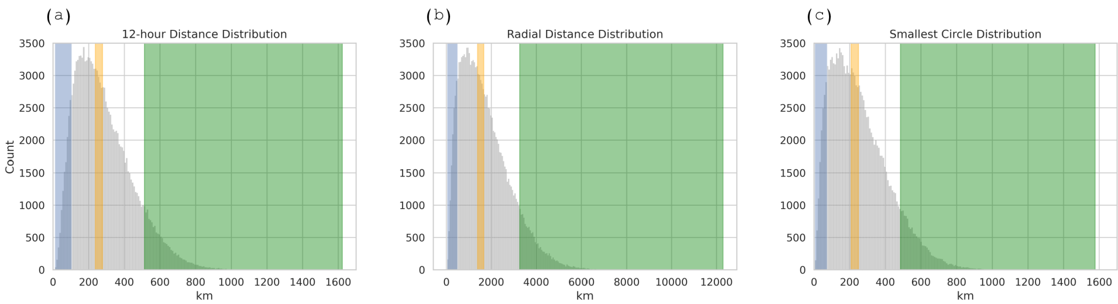

Figure 8: Distribution of the (a) 12-hour distances, (b) radial distances and (c) smallest-circles radii of the cyclones of the dataset. The along-track categories of the percentiles 0-10%, 45-55% and 90-100% are colored in blue, orange and green, respectively.

Figure 9 shows that the AT measures correlate more strongly positively with each other than the FT measures (see Section 3.1, Fig. 5). The further a cyclone travels within 12 hours, the farther apart the corresponding 13 track points tend to be, and therefore the larger the (circular) area the cyclone traverses. Nevertheless, an increasing spread can be observed; a cyclone with large AT measures shows more variability than quasi-stationary cyclones.

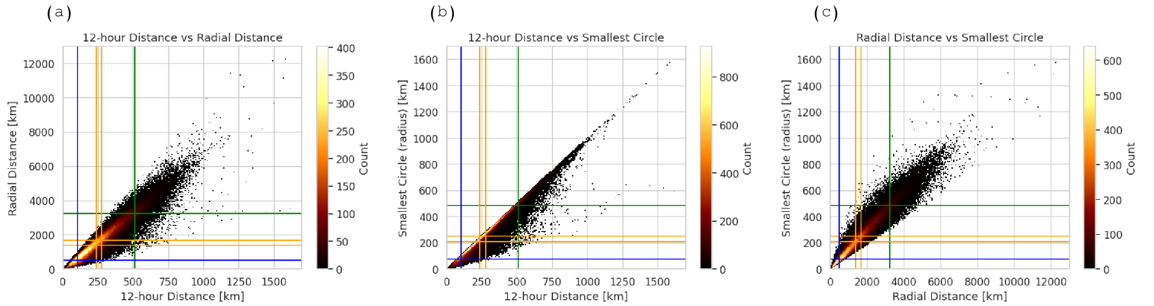

Figure 9: Comparison of the (a) 12-hour distance (x-axis) and radial distance (y-axis), (b) the 12-hour distance (x-axis) and the radius of the smallest circle (y-axis) and (c) the radial distance (x-axis) and the radius of the smallest circle (y-axis).

3.2.1 Intensity and Duration

As observed for the categories based on FT metrics also those based on AT metrics show a very similar distribution of maximum intensities (Fig. 10, top row). Again, the majority of cyclones are strongest at a pressure of 1002-1006 hPa (Fig. 10, top row). However, there is a slight difference noticeable, the most prominent between deep and shallow cyclones: the latter are more likely to have quasi-stationary sections along their track (blue) than deep cyclones, a tendency that already emerged in the FT results (see Section 3.1.1). However, it should be noted that the maximum intensity here also refers to the entire track and not to individual track sections.

The total lifetime (duration) of a cyclone does not show any striking differences among the categories, with the most of them lasting around 3 days (Fig. 10, bottom row).

