Response to Reviewer comments on "Assessing the impact of SSTs on a simulated medicane using ensemble simulations".

R Noyelle, U Ulbrich, N Becker, EP Meredith

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1 Preliminaries

We would like to thank both anonymous reviewers and Mario Miglietta for their comments on our manuscript. We find the comments constructive and appropriate, and think that they have improved the manuscript.

In the following pages we set out in detail our responses to the comments and how we have acted on them.

2 Response to Anonymous Reviewer #1 (RC1)

The paper discusses the sensitivity of a simulation of a medicane to uniform changes on sea surface temperature (SST). It clearly shows that the impact of SST is primarily on the intensity of the medicane. The results are well presented and the paper well written. However the paper suffers from a lack of documentation of the medicane and its environment (large-scale flow and SST). The major comments listed below should be considered before publication in NHESS.

Major comments

Description of the medicane. This should be done in terms of track and MSLP minimum. A description of the upper-level steering flow and of SST is also needed.

We thank the reviewer for this suggestion. As mentioned in our initial response (AC1), a synthesized description of the medicane case is already provided in Mazza et al. (2017). There are additionally detailed descriptions of the medicane in Reale and Atlas (2001) and Cavicchia and von Storch (2012). To avoid repitition of the aforementioned works while also recognising the valid comments of the reviewer, we have therefore added a brief overview of medicane Cornelia in a new Section 2, which includes an accompanying new figure. Our new Section 2 contains a decription of Cornelia in terms of its sea-level pressure, track, steering flow and accompanying SSTs. These paramenters are all also represented in the new Figure 1. Within the new Section 2 readers are referred to the aforementioned studies for a more detailed synoptic discussion. Figure 1 covers the spatial extent of the inner simulation domain and thus also serves to better illustrate the experimental design.

Justification on SST change. The SST field in a range of -4K to +6K. What is the rationale for changing SST over such a wide range, largely beyond the uncertainty in the SST measurement?

We have added an explaination of our rationale to the penultimate paragraph of the Introduction (P2 L19-23), making clear that the SST range is chosen based on our interest in exploring (1) the sensitivity of the medicane to larger SST changes which would be more typically associated with natural variability or anthropogenic climate change, and (2) to try to identify any threshold and/or non-linear behaviour in the system.

Other comments

Page 4, line 3. The Hart diagram was first applied to medicanes by Chaboureau et al. (2012). It was not used by Davolio et al. (2009)

Thank you for pointing this out. We have corrected this statement in the revised manuscript and also removed the reference to Cavicchia and von Storch (2012) (P4 L22-24).

Page 5, line 24. At $\triangle SST = 0K$, only 80% of the ensemble generate a medicane. This suggests that other factors than SST are important for the development of the medicane. It would be worthwhile to comment this result.

We have commented on this result in Section 4.1 of the results (P6 L20-24). We now highlight that observed SSTs do not guarantee medicane formation and emphasize that (i) medicane formation should be considered probabilistically, (ii) the observed medicane was just one of many potential realizations for observed SST, and (iii) that small changes in initial conditions can propogate to inhibit medicane formation in the real and model worlds. In addition to this, we also touch on this theme in Section 4.2 (P8 L5-9).

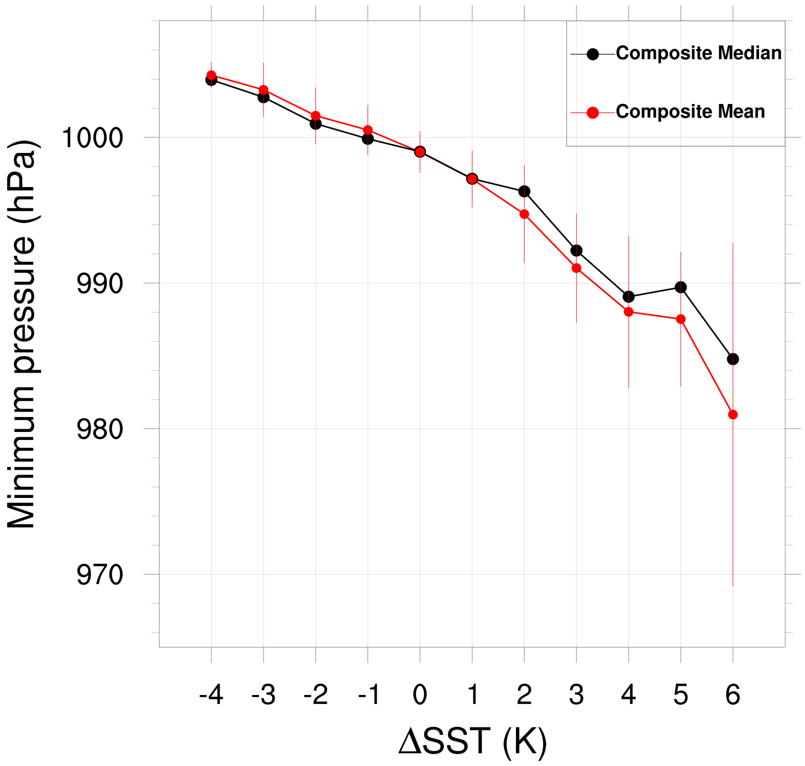

Figure 1: As in Figure 5 of the manuscript ("Dependence of composite minimum pressure on SST change."), except also showing the composite median (black) alongside the composite mean (red).

> *Page 6, line 8. As the large-scale steering flow plays a dominant role, it should therefore be documented somehow in a figure.*

As mentioned above, this has been included in a figure which accompanies the new Section 2, after the introduction.

> *Page 6, line 21. Please justify why the **composite** minimum of mslp is shown, instead of the median value for example. The same question holds for Figures 6, 7 and 8.*

We have firstly re-worded the relevant sentences on (P7 L22-24) to try and better explain what we are doing. As the reviewer comment is relevant to a number of figures, i.e. all those based on compositing, we have secondly used Section 3.6 to explain the rationale behind our approach (P6 L11-14). We have thirdly confirmed that the results are not sensitive to whether we chose the composite mean or median, and duly mention this in Section 3.6 (P6 L13-14); see Figure 1.

> *Page 6, line 27. Please plot a map of SST to show its not uniform distribution.*

As mentioned above, this has been included in a figure which accompanies the new Section 2, after the introduction.

3 Response to Anonymous Reviewer #2 (RC2)

The paper "Assessing the impact of SSTs on a simulated medicane using ensemble simulations" from R. Noyelle et al. exploits a large ensemble of regional climate model simulations to analyze the impact of varying sea surface temperatures on various properties of a historical medicane case. This topic is interesting an relevant to the ongoing research on medicanes, given the potential implications for both forecasting and better understanding of climate projection for such impactful phenomena. I find the scientific goals clearly set out, the paper well written, and the provided analysis well supporting the conclusions. I only have a number of (mostly minor) comments that in my opinion should be addressed prior to publication on NHESS.

GENERAL COMMENTS:
- while reading the paper in several occasions I wondered what the spatial pattern and numerical values of the SST field look like at the time of the medicane occurrence. I think it would be useful if a figure with e.g. the original prescribed SST field could be added.

We thank the reviewer for this suggestion. As promised in our initial response (AC1), we have included a short new section (Section 2) after the introduction which provides a brief decription of the medicane, while referring the reader to previous studies for more detail. A new Figure 1 accompanies this section, in which the observed SSTs at the time of the medicane are plotted, alongside the sea-level pressure field, cyclone track, and steering flow.

- one could wonder if the domain shifting technique can potentially introduce some systematic effects (e.g. anomalies in the atmospheric circulation) that could have a comparable role to variations of the SSTs on the evolution of the cyclones. Even if it is not in the scope of this paper, it would be useful if the authors can somewhere in the paper shortly comment on this issue.