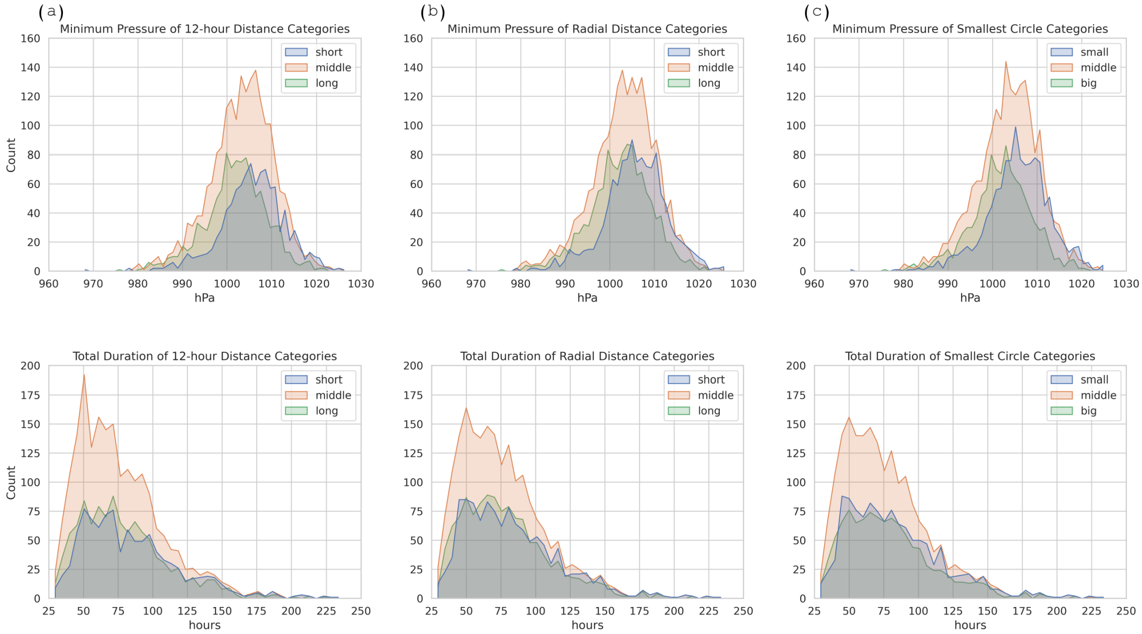

Figure 10: Comparison of the the maximum intensities (top row) and total durations (bottom row) of the cyclones classified by the (a) AT 12-hour distance, (b) AT radial distance and (c) AT smallest circle definitions (column wise). The categories of the percentiles 0-10%, 45-55% and 90-100% are colored in blue, orange and green, respectively.

3.2.2 Spatial Distribution

As with the two FT approaches, the results of the AT methods are very similar to each other (Fig. 11d-f). This time, however, the spatial patterns between the cyclone categories clearly differ. The majority of the cyclones falling into the percentile 90-100% concentrate in the Tyrrhenian Sea (Fig. 11d-f, top row). This region appears once again in the middle category, together with the seas around Italy in general, including the Ionian and Adriatic (Fig. 11d-f, middle row). Finally, the quasi-stationary cyclones show strikingly well-defined hotspots, two in the Turkish gulfs of Antalya and Alexandretta and one off the Georgian coast in the Black Sea (Fig. 11d-f, bottom row).

Regions appearing in all categories are the Gulf of Genoa and the Sahara, the latter with two clusters that stood out already before removing the heat lows from the dataset. The only difference here is that cyclones of the upper 10% tend to be more prominent in the Sahara and those of the middle and lower 10% in the Gulf of Genoa.

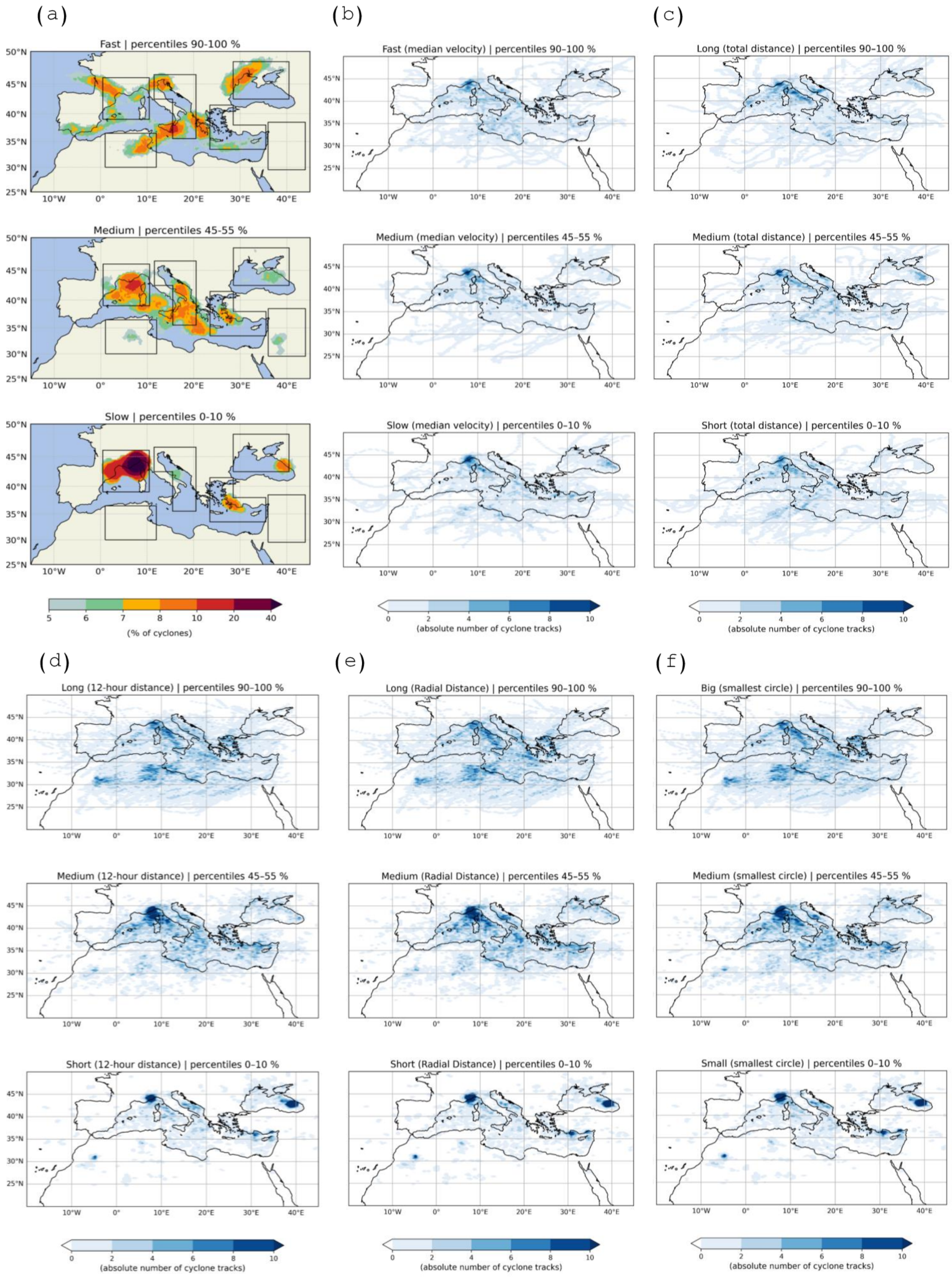

Figure 11: Mediterranean cyclone track density according to (a) FT median velocity according to Doiteau et al. (2024, preprint), (b) FT median velocity according to our results, (c) FT total distance, (d) AT 12-hour distance, (e) AT radial distance and (f) AT smallest circle. For each method, the percentile 0-10% is shown in the subplot on the bottom, the percentile 45-55% in the middle and the percentile 90-100% on the top.

When comparing the two types of approaches, the full-track view tends to capture the average structures of the cyclone tracks, while the along-track perspective reveals more of the subtle variations of the tracks.

Interestingly, Doiteau et al. (2024, preprint) identified those nuances already by applying their median velocity-based FT approach, thereby showing strikingly similar results to our AT approaches. Nevertheless, also the AT approaches lead to the slight offset of the spatial pattern compared to Doiteau et al. (2024, preprint), the possible cause of which we already discussed in Section 3.1.2. Furthermore, we do find the western hotspot in the Sahara in contrast to Doiteau et al. (2024, preprint), which could confirm their assumption of having lost it by excluding the weakest cyclones from their study.

Now, taking all the individual spatial patterns of the categories together, they reflect the locations of the most prominent topographical features in the Mediterranean. The majority of all the hotspots mentioned earlier lie either close to a mountain range or directly in its lee area, that is to say: The seas around Italy in the vicinity of the Apennines and the Dinarides, the Turkish gulfs south of the Taurus Mountains, the Georgian coast in front of the Caucasus, the Gulf of Genoa enclosed by the Alps and the Apennines, and the two spots in the Sahara adjacent to the Atlas Mountains. As such, there is a great possible influence of orography on the propagation of (lee) cyclones in the Mediterranean, which has already been discussed in previous studies (Lionello et al., 2006; Campins et al., 2011; Flaounas et al., 2022; Givon et al., 2024).

However, the prevalence of certain cyclone types at certain location suggests that there are processes, shaped by the location itself, which contribute to affecting the stationarity of cyclones or even dominate the orographic signal. This assumption has already been raised with regard to other characteristics of Mediterranean cyclones (for example intensity) and discussed for their potential upper- and lower-level triggers (for example large-scale dynamics and diabatic processes) (Campins et al., 2011; Givon et al., 2024). However, the relationship between location and the stationarity of a Mediterranean cyclone has not yet been investigated, for which Doiteau et al. (2024, preprint)'s and our study now provide a start.

3.3 (Quasi-) Stationarity Table

Table 2 below summarizes the results of applying various stationarity definitions to the dataset. Besides the information contained in Table 1 (see Section 2.1), additional columns describe for each track point (row index, lon, lat) of a cyclone (id):

- whether it is part of a track crossing the Mediterranean basin (column "medi_track"),
- which category of which stationarity definition it belongs to (columns ending with "_c", with 1.0, 2.0, 3.0 indicating the categories of the percentiles 0-10%, 45-55% and 90-100%, respectively, and 0 meaning none of the above),
- which quantile it falls into (columns ending with "_q"), and
- what value corresponds to it (columns ending with "_v").

As an example, the track point of cyclone 3807 with coordinates 36.51, 44.24 (last in Table) is 1) part of a track crossing the sea, 2) belonging to the lowest 10% of the FT median velocity definition, 3) falling into quantile 0.08, and 4) attributed with a value of 10.43 km/h.

Table 2: Excerpt of the QS Table.

id	lon	lat	...	medi_track	FT_MED_VEL_c	FT_MED_VEL_q	..._v
4	0.96	40.70	...	TRUE	0.0	0.83	31.01
4	1.08	40.76	...	TRUE	0.0	0.83	31.01
4	1.30	40.75	...	TRUE	0.0	0.83	31.01
4	1.62	40.70	...	TRUE	0.0	0.83	31.01
...	...	...	...	...	...	...	...
3807	36.41	44.20	...	TRUE	1.0	0.08	10.43
3807	36.51	44.24	...	TRUE	1.0	0.08	10.43

3.3.1 Case Studies from the QS Table

So far, our stationarity analysis of the studied cyclones has shown that it leads to somewhat different results depending on the definition's perspective. In this Section, we discuss how the classification methods affect individual cyclone tracks in detail.