We have addressed this point by adding clarifying text to Section 3.2 of the Methods ("Ensemble generation", P4 L5-12), which now empasizes that all domain-shifts, including the central (unshifted) domain, are equally valid and that there is no "correct" domain position. Any "anomalous" circulation thus introduced to the system is within the range of inherent uncertainty due to imperfect observations (i.e. reanalysis) and the chaotic nature of the system. In addition to this change, please also see the actions taken (below) in response to the comment about P5-L18 (below), which are relevant for addressing the above comment.

SPECIFIC COMMENTS:
PAGE1-LINE2: it is not immediate to understand that the size of the ensemble is 24x11, I suggest to rephrase the sentence to make it more clear that 11 members with perturbed SSTs are produced for each of the 24 domain-shifted ensemble members.

Thanks for pointing this out. We have added an extra sentence at the beginning of the abstract to make clear that there are 11 SST states and 24 members per SST state (P1 L2-3).

P3-L3: I suggest to move the information on the boundary conditions earlier in the paragraph (e.g. "... resolution parent domain, driven by 0.7 resolution ERA-Interim, in which ..."

We have moved the mention of ERA-Interim towards the beginning of Section 3.1 (P3 L11-13). The mention of ERA-Interim from the end of this paragraph has thus been removed and the downscaling procedure is now described over two sentences as follows: "*The two-step downscaling configuration begins with a* 257×271 *grid point, 0.165°-resolution parent domain which is forced at the lateral boundaries by ERA-Interim reanalyis* (Dee et al., 2011). *A* 288×192 *grid point, 0.0625°-resolution domain is then nested within the 0.165° parent domain.*"

P3-L13: in order to provide complete information to the reader, the central domain over Europe should be described or shown (or if it is the same as in Mazza 2017 specify something like "as shown in Figure xx of

Mazza et al. (2017)")
P3-L19: same as above for the inner domain.

Thanks for the suggestion. The domains are indeed the same as in Mazza et al. (2017). We have used the new Figure 1 (SSTs, SLP, etc.) to also show the reader the full spatial extent of the inner domain. In the revised version we thus refer the reader to this figure as appropriate in Sections 3.1 and 3.2. For the larger domain over Europe, we now state in Section 3.1 that this (i) covers an area slightly smaller than the EURO-CORDEX domain, and (ii) is shown in Mazza et al. (2017) (P3 L13-15). In Section 3.2 we now also state that the larger domain over Europe is the same as that in Mazza et al. (2017) (P3 L29).

P4-L4: It could be useful for readers not familiar with Hart phase space if it is explicitly mentioned what the modifications with respect to the original phase space are (reduced radius and change of the upper bound for VTU from 300 to 400 hPa)

We have added this information to the second paragraph of Section 3.4 ("Cyclone phase space", P4 L3-6).

P5-L5: "this period is excluded from the analysis". Do you mean the "early phase of the cyclone" is the phase before MWTC-20h? This should be made clearer as at this stage of the paper since you have not specified yet what period of the cyclone lifetime you are going to analyze.

We have addressed this issue by stating that the earliest period of analysis is 20 hours before the time of maximum warm-core strength and further adding a reference to the following section on cyclone compositing, where MWCT is first defined (P5 L25-27).

P5-L7: "Vtu on its own proved ...". I find this a bit confusing since there is no universal definition of what a medicane is, and you have stated earlier (Page 4, lines 15,16) that your definition of a medicane involves all the three parameters. Please clarify.

We have added the following sentence to the Section 3.4 (formerly Section 2.4): *While our method to distinguish a medicane from a non-medicane requires that all criteria mentioned in Section 3.4 are fulfilled simultaneously, for the systems considered in this study the evaluation of* $-\mathrm{V}_T^U$ *alone would have led to the same systems being identified.* With this new sentence (P5 L29-31), we hope to more clearly explain that at any time when $-\mathrm{V}_T^U > 0$ for a given cyclone, that we also always had $|B| < 10m$ and $-\mathrm{V}_T^L > 0$ at the same time. Therefore, using $-\mathrm{V}_T^U > 0$ as the sole discriminating parameter would have led to the same cyclones being identified.

P5-L16: do you find for all the cyclones (also the non transitioning ones) at least one instant where $B < 10$ *and* $-Vtl > 0$*? If not, how do you define MWCT for the cyclones that don't satisfy the condition?*

We do find for all cyclones (also the non-transitioning ones) at least one instant where $|B| < 10m$ and $-\mathrm{V}_T^L > 0$. We have mentioned this fact in the revised sub-section on cyclone compositing (P6 L10-11). As mentioned in the initial author comments (AC1), for the composite plots (Figs. 5, 7-11) we anyway only include cyclones which transition to medicanes, so these figures are unaffected. For Figure 6, however, we include all cyclones (also non-transitioning ones), so for Figure 6 we have added further text to the caption to state that the analysis is based on all cyclones.

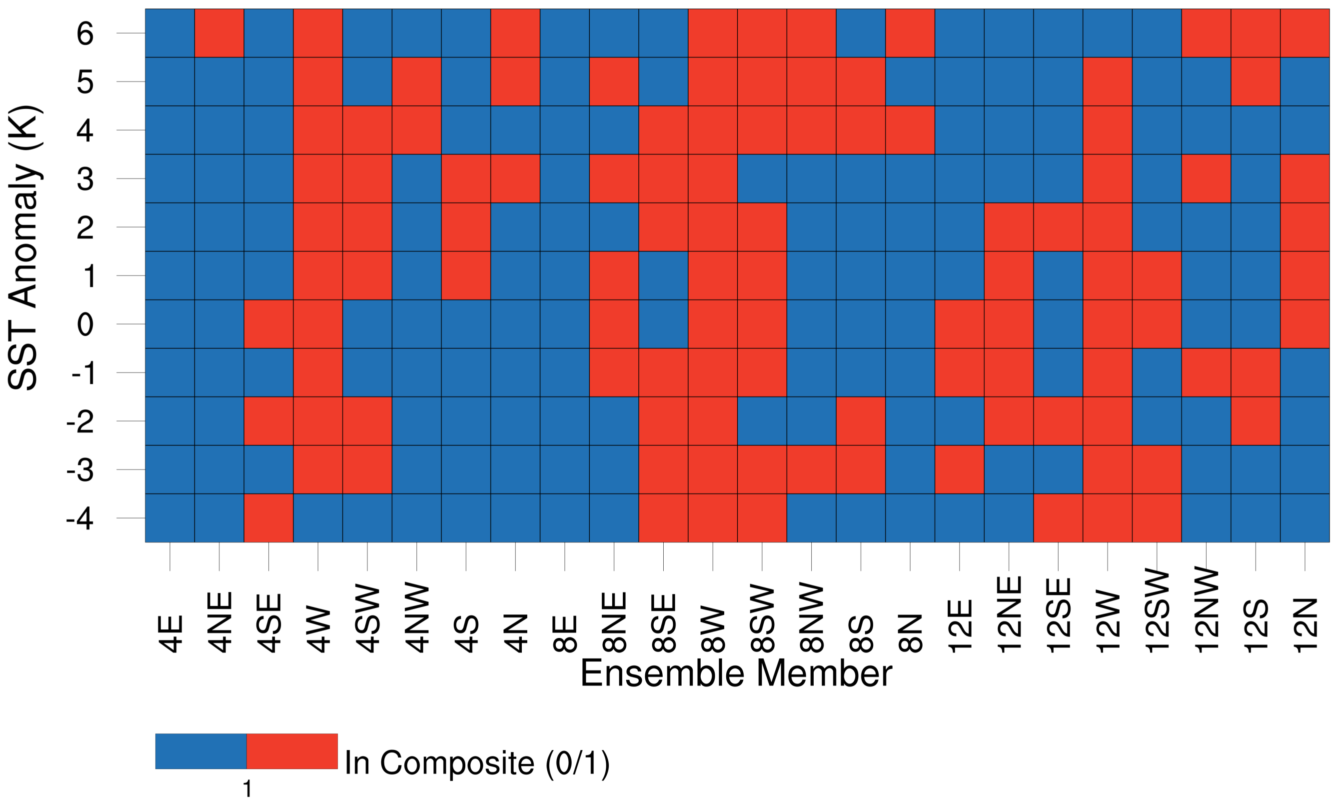

Figure 2: Ensemble members which enter the 10-member composite, based on the 10 strongest medicanes for each SST state (red boxes). Ensemble members are shown on the x-axis, with the number representing the size of the domain shift (number of grid cells) and the letters representing the direction of the domain sift. Ensemble members which do not enter the composite are marked in blue. Note that for the -4 K ensemble, only 7 members underwent tropical transition.