Figures 12 to 15 present case studies of selected tracks that have been classified as quasi-stationary in one way or another. A brief description of their main features serves to illustrate how the QS Table (Table 2, Section 3.3) can be queried for quasi-stationary tracks depending on the research objective. In addition, Figure 18 in the Appendix provides an overview of the number of quasi-stationary cyclones commonly identified by the used approaches.

Case 1: Medicanes

In their study, Avolio et al. (2024) investigated Mediterranean cyclones that took on tropical-like characteristics at some point in their life cycle, also known as Mediterranean tropical-like cyclones (Medicanes). Unlike extratropical cyclones, Medicanes are generally driven by relatively weak upper-level winds (Wood et al., 2023), among others, making them more likely to have quasi-stationary sections along their path(Luque et al., 2007).

Interestingly, almost all of the Medicanes studied by Avolio et al. (2024) (up to 2020) are detected by our AT approaches. The only exception is Medicane Callisto (1983, ID 409). Its track shows a few 12-hour windows in which Callisto traveled medium distances/radii, but most of its AT measures lie outside the three 10%-percentiles (Fig. 12c, red dots). Also, Callisto traveled a little too fast and much too far to be classified by the FT methods as quasi-stationary (Fig. 12b, red dot).

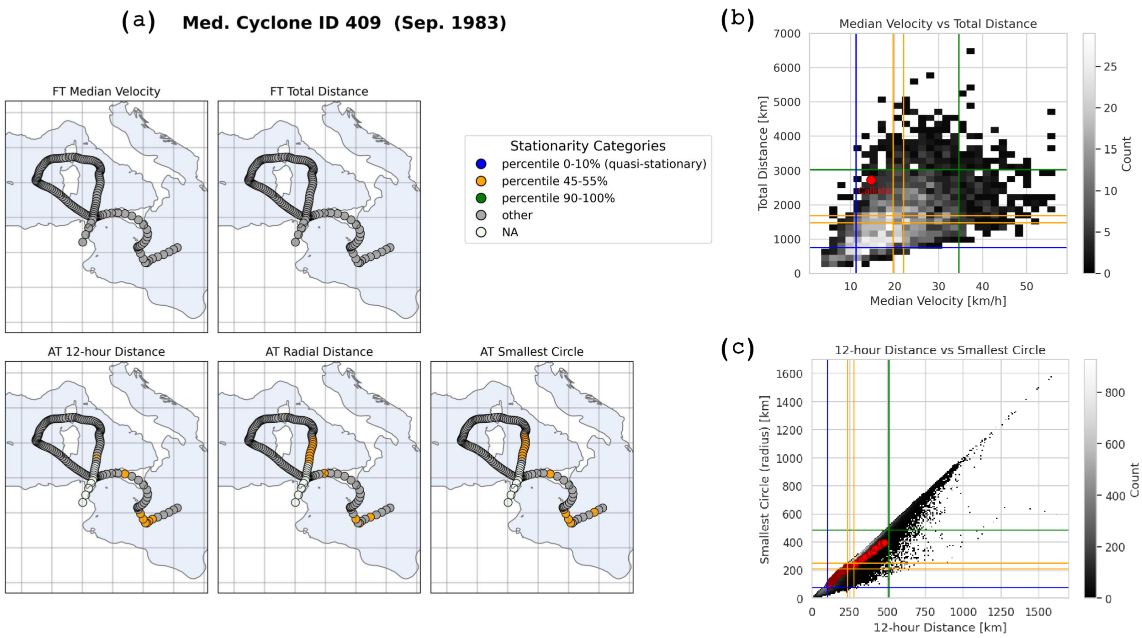

Figure 12: (a) Track of Medicane Callisto (1983, ID 409). Each track point is colored depending on the category it belongs to, i.e. blue: percentile 0-10%, orange: percentile 45-55%, green: percentile 90-100%, gray: other, white: not classified. On the right, Callisto's values (red dots) are shown in the (b) FT and one (c) AT histograms.

Another special case is Medicane Leucosia (1982, ID 274). Unlike Callisto, Leucosia fulfills all AT and an additional FT requirement for quasi-stationarity. The comparison with Medicane Quendresa (2014, ID 3243) shows that despite sharing a remarkably similar track, Leucosia is classified as a slow-traveling, quasi-stationary cyclone by the FT median velocity approach (Fig. 13a) while Quendresa travels at a rather moderate pace (Fig. 13b).