> *P5-L18: do you find that the the 10 cyclones that enter the composite come more often from some specific 24 domain-shifted ensemble members, or are they uniformly distributed across the ensemble? This is related to general comment 1 above, as it could give some indication on atmospheric patterns that influence the cyclone evolution.*

We have performed the requested analysis and have found that there are certain members which appear more often in the composite (Figure 2). This suggests that while increased SSTs increase the probability of tropical transition (Figure 2 of manuscript), it is not the sole criterion for an intense medicane. A mesoscale environment supportive of rapid intensification and tropical transition is also crucial. We have added text to this effect and stating the aforementioned findings to the results section (P8 L5-9). We have also re-emphasized this point in the discussion (P10 L5-6).

> *P5-L22: is tropical transition defined as any number of time steps where the cyclone is classified as a medicane or there is some minimum duration of the transition?*

We have clarified in the Methods sub-section on the cyclone phase space that these criteria must apply simultaneously at at least one time step (P4 L9).

> *P6-L10-19: does the presence of two separate maxima also indicate that the cyclones that have a tropical*

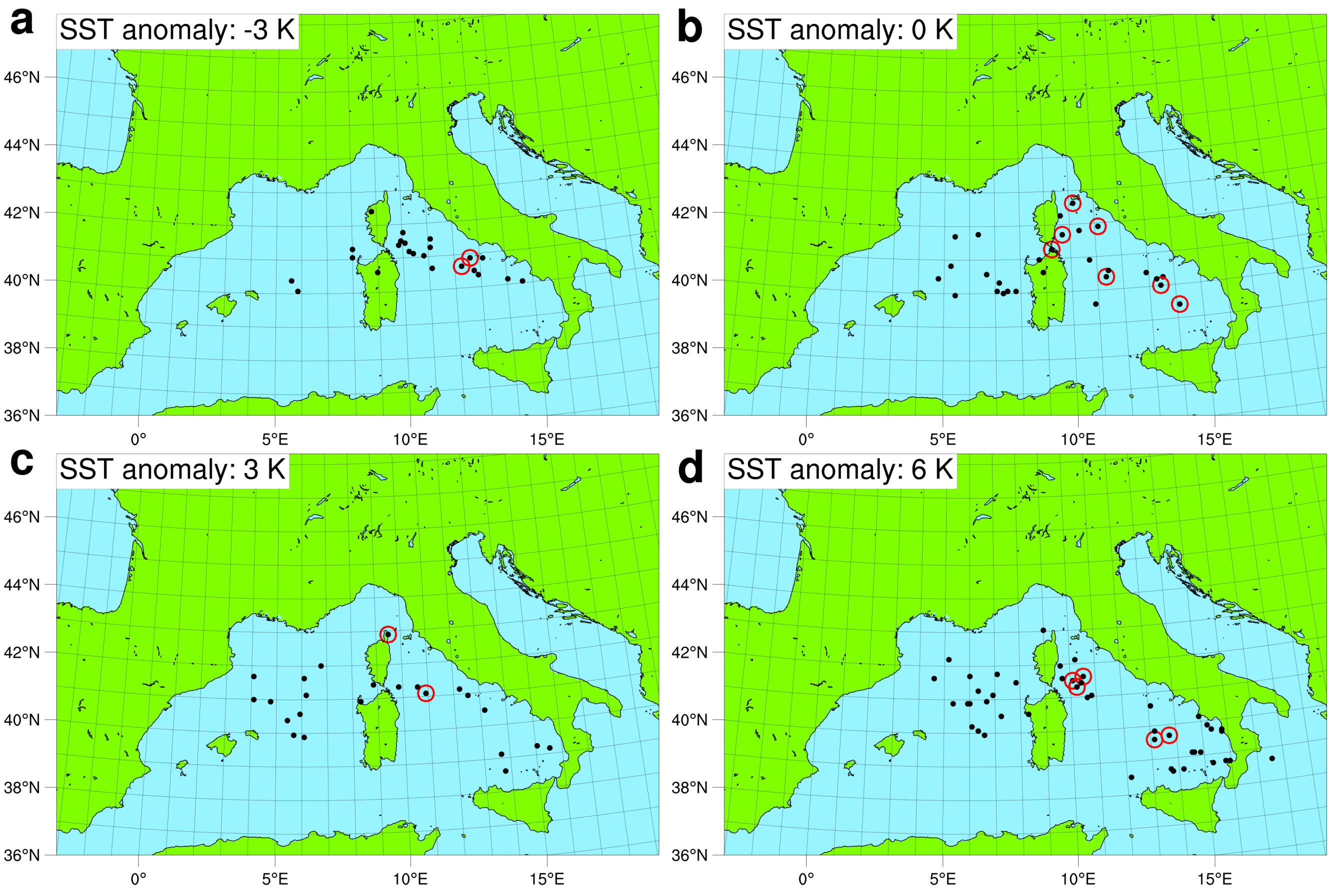

Figure 3: **Medicane transitions and re-transitions.** Transitions to medicane status are shown for all cyclones by black dots. Black dots surrounded by a red circle denote cyclones which re-transition to medicane status having previously lost medicane status while crossing Sardinia and Corsica. To identify such re-transitioning medicanes, cyclones which lost medicane status between 7.5 °E and 10.0 °E are first identified, and the location of their subsequent re-transitioning (if any) is marked with a red circle.

> *transition to the west of Sardinia temporarily lose their tropical nature while crossing the island and have a second transition after moving on the sea again?*

In our original response we stated that we had not detected any cyclones which re-transition to the east of Sardinia, having lost their medicane status while crossing Sardinia, but that we would investigate this in more detail for the revised version. We have now further investigated the issue (Figure 3) and can confirm that the hypothesis has some validity, though cannot completely explain the two separate maxima shown in Fig. 4 (formerly Fig. 3) of the main manuscript. As can be seen in Figure 3, some cyclones do re-transition to medicane status to the east of Corsica and Sardinia, having previously lost their medicane status while transiting the islands. In addition to that, some ensemble members have cyclones which lose medicane status while crossing the aforementioned islands and do not subsequently regain medicane status. In other ensemble members, medicane status is first achieved to the east of Sardinia and Corsica. Taken together, these points explain the double maxima referred to by the reviewer. We have added discussion of this information to the results section (P7 L15-17).

> *P6-L24: just looking at the figure, it doesn't look obvious to me - taking into account the error bars - that*

linearity can be excluded, did you do any statistical test?

We have performed a statistical test and linearity can be rejected at a significance level of 0.01. This test and result is now described in the Section 4.2 (P7 L26-29).

P7-L5: "they diverge when MWCT is approaching to reach a minimum at MWCT". The meaning of this sentence is not clear.

Thank you for pointing this out. We have re-worded the sentence as follows: "The curves are almost all equally spaced at -20 h, but they diverge as MWCT is approaching, and reach a minimum at MWCT for almost all SST states" (P8 L11-12).

Figure 6 and Figure 8: it seems that the minimum of mslp and the maximum of VTL are reached at MWCT for DeltaSSTs of +1 and larger, but not for negative SST anomalies. Maybe also an indication that the coherent warm core structure is lost when SST is decreased?

As discussed in the original response document, Figs. 6 and 8 (now Figs. 7 and 9) are produced based on composites of the strongest ten cyclones (from each SST state) which were classified as medicanes based on the objective medicane classification criteria. In particular, to be classified as medicanes all cyclones need to have a thermal symmetry (**B**) within an acceptable range indicative of tropical transition and this thermal symmetry criterion must also be met for MWCT to be defined. Having said that, being classified as a medicane at some point along its track ($-\mathrm{V}_T^U > 0$, $|B| < 10m$, $-\mathrm{V}_T^L > 0$) does not guarantee that the cyclone is still a medicane at MWCT ($-\mathrm{V}_T^U$ maximum, $|B| < 10m$, $-\mathrm{V}_T^L > 0$). Indeed, as stated in our response to the comment about P5-L16, we do find for all cyclones (even non-transitioning cyclones) at least one instant where MWCT can be defined. It is thus reasonable to speculate, as one could extrapolate from the reviewer's comment, that some of the low-SST cyclones which met the medicane criteria at some point along their tracks were no longer medicanes at MWCT, thus explaining why the maxima of $-\mathrm{V}_T^L$ and minima of MSLP come slightly before MWCT for the colder SST states (Figures 6 and 8 in original manuscript; now Figures 7 and 9) and suggesting the loss of a coherent warm-core structure.

Based on the above, we have carried out two additional analyses. We firstly investigated whether all members of the composites indeed retain their medicane status up to MWCT and how many members of each composite (i.e. one compostite per SST state) have medicane status at a given time relative to MWCT (Figure 4). Figure 4 shows that the loss of medicane status prior to MWCT, and by implication a coherent warm core stucture, does not explain why the maxima (minima) of $-\mathrm{V}_T^L$ (MSLP) are reached before MWCT in the colder SST ensembles. All members of all composites can be classified as medicanes at MWCT and there is no evidence of a decrease at colder SSTs in the number of composite members which can be classified as medicanes in the lead-up to MWCT.

We secondly carried out a regression between the magnitudes of $-\mathrm{V}_T^L$ and $-\mathrm{V}_T^U$ in the pre-MWCT period across all composite members, for each SST-state (Figure 5). Figure 5 shows the regression coefficients for each of these 11 regressions (one per SST state). From this analysis it is found that the warmer SST states show higher regression coefficients, implying that the magnitudes of $-\mathrm{V}_T^L$ and $-\mathrm{V}_T^U$ (a) are more similar and (b) evolve in greater temporal unison at warmer SST states than at colder SST states. In particular, the smaller differences between the magnitudes of $-\mathrm{V}_T^L$ and $-\mathrm{V}_T^U$ at warmer SST states suggests the devlopment of a deeper warm core. The development of a deep warm core is only possible in the presence of suffient latent heat release from convective updraughts, thus suggesting that this is lacking in the medicanes which form at colder SST states. This hypothesis is additionally supported by Figure 11 in the main manuscript (Figure 10 in old version), where it can be seen that during the pre-MWCT period, mean vertical transport through the 500 hPa surface in the colder SST medicanes is only a fraction of that found for warmer SST states.

Based on the above analyses, we have added further discussion to Section 4.2 (P8 L21-25). Here we state the outcome of the second analysis, what this suggests and how it should be interpreted with respect to the thermal

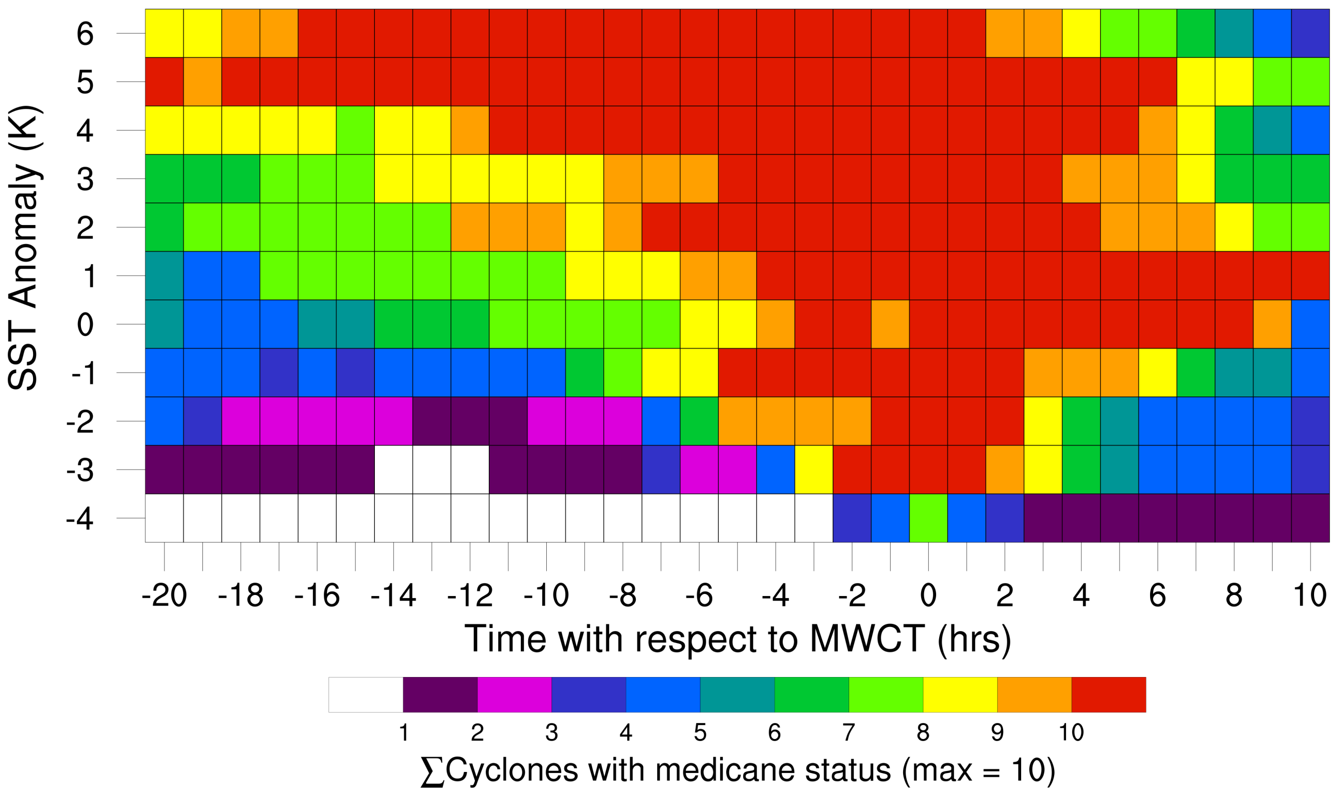

Figure 4: Number of medicanes in each composite (one composite per SST state; y-axis) which have medicane status at a given time relative to MWCT. Note that each composite contains 10 members, except for the -4 K anomaly SST composite, which contains only 7 members as only 7 members underwent transition. It is thus clear that for all composites, all members have medicane status at MWCT.

coherence of the medicanes at lower and higher SSTs (as mentioned in the preceding paragraph). We have also added Figure 4 in an appendix.

> *Figure 10: I find it would be clearer if the panels are arranged in two columns, with time increasing from left to right as as in Fig 9*

The panels have been revised as suggested.

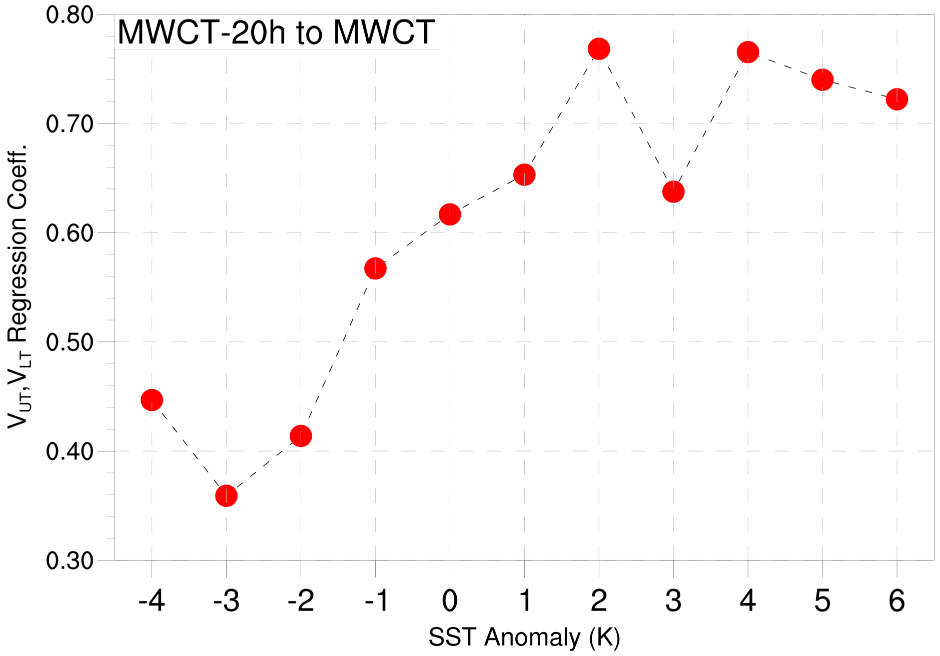

Figure 5: Regression coefficients between $-\mathrm{V}_T^L$ and $-\mathrm{V}_T^U$ in the period MWCT-20h to MWCT, for each SST state.