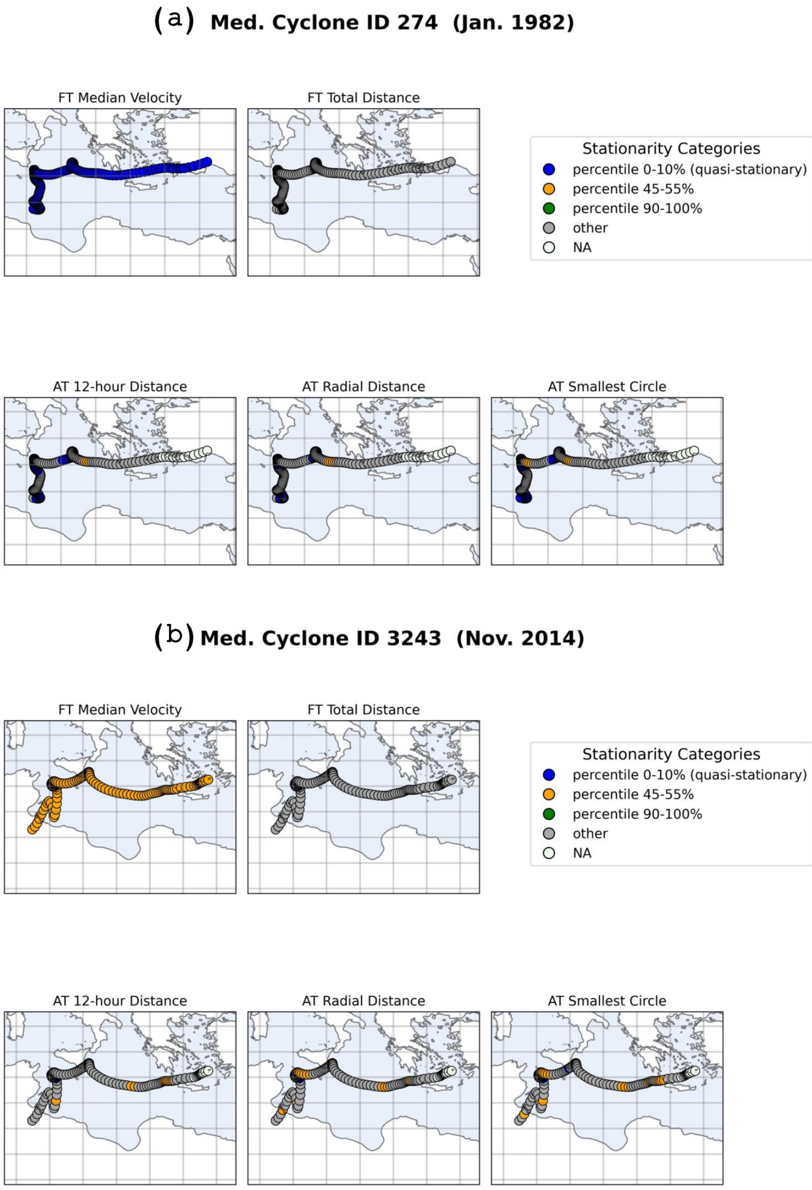

Figure 13: Comparison of the tracks of (a) Medicanes Leucosia, ID 274 and (b) Quendresa, ID 3243. Each track point is colored depending on the category it belongs to, i.e. blue: percentile 0-10%, orange: percentile 45-55%, green: percentile 90-100%, gray: other, white: not classified.

With regard to Medicanes, the AT-view can be used to identify them given their quasi-stationary phases. Nevertheless, the examples of Callisto (Fig. 12) and Leucosia (Fig. 13a) illustrate that rare cases may depend crucially on where the percentile thresholds of the stationarity categories are set.

Case 2: Obvious Quasi-Stationarity. Or not?

In the summer of 1994, the cyclone with ID 1407 lingered over the eastern Black Sea for several days. Moving in very small circles and with its center always over the sea, the cyclone's track would clearly be described as quasi-stationary upon visual inspection (Fig. 14a). As such, it is also classified by the FT median velocity and the AT methods; with a median speed of just 9 km/h and 12-hour metrics of up to 200-250 km (Fig. 14b and c, respectively).

However, due to its longevity, the cyclone ID 1407 travels such a large total distance, almost 2300 km, that it exceeds the percentile 55% of the associated FT method and thus travels farther than the medium-distance traveling cyclones (Fig. 14b).