4 Response to Short Comment #1 (Mario Marcello Miglietta)

I would like to congratulate with the Authors for the interesting and comprehensive study of the Medicane Cornelia. I am actually performing simulations of the same case (but without changing SST) reaching similar conclusions.

Just a comment: I think that the Authors should make more clear that these simulations have to be interpreted in a statistical sense in the "numerical" world, so may not correspond exactly to the observed cyclone track (which I believe, is a bit southward compared to the track density in Figure 2b).

Also, numerical simulations with a coupled numerical atmospheric-wave-model of a Medicane have been recently published after Akthar et al. (2014). Ricchi et al. (Sesitivity of a Mediterranean tropical-like cyclone to different model configurations and coupling strategies, Atmosphere, 8, 92, 1-32, 2017) considered the case of November 2011 from a coupling modelling perspective. This paper may be helpful for the conclusive discussion.

best regards

Mario Marcello Miglietta

We thank the contributor for his comments. We have added a statement emphasizing that the results must be interpreted in a statistical/probabilistic sense to the Methods sub-section dealing with ensemble generation (P4 L5-12). We have further emphasized the statistical element in results Section 4.1 ("Probability of transition and track density", P6 L20-24). We also thank the contributor for the references, which are now both included in the Discussion (P11 L2-3).

References

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Assessing the impact of SSTs on a simulated medicane using ensemble simulations

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Abstract.

The sensitivity of the October 1996 medicane in the western Mediterranean basin to sea surface temperatures (SSTs) is investigated ~~via 24-member ensembles of~~ with a regional climate model ~~simulations. Eleven ensembles are created by uniformly changing SSTs in a range of~~ via ensemble sensitivity simulations. For eleven SST states, ranging from -4 K below to $+6$ K ~~from the observed field, with a~~ above the observed SST field (in 1 K ~~step~~steps), 24-member ensembles of the medicane are simulated. By using a modified phase space diagram and a simple compositing method, it is shown that the SST state has a minor influence on the tracks of the cyclones, but a strong influence on their intensities. Increased SSTs lead to greater probabilities of tropical transitions, to stronger low- and upper-level warm cores, and to lower pressure minima. The tropical transition occurs sooner and lasts longer, which enables a greater number of transitioning cyclones to survive landfall over Sardinia and to re-intensify in the Tyrrhenian Sea. The results demonstrate that SSTs influence the intensity of fluxes from the sea, which leads to greater convective activity before the storms reach their maturity. These results suggest that the processes at steady-state for medicanes are very similar to tropical cyclones.

1 Introduction

The Mediterranean basin is one of the most cyclogenetic regions in the world, a majority of its cyclones being baroclinic (Wernli and Schwierz, 2006). However, it has been shown since the 1960s, using remote sensing instruments, that unusual cyclones with a visual similarity to tropical cyclones are also sometimes observed (Ernst and Matson, 1983; Mayengon, 1984; Rasmussen and Zick, 1987). In contrast to asymmetric, synoptic scale extratropical cyclones, these cyclones are of a smaller scale, axisymmetric, frontless and, sometimes, with a well defined eye at their center. These cyclones are now referred to as Tropical-Like Mediterranean Cyclones, or Medicanes. According to the climatological study of Cavicchia et al. (2014a) over the last 60 years, medicanes have a low frequency activity of 1.57 ± 1.30 events per year.

Medicanes are intense low pressure systems that present similar characteristics to tropical cyclones: an area with no cloud at the center, spiral bands surrounded by deep convection, intense surface winds, a low- and upper-troposphere warm-core, formation over the sea, and a rapid dissipation after landfall (Pytharoulis, 2018). In recent decades, thanks to high-resolution regional numerical weather prediction models and observational data, detailed examinations of several medicane cases have been carried out (e.g. Reale and Atlas, 2001; Chaboureau et al., 2012; Miglietta et al., 2013; Tous and Romero, 2013; Tous et al., 2013; Picornell et al., 2013; Miglietta et al., 2015; Cioni et al., 2016; Miglietta et al., 2017).

The question of the influence of sea surface temperatures (SSTs) on the development and the characteristics of medicanes has been tackled by several studies. Reed et al. (2001) found a minor influence of small SST anomalies on the medicane of 23 January 1982. Homar et al. (2003) showed that the scenario of development of the medicane of 12 September 1996 had many similarities with the air-sea interaction instability mechanism, especially the latent-heat fluxes acting as a sustainer of convection. According to them, the medicane would have been both weaker and had a delayed development if the SSTs had been colder. Using an axisymmetric cloud-resolving model in which other environmental influences were not included, Fita et al. (2007) showed a strong sensitivity of the same medicane to SSTs. Miglietta et al. (2011) studied the impact of systematic changing of SSTs in a simulation of the 26 September 2006 medicane. According to them, the cyclone was mainly sensitive to uniform SST changes larger than 2 K and increasingly lost its tropical features as the SSTs became colder. Pytharoulis (2018) investigated the influence of SSTs through the imposition of climatological SSTs and uniform warm and cold SST anomalies on the 7 November 2014 medicane. A linear deepening and a longer lifetime of the medicane were observed as the SST anomalies increased from -3 K to $+1$ K.

The October 1996 Medicane was previously studied by Mazza et al. (2017), using a 50-member ensemble of regional climate model simulations. It was shown that standard extratropical dynamics were responsible for the cyclogenesis and that the tropical transition of the cyclone resulted from a warm seclusion process. Our present study aims to assess the role of SSTs in the development and the intensity of this cyclone. Ensembles are created for different SST states through dynamical downscaling of reanalysis data and applying a uniform change to the observed SST field in a range of -4 K to $+6$ K. As such, we seek to assess the sensitivity of the medicane to a range of SST changes extending well beyond observational uncertainty, and to instead consider SST changes in ranges more typically associated with natural or externally forced variability. To identify any potential threshold and/or non-linear behaviour in the system, we further extend the SST states to encompass the range -4 K to $+6$ K. To the best of our knowledge, ours is the first study to use ensemble simulations combined with uniform SST changes to evaluate the influence of SSTs on the formation of a particular medicane.

Section 2.1 provides an overview of the medicane case, while section 3 describes the model setup and ~~the methodology. The results~~ methodology. Results are presented in section 4, while the discussion and conclusions are included in section 5.

2 ~~Data and methodology~~Medicane case

2.1 ~~Experimental setup~~

In this paper we study medicane Cornelia, which occurred in the western Mediterranean between 7 and 10 October 1996. The cyclone ~~formed~~ is discussed in detail in Reale and Atlas (2001) and Cavicchia and von Storch (2012), with a synthesized description of the case in Mazza et al. (2017). Here we provide an abridged overview of the case.

Medicane Cornelia began its life as an extra-tropical cyclone with frontal structures on 6 October 1996 near the Algerian coast. By 1200 UTC 7 October it had tracked northwards under the steering flow of a 500 hPa cutoff low to lie between the Balearic Islands and Sardinia~~, then moved through Sardinia ,~~ . A clear eye-like structure was present by this stage (Mazza et al., 2017) and the central pressure had deepened below 1000 hPa (Reale and Atlas, 2001), with SSTs close to 20 °C (Figure 1). From here Cornelia tracked eastwards, crossing Sardinia on 8 October and weakening over land, before re-intensifying as it tracked east into the Tyrrhenian Sea ~~and finally dissipated after landfall over Calabria. For a synthesized description of the case see Mazza et al. (2017), and see Reale and Atlas (2001) and Cavicchia and von Storch (2012) for a more extensive report~~(Cavicchia and von Storch, 2012). By 9 October the medicane was situated north of Sicilly, with the central vortex having become more intense and compact (Reale and Atlas, 2001). Cornelia then tracked south-eastwards, crossing Calabria on the night of 9 October, where intense winds were recorded, before dissipating in the Ionian Sea during 10 October (Reale and Atlas, 2001).

3 Data and methodology

3.1 Experimental setup

The numerical simulations are performed with the full-physics, non-hydrostatic COSMO Climate Limited-Area Model (CCLM; Rockel et al. (2008)) version cosmo4.8-clm19. CCLM is the community model of the German regional climate research community jointly further developed by the CLM-Community. The two-step downscaling configuration ~~consists of~~ begins with a 257×271 grid point, 0.165°-resolution parent domain ~~in which a~~ which is forced at the lateral boundaries by ERA-Interim reanalysis (Dee et al., 2011). A 288×192 grid point, 0.0625°-resolution ~~inner domain is nested~~domain (Figure 1) is then nested within the 0.165° parent domain; the 0.165° domain covers an area slightly smaller than the EURO-CORDEX domain (Jacob et al., 2014) and is shown in Mazza et al. (2017). For both downscaling steps the model setup includes an extended microphysics scheme accounting for cloud water and cloud ice for grid-scale precipitation based on Kessler (1969), the Ritter and Geleyn (1992) radiation scheme, and the Tiedtke parametrization scheme for convection (Tiedtke, 1989). Heat fluxes from the ocean to the atmosphere are parameterized using a stability and roughness-length dependent surface flux formulation based on Louis (1979). Both domains feature 40 vertical levels and a 6-hourly update of the boundary conditions. One ensemble is performed, driven by the 0.7° resolution ERA-Interim reanalysis (Dee et al., 2011).

3.2 Ensemble generation

According to previous studies (Davolio et al., 2009; Chaboureau et al., 2012; Cioni et al., 2016; Mazza et al., 2017), numerical forecasts are highly sensitive to initial and boundary conditions. In particular, the location of the lateral boundaries can have a strong ~~impacts~~ impact on circulation anomalies within the model domain (e.g. Miguez-Macho et al., 2004; Becker et al., 2018). In this study, the technique of domain shifting is employed to generate an ensemble (Pardowitz et al., 2016). This technique consists of two downscaling steps with a series of simulations with domains which are slightly shifted in space. We use the same procedure as in Mazza et al. (2017):

- 1st downscaling step:

- Locate a central domain over Europe (same as in Mazza et al. (2017))
- Shift the central domain in longitude and latitude in eight directions (north, south, east, west, northeast, northwest, southeast, southwest) in three steps (0.25°, 0.50°and 0.75°)
- Run the model on each of the 24 domains using ERA-Interim as initial and boundary conditions

- 2nd downscaling step:
  - Use the 24 simulations of the 1st downscaling step as initial and boundary conditions for the smaller, nested domain (Figure 1) with a finer resolution over the western and central Mediterranean basin

This results in one set of 24 simulations for the reference (observed) SSTs from ERA-Interim. It is important to emphasize that all choices of domain boundaries are equally valid and that the central "un-shifted" domain is not the "correct" domain. Any simulated differences between the ensemble members are thus a consequence of the inherent uncertainty resulting from forcing the regional model with imperfect boundary conditions (i.e. reanalysis) and the chaotic nature in which the system responds to differences in the lateral boundary conditions. As such, the potential subsequent formation of a medicane should always be considered in a probabilistic rather than a deterministic manner. Simulated characteristics of the medicane, for example its track, must thus also be interpreted in a statistical sense and the ensemble mean characteristics may not correspond exactly to the observed characteristics, which are themselves just one of many potential realizations.

As in Mazza et al. (2017), the initialization time of the first step simulations is 0000 UTC 1 October 1996, while the inner domains are initialized at 0000 UTC 4 October 1996. A 72-h lag was previously found to be a satisfactory compromise between introducing sufficient spread in the ensemble and the ability to capture the event in the simulations (Mazza et al., 2017).

3.3 SST changes

To assess the sensitivity of the October 1996 medicane to SSTs, we perturb the SST forcing in the 0.0625° domain by adding SST anomalies in a range of -4 K to $+6$ K, in 1 K increments, to the observed SST field. In addition to the observed-SST ensemble, this creates 10 extra 24-member ensembles of the case, each with their own unique SST forcing. SSTs were modified uniformly across the entire 0.0625° domain.

3.4 Cyclone phase space

We ~~use~~ base our analyses on the three-dimensional ~~diagnostic methodology~~ diagnostics proposed by Hart (2003), which ~~has already been successfully~~ was first applied to the study of medicanes ~~(Davolio et al., 2009; Cavicchia and von Storch, 2012; Miglietta et al.,~~ ~~analyze their~~ by Chaboureau et al. (2012) and subsequently by others (Miglietta et al., 2013; Mazza et al., 2017), to analyze medicane tropical transition. ~~We use a modified version of the original phase space to take into account the limited vertical extent and the smaller spatial scale of medicanes compared to tropical cyclones (Picornell et al., 2013; Miglietta et al., 2013; Cioni et al., 20~~ The three following parameters ~~that define the phase space~~ are computed in a radius of 150 km from the cyclone's centre (as successfully used by Mazza et al. (2017)) ~~:~~ and are used to define the cyclone phase space:

– The thermal symmetry in the lower troposphere (B): the difference in mean 600-900 hPa thickness between left and right semi-circles with respect to the cyclone's trajectory

– The lower-tropospheric thermal wind ($-\mathrm{V}_T^L$): the vertical derivative of the cyclone's geopotential height perturbation between 900 and 600 hPa

– The upper-tropospheric thermal wind ($-\mathrm{V}_T^U$): the vertical derivative of the cyclone's geopotential height perturbation between 600 and 400 hPa

The exact definitions which we use for these parameters represent a modified version of the diagnosticss proposed by Hart (2003), which take into account the limited vertical extent and the smaller spatial scale of medicanes compared to tropical cyclones (Picornell et al., 2013; Miglietta et al., 2013; Cioni et al., 2016; Mazza et al., 2017). Our exploration radius is thus reduced from 500 km to 150 km and the upper bound of $-\mathrm{V}_T^U$ is reduced from 300 hPa to 400 hPa. The resulting phase space diagrams can be very erratic at an hourly time scale. Therefore, a 3-hour running mean is applied to the computed parameters to give the final phase space diagram. Following Hart (2003), in order to classify a cyclone as a medicane the following objective criteria must apply simultaneously at at least one time step: $\mathrm{B} < 10$ m, $-\mathrm{V}_T^L > 0$ and $-\mathrm{V}_T^U > 0$.

3.5 Cyclone tracking

The simulated cyclones are tracked based on the mean sea-level pressure (MSLP). As hourly data was used, this proved to be sufficient to correctly follow the cyclone track. The tracking algorithm works as follows:

– Initially, the location of the minimum of pressure is identified within the area of the western Mediterranean basin at 0000 UTC 8 October; at that point in time the cyclone is fully developed with core pressure below 1013 hPa, it is located over Sardinia and is found in every simulation

– The positions of the MSLP minima in the adjacent time steps (backward and forward in time) are determined using a nearest-neighbor algorithm, applied within a circle with a radius of 0.9° from the previous MSLP minimum

– The algorithm stops if the cyclone's minimum pressure exceeds 1013 hPa or has made landfall at the French or Spanish coastline (Corsica, Sardinia, Sicilia and continental Italy are not considered as landfall)

– Every track is verified manually with respect to its consistency with the MSLP fields

This algorithm gives coherent trajectories, both for cyclones with and without a tropical transition. The algorithm assures that only one cyclone track is identified in each ensemble member. Continental Italy is not considered as landfall in order to follow the medicanes even when they make landfall, in particular in order to calculate the evolution of the phase space parameters after landfall. In practice, medicanes dissipate rapidly after landfall.