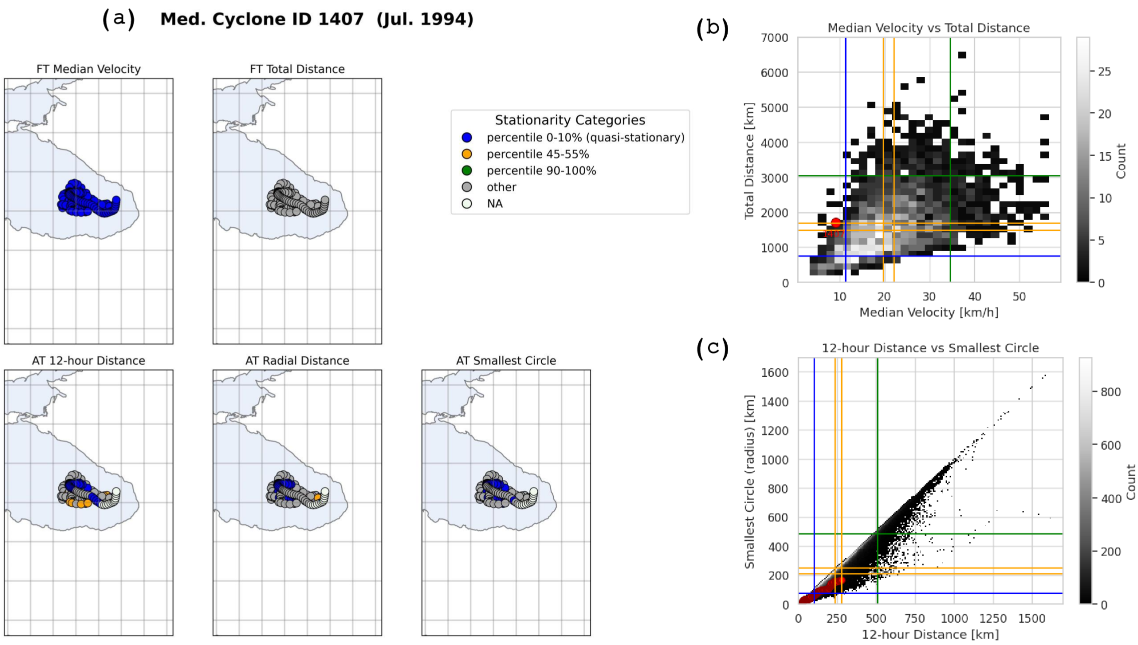

Figure 14: (a) Track of cyclone ID 1407. Each track point is colored depending on the category it belongs to, i.e. blue: percentile 0-10%, orange: percentile 45-55%, green: percentile 90-100%, gray: other, white: not classified. On the right, the cyclone's values (red dots) are shown in the (b) FT and one (c) AT histograms.

In winter of 2001, another cyclone (ID 2007) with quasi-stationary-like characteristics occurred (Fig. 15). Shortly after its formation, it persisted off the coast of North Africa for several hours and triggered heavy rainfall over the near mainland. The consequences were devastating: In Algeria, more than 700 people lost their lives in floods. Remembered as "el hemla", this natural disaster went down as one of the most severe in the history of the North African country (Tripoli et al., 2005; Thomas et al., 2011).

Some of the cyclone's quasi-stationary track sections are identified by the AT methods (Fig. 15ac), but not the episode that finally led to the extreme precipitation events. The two FT approaches do not capture the cyclone either, with its median velocity of 19 km/h and total track length of 1443 km near the percentile 45-55% (Fig. 15b, red dots).

The determining factor for the poor results is most likely the duration of the quasi-stationary episode, that led to the devastating consequences in Algeria: it 'only' lasted 9 hours. Those were likely smoothed out within the corresponding 12-hour track section and within the entire track, which is why the episode ultimately failed to be recognized as quasi-stationary.

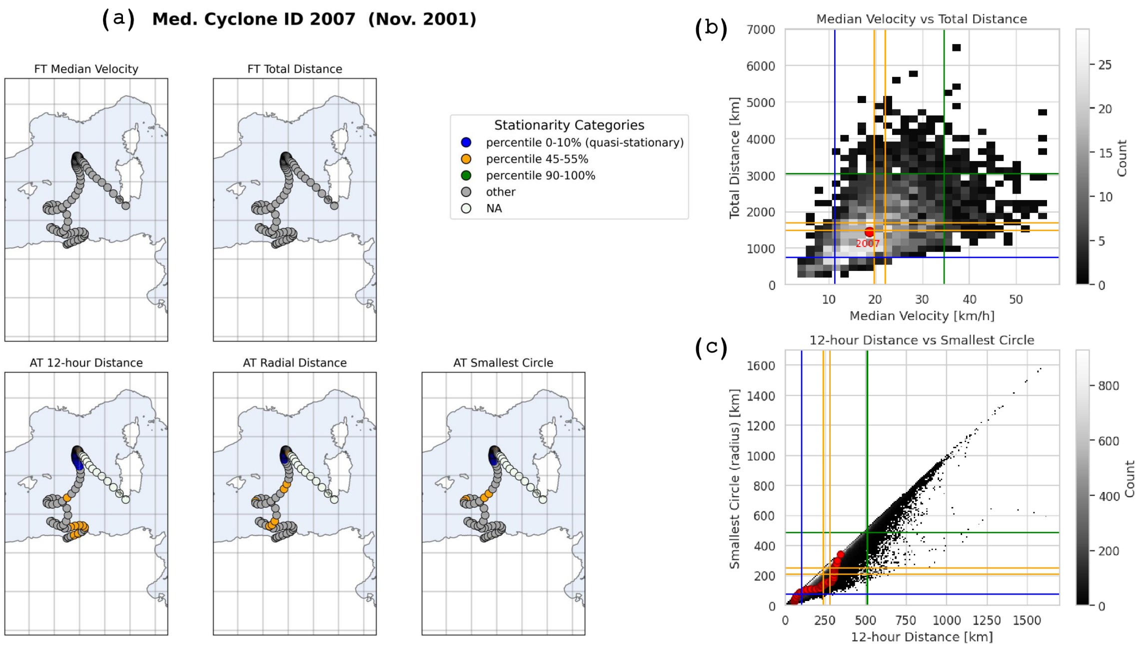

Figure 15: (a) Track of cyclone ID 2007. Each track point is colored depending on the category it belongs to, i.e. blue: percentile 0-10%, orange: percentile 45-55%, green: percentile 90-100%, gray: other, white: not classified. On the right, the cyclone's values (red dots) are shown in the (b) FT and one (c) AT histograms.

The examples of the cyclones with ID 1407 and ID 2007 illustrate that the application of a particular approach and its ability to capture the stationarity characteristics of a cyclone are inevitably linked to the context in which the cyclone occurs. In these examples, it was the duration of the life cycle (cyclone ID 1407, Fig. 14) or episode (cyclone ID 2007, Fig. 15) that was too long (in the former case) or too short (in the latter case) to be recognized as quasi-stationary by certain methods, which is why their application is ineffective in this context.

4 Conclusion and Outlook

Cyclones are among the atmospheric phenomena with high-impact in the Mediterranean. On the one hand, they are important suppliers of water and, on the other, one of the greatest natural hazards in the region. Heavy rainfall, especially prolonged and confined to a small area, has in the Mediterranean already lead to fatal consequences (Tripoli et al., 2005; Thomas et al., 2011). Often the cause of such persistent weather is also a persistent atmospheric condition, such as a quasi-stationary cyclone (Mastrantonas et al., 2020;

Tuel and Martius, 2023). Because the Mediterranean is known as a highly active cyclone birthplace, there are numerous studies that classify the cyclones occurring in the region into different groups or types (Lionello et al., 2006; Campins et al., 2011; Lionello et al., 2016; Givon et al., 2024; Flaounas et al., 2022). However, there is hardly any classification focusing specifically on persistence or (quasi-) stationarity (Campins et al., 2011; Doiteau et al., 2024, preprint).

The aim of this master's thesis is to fill this gap by characterizing the stationarity of the Mediterranean cyclones in the dataset. For this, we apply several classification methods that are based on propagation speed and spatial distance. Following the example of Doiteau et al. (2024, preprint), whose median velocity-based approach is also among the definitions tested, we work out three cyclone categories for each approach and compare them in terms of intensity, duration and spatial distribution. Of particular interest are quasi-stationary tracks or track sections because of their great potential for extreme surface weather.

What is new in our study is that we base our analysis on composite tracks found by 10 individual tracking methods in ERA5 of the period 1979-2020, different from Doiteau et al. (2024, preprint). Additionally, our approach is novel in that it includes sub-track metrics to assess 12-hour periods of cyclone propagation (along-track, AT) instead of just entire cyclone tracks (full-track, FT), thereby providing a more nuanced view to characterize cyclone stationarity.

Regarding the metrics used per definition type, that is to say median velocity and total distance for the FT and several distance-based 12-hour metrics for the AT approaches, they correlate slightly positively with each other. Thereby, the spread is smallest for the category of the percentile 0-10% and increases then steadily. It follows that a cyclone identified as quasi-stationary by one approach is most likely also classified as such by another approach. Conversely, cyclones of higher percentile categories show ever greater variability in their FT and AT metrics.

In terms of cyclone intensity and duration, all distance-based approaches (see Fig. 2, Section 2.2) indicate that it is rather the shallow cyclones that tend to remain quasi-stationary and less frequently the strong ones. However, the categories hardly differ in terms of the total lifetime of the cyclones.

Our results on spatial distribution reveal well-defined hotspots for the quasi-stationary cyclones, with the most prominent in the Gulf of Genoa. Somewhat weaker but still frequent are the areas in the Black Sea off the Georgian coast and the Turkish gulfs of Antalya and Alexandretta. Two other centers, in the West and East Sahara, only appear in the AT results. The spatial patterns of the other cyclone categories are usually less pronounced and differ more between the FT and AT results. Nevertheless, the Gulf of Genoa and, among the AT results, the Sahara emerge throughout, confirming them as well-known birth- and transit places of cyclones of various kinds (Lionello et al., 2006; Campins et al., 2011; Lionello et al., 2016; Michaelides et al., 2018; Flaounas et al., 2022).

The combination of all spatial patterns identified in this study draws attention to prominent orographic features in the Mediterranean region and their great potential to influence the propagation of cyclones (Lionello et al., 2006; Campins et al., 2011; Givon et al., 2024). Nevertheless, the results of the AT approaches show that certain stationarity characteristics are found preferentially at certain locations in the Mediterranean. This relationship suggests that location-specific triggers, be they upper- or lower-level atmospheric processes, additionally or even decisively affect the stationarity of cyclones in the Mediterranean.

Overall, we find that two factors can have a decisive effect on the stationarity analysis. First, the detection and selection of the cyclones to be studied. For example, Doiteau et al. (2024, preprint) identified their cyclones in the 850 hPa relative vorticity field instead of MSLP, which in the end results in a slight but consistent offset of the spatial patterns relative to ours. Also, whether and by what criteria the dataset is filtered prior to the analysis can cause hotspots to disappear from the final spatial pattern (for example the western cluster in the Sahara in Doiteau et al. (2024, preprint)) or to appear too prominent (for example both clusters in Northern Africa in our results).

Second, regarding the definition of stationarity itself, both its perspective on a cyclone's track as well as the context in which the cyclone occurs are key here. In our study, for example, taking the whole track into account (FT) gives access to the average characteristics of cyclone propagation whereas the AT definitions rather capture the subtle variations distinguishing the tracks from each other. In contrast,(Doiteau et al., 2024, preprint) discovered different stationarity properties of the cyclones already with the FT perspective. This contradiction may be purely a matter of visualizing the results, but could also have another cause, which is worth investigating in a follow-up study.