This method gives reasonable tracks during most of the cyclone's life time, which allows the computation of the phase space parameters. In the early phase of the cyclone the tracks can be slightly erratic. However, this does not affect the results, because this period is ~~excluded from the analysis~~before the earliest stage of the cyclone's life used for composite analysis (20 hours before the time of maximum warm-core strength; see Section 3.6). The phase space parameter B could significantly change with a more sophisticated tracking algorithm, because it is sensitive to the exact location of the track position. ~~However,~~ While our method to distinguish a medicane from a non-medicane requires that all criteria mentioned in Section 3.4 are fulfilled simultaneously, for the systems considered in this study the evaluation of $-\mathrm{V}_T^U$ ~~on its own proved to be sufficient to discriminate between medicanes and non-medicanes~~alone would have led to the same systems being identified.

Track density plots are obtained by counting, for each grid point, the number of tracks that cross a 50 km radius circle around the respective grid point for all members of a given SST ensemble, and dividing by the total number of tracks (see Kruschke et al. (2016) for a similar method applied to Northern Hemisphere winter storms).

3.6 Cyclone compositing

In order to extract the mean signal from fields that show large variability, we use a simple arithmetic averaging technique called cyclone compositing. This technique has been frequently applied to both extratropical and tropical cyclones (e.g. Frank, 1977; Bracken and Bosart, 2000; Bengtsson et al., 2007; Catto et al., 2010; Mazza et al., 2017). Following Mazza et al. (2017), we align the temporal evolution of the simulated cyclones to a common reference time: for each track we identify the time step when $-\mathrm{V}_T^U$ is maximum, $B < 10$ m and $-\mathrm{V}_T^L > 0$. This instant is meant to reflect the stage of maximum warm-core strength, and is hence referred to as the maximum warm-core time (MWCT).

Such an instant is found for all cyclones analysed in this study, even non-transitioning ones. As we focus on transitioning cyclones, ~~we build one composite for each SST state by averaging~~ for studying mechanisms it proves most instructive to base our analyses on composites of the 10 ~~transitioning cyclones~~ most powerful transitioning cyclones for each SST, i.e. those that have the ~~largest~~ greatest $-\mathrm{V}_T^U$ at MWCT (except when $\Delta\mathrm{SST} = -4$ °C because ~~there~~ here only 7 ~~transitioning cyclones occur).~~ cyclones transition). Results are insensitive to whether we take the mean or median of the composited cyclones.

4 Results

4.1 Probability of transition and track density

With the specified criteria based on the phase space parameters, it is determined if a cyclone ~~encounters~~ undergoes a tropical transition, i.e. if it can be regarded as a medicane. This is done for each of the 24 ensemble members of each of the 11 SST ~~settings~~states. It is ~~shown~~ found that increasing SSTs leads to an increasing number of medicanes (~~Fig.~~ Figure 2a). While at $\Delta\mathrm{SST} = -4$ K only 30% of the ensemble members generate a transitioning cyclone, at +5 K and +6 K all members produce a medicane. Worth noting is that even with observed SSTs, i.e. $\Delta\mathrm{SST} = 0$ K, medicane transition probability is less than 85%. This points towards the probabilistic nature of medicane formation: the observed medicane was one of many potential realisations for the observed SST state; small changes in the observed initial conditions could have developed to inhibit the real-world formation of medicane Cornelia too. The largest increase in medicane development rate is found between -4 K and

-3 K (from 7 to 16 medicanes). It could be speculated that this sudden increase is related to a specific SST threshold, similar to the empirical threshold of 26.5°C, which is found for the development of tropical cyclones (Gray and Brody, 1967). However, here the SSTs are much lower, around 20 °C.

From each ensemble, those cyclones which are classified as a medicane are selected. For this subset, the mean and standard deviation of the period of time during which the cyclone was classified as a medicane is calculated. The length of this period increases almost linearly with increasing SSTs (~~Fig.~~ Figure 2b). For an SST change of -4 K, the period of time is very short with values of around 5 h. In contrast, the period of time lasts longer at higher SSTs. For example, at $\Delta\mathrm{SST} = +6$ K the cyclones are classified as medicanes on average for about 104 h. Not only the mean, but also the standard deviation between the time periods in the different ensemble members increases with increasing SSTs.

Figure 3 presents track densities of cyclones for an SST change of -3 K, 0 K, +3 K and +6 K. The figure must be viewed taking into account that cyclones begin to form between Sardinia and the Balearic Islands, then move through Sardinia and finally go south-east of the Tyrrhenian Sea. All track density plots are very similar when SSTs change and it only seems to be a greater dispersion of tracks when we increased SSTs, especially east of Sardinia and south of continental Italy. Therefore, one can conclude that the SST state has little influence on the track of the medicane, with the large-scale steering flow instead playing the dominant role.

However, ~~figure~~ Figure 4 shows the track densities obtained with the same method, but where tracks are taken into account only when cyclones are classified as medicanes. The two local maxima of density east and west of Sardinia illustrate that the simulations exhibit two distinct classes of medicane formation: those for which MWCT occurs before crossing Sardinia, and which weaken after the crossing, and those for which MWCT occurs after crossing Sardinia, mostly near the Italian peninsula, and continue to deepen after the crossing. It is observed that between 60% to 85% of the medicanes are of the second type, depending on the SST change. However, there is no systematic dependency between the observed percentage and ΔSST. ~~Fig.~~ While some medicanes of the first type which lose their medicane status while crossing Sardinia go on to re-transition in the Tyrrhenian Sea, others fail to regain medicane status. In addition to this, many medicanes of the second type first achive medicane status in the Tyrrhenian Sea, as suggested by the two local maxima. Figure 4 also shows that, apart from increasing the period of time when cyclones are transitioning, the track is always similar: first transition before Sardinia, crossing Sardinia then moving south-east to Calabria through the Tyrrhenian Sea. Even if the variability is increasing with higher SSTs, it seems that tracks are not SST-dependent.

4.2 Intensity of the cyclones

As a first step, the intensities of the cyclones are analyzed in terms of the minimum core pressure. For this purpose, the composite ~~minimum of mean~~ (see Section 3.6) sea-level pressure minimum (i.e. the mean of ~~minimum pressure along the track~~ the ten pressure minima from the tracks of the ten cyclones that have the greatest $-\mathrm{V}_T^U$ at MWCT) is calculated for each ΔSST. The composite ~~minimum of MSLP decreases non-linearly~~ mean of the minimum MSLP decreases from 1004 hPa at -4 K to 981 hPa at $+6$ K~~(Fig. 5). Although~~ , while the standard deviation, i.e. the variability, ~~becomes very high for an SST change of +6 K, it is clear~~ between the individual ensemble members strongly increases at higher SSTs (Figure 5). A regression equation specification error test (Ramsey, 1969) showed that the null hypothesis that the relationship between ΔSST and minimum MSLP is linear can be rejected at a significance level of 0.01. That means that there is a non-linear relationship between SSTs and the minimum of pressure of the medicanes. SSTs seem to act as an amplifying factor of an already existing minimum of pressure caused by a higher tropospheric feature.