However, ultimately it is the context in which a cyclone occurs that determines which type of stationarity it is classified as by a certain method. As shown in the example of cyclone ID 1407 (see Section 3.3.1, Fig. 14), a cyclone's longevity can have a negative impact on its total track length (extend it) precisely because the cyclone has the commonly known quasi-stationary characteristic of persisting in more or less the same place for a long time. In this example, the longevity prevents the FT total distance approach from successfully identifying the cyclone ID 1407. Considering the context of a cyclone in the application of a certain method becomes particularly important for the identification of quasi-stationary cyclones and their severe weather potential in the Mediterranean. This has been shown in the example of the cyclone ID 2007 (Fig. 15) and its devastating consequences in Algeria (Tripoli et al., 2005; Thomas et al., 2011).

Regarding future research on the stationarity of Mediterranean cyclones, our QS Table (Table 2 in Section 3.3) can serve as a basis. Building on it, follow-up studies could be devoted to the large-scale circulation patterns and small-scale conditions that potentially support a cyclone's (quasi-) stationarity in time and space.

Furthermore, there is still the open question of how quasi-stationary Mediterranean cyclones impact the region's surface, especially with regard to extreme weather like torrential rainfall and its consequences (Flaounas et al., 2022). For this, a study could compare the spatial pattern of 12-hour precipitation totals with our findings of the AT methods and examine, how the results change when the length of the time interval is modified, for example, from a 12- to a 6-hour, 24-hour or even several-day period.

Finally, it would be particularly interesting to understand which cyclone type of stationarity links which triggers and impacts together and what role different definitions of stationarity play in this regard.

A Appendix

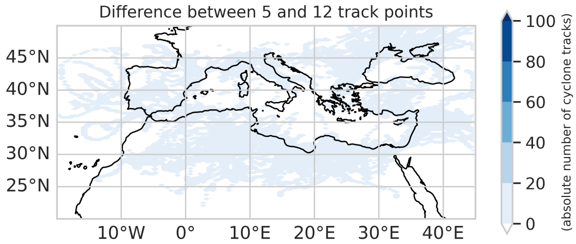

Figure 16: Mediterranean cyclone tracks that disappear when the number of required Mediterranean-crossing track points is increased from 5 to 12 track points over the sea.

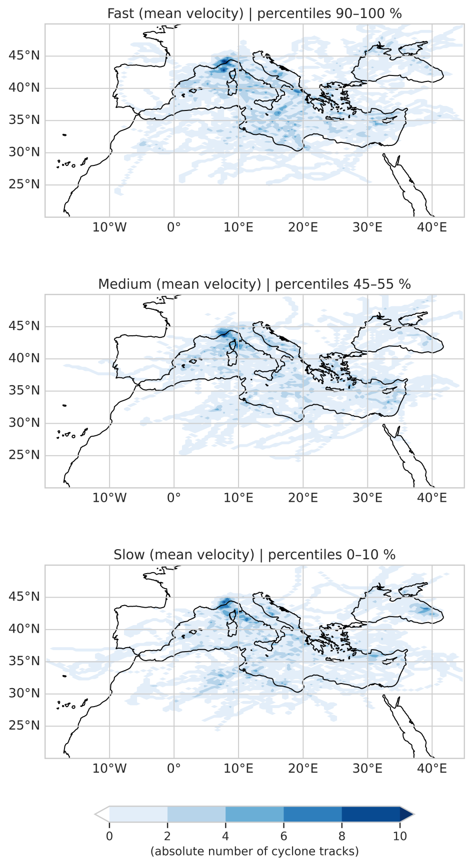

Figure 17: Mediterranean cyclone track density according to FT mean velocity. In the column, the percentile 0-10% is shown on the bottom, the percentile 45-55% in the middle and the percentile 90-100% on the top subplot.

	FTMV	FTTD	AT12D	ATRD	ATSC
FTMV	**231**	121	236	234	234
FTTD		**239**	170	186	187
AT12D			**973**	901	897
ATRD				**1182**	1121
ATSC					**1180**

Figure 18: Intersection matrix of the number of cyclones commonly identified as quasi-stationary by the approaches. FTMV: full-track median velocity, FTTD: full-track total distance, AT12D: along-track 12-hour distance, ATRD: along-track radial distance, ATSC: along-track smallest circle.

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Acknowledgements

I would like to sincerely thank my two advisors Dr. Alice Portal and Duncan Pappert for constantly supporting me with patience and time and for inspiring me with new ideas. I am also deeply grateful to my supervisor Prof. Dr. Olivia Romppainen-Martius for the opportunity to write this exciting thesis and to be part of her exceptionally passionate research team. Devoting myself entirely to the study of Mediterranean quasi-stationary cyclones was a unique experience that will stay with me in the times to come. And last but not least, I would like to thank my family and my friends for bearing with my anticyclonic (highs) and cyclonic (lows) periods and for even being inspired by them at times.

Declaration of consent

on the basis of Article 30 of the RSL Phil.-nat. 18

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Study program: Msc in Climate Sciences with specialization in Atmospheric Science

Bachelor ☐ Master ☑ Dissertation ☐

Title of the thesis: Quasi-stationary Mediterranean Cyclones

Supervisor: Prof. Dr. Olivia Romppainen-Martius

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