As the SSTs are not uniformly distributed in the Mediterranean Sea, one may ask whether the differences between the different realizations of the cyclone are caused by differences in the local SSTs along the specific cyclone tracks of the individual ensemble members. To assess the role of local SSTs along the cyclone tracks, we calculate the mean SSTs in a radius of 150 km around the cyclone center and take the average of those values from MWCT−20 h until MWCT for each track. These average SST values are presented together with the minimum pressure for all ensemble members of all SST states (including non-transitioning cyclones) in Figure 6. For each SST state, the local SSTs encountered by all cyclones before MWCT vary in a range of 1 K around a mean value. In each ensemble the local SSTs along the cyclone track are thus roughly similar. The minimum of pressure, however, can still vary considerably. For example, at +6 K the simulated values of minimum pressure range from 954 hPa to 1002 hPa. ~~This indicates that on the one hand~~ In addition to this, we also find that there are certain ensemble members, i.e. those with particular domain shifts, that enter the 10-member composites more often than others across the range of SST states. Taken together, these findings indicate that while there is a clear tendency ~~to have more intense cyclones~~ towards more intense medicanes at higher SSTs, ~~while on the other hand, the~~ higher SSTs are not the sole criterion for an intense medicane. A mesoscale environment supportive of rapid intensification and tropical transition is also crucial, and local SSTs are not sufficient to fully account for the variability of the cyclones' minimum pressure.

Figure 7 shows the temporal evolution of the composite minimum of sea level pressure for all ΔSST from −20 h before to +10 h after MWCT. ~~Every lines~~ The curves are almost equally spaced at −20 h, but they diverge ~~when~~ as MWCT is approaching~~to~~, and reach a minimum at MWCT for almost ~~every SST change~~all SST states. It is evident that at higher SSTs ~~the deepening process of the medicane begins earlier and that~~ medicane transition and deepening begins earlier, the deepening rate is larger~~than~~, and the medicanes retain their tropical-like structure longer compared to at lower SSTs (Figs. 7, A1).

It is observed that the phase space parameters $-\mathrm{V}_T^U$ and $-\mathrm{V}_T^L$ at MWCT increase linearly with increasing SSTs (~~Fig.~~ Figure 8). It is obvious that medicanes are getting stronger when SSTs increase, as the thermal winds between 600-900 hPa and 400-600 hPa at MWCT are increasing in almost the same proportion. ~~Fig.~~ Figure 9 presents the temporal evolution of the composite of those two parameters from −20 h before to +10 h after MWCT for each ΔSST. There is roughly a parallel evolution for each ΔSST for the parameter $-\mathrm{V}_T^U$, with similar rates of increase. This contrasts to the evolution of minimum pressure, which showed different rates for different ΔSST (~~Fig.~~ Figure 7). The evolution for the parameter $-\mathrm{V}_T^L$ is more erratic but, at least for positive SST changes, the observation is similar. Regressing the hourly magnitudes of $-\mathrm{V}_T^U$ and $-\mathrm{V}_T^L$ against each other in the period MWCT-20 h to MWCT, separately for each SST state composite, reveals greater differences in the magnitudes of $-\mathrm{V}_T^U$ and $-\mathrm{V}_T^U$ at colder SST states. This suggests the development of a deeper medicane warm core with higher thermal coherence in the warmer SST composites, likely generated by enhanced upper-level latent heat release from more intense convective updraughts at higher SSTs (Figure 10).

4.3 The influence of the fluxes from the sea

Similarly to tropical cyclones, the main source of potential energy of medicanes is the thermodynamic disequilibrium between the atmosphere and the underlying sea surface. Therefore, it is generally accepted that there is a direct relationship between SST and cyclone intensity (Miglietta et al., 2011). The prescribed SST changes directly affect the sensible and latent heat fluxes from the ocean into the atmospheric boundary layer. To analyze the heat fluxes under the different SST conditions, the composite structure of the latent heat fluxes from the sea are computed 20 h and 10 h before MWCT, and at MWCT. The horizontal structure of the medicane is remarkably well defined for ΔSST $= +3$ and $+6$ K, with strong gradients of pressure near the center of the cyclone, very low heat fluxes in the eye region and the strongest heat fluxes of more than 400 W/m2 in a radius between 50 and 100 km around the center (~~Fig.~~ Figure 11). This structure is consistent with the air-sea interaction proposed by Emanuel (1986) for tropical cyclones. It is worth noting that the horizontal structure of the fluxes is not perfectly symmetrical, which is caused by the surrounding islands and continental land area. In particular, there are systematically weaker fluxes north-east of the composite medicane. This effect is the imprint of continental Italy, which is characterized by considerably lower latent heat fluxes than the ocean areas.

For ΔSST $= -3$ K there is no well defined spatial structure in the composite heat fluxes and the heat fluxes are very low with values below 150 W/m2 (~~Fig.~~ Figure 11, top row). Nevertheless, the cyclones of this composite are classified as a medicane based on the phase space parameters. Therefore, the fluxes from the sea might play a minor role in the formation of those medicanes.

In composites of vertical cross section around the cyclone centers, the vertical wind speeds were analyzed (not shown). It was found that the largest vertical wind speeds occur in the middle troposphere around 500 hPa. Figure 10 shows the 10 h mean of the vertical wind speeds at the 500 hPa level of the composite medicane and its evolution before MWCT. Maximum vertical wind speeds occur around 50 km away from the center of the cyclone, similar to the strongest heat fluxes. This reflects the development of deep convection in the entire troposphere, i.e. the deepening process which leads to the intensification of the medicane. As in the case of the heat fluxes, the intensity of the vertical wind speeds increases with increasing SSTs.

As one would expect, fluxes from the sea are higher when SSTs increase, leading to greater vertical wind speeds and hence more intense deep convection throughout the troposphere. This in turn leads to a more intense deepening of the medicane and stronger sea level pressure gradients, thus more intense medicanes. This chain of processes is coherent with the classical model of Emanuel (1986) for the steady-state of tropical cyclones.

5 ~~Discussion and conclusions~~

5 Discussion and conclusions

In this study the sensitivity of a simulated medicane in the western Mediterranean to SSTs was analyzed in an ensemble of full-physics, non-hydrostatic regional model simulations with COSMO-CLM. In a first downscaling step, 24-member ensembles were created by systematic shifts of the model domain. In a second downscaling step with a horizontal resolution of 0.0625°, SSTs were changed uniformly by adding SST anomalies in a range of -4 K to +6 K, in 1 K increments, to the observed SST field, creating eleven 24-member ensembles.

The cyclones were analyzed and classified according to a modified cyclone phase space following Hart (2003). For each SST change, out of the transitioning cyclones, the 10 cyclones featuring the strongest upper-level warm cores were composited (except when $\Delta\mathrm{SST} = -4$ K because there are only 7 transitioning cyclones; see Section 3.6).

It was shown that the number of transitioning cyclones increases with increasing SSTs. A particularly strong increase was found between $\Delta\mathrm{SST} = -4$ K and -3 K, which corresponds to average SST values of around 16 °C within the area of medicane development. These results support the idea that a threshold exists for tropical-like cyclones in the Mediterranean Sea, similar to for tropical cyclones (Gray and Brody, 1967). Miglietta et al. (2011) suggested that, as the presence of medicanes is associated with cold-air intrusions, they can form even when the SSTs are below the threshold of 26.5 °C for tropical cyclones. Similarly, the duration of the transition increased almost linearly with SSTs. The cyclone tracks showed small random variations in the different ensemble members. However, the tracks of the cyclones, with or without tropical transition, showed no systematic dependency on SSTs compared to the control situation ($\Delta\mathrm{SST} = 0$ K). This suggests that the track characteristics depend rather on the large-scale dynamics of the upper-level low, which determines the environmental steering conditions relevant for the movement of the medicane.

~~The intensity of the composite medicane~~ Once the mesoscale environment is conducive to tropical transition and the formation of a strong medicane, medicane intensity depends strongly on SSTs~~. Its~~ , as found in our composites. The composite medicane's minimum of pressure decreases when SSTs increase, following a non-linear relationship, in contrast to the intensity of its low- and upper-troposphere warm core, which follow the linear evolution of the duration of the medicane. The process of transitioning is roughly similar when SSTs change, except that the cyclones transition earlier and are less affected by orography when crossing Sardinia. As SSTs increase, the sensible and latent heat fluxes from the sea into the atmosphere increase. The vertical wind speeds in a region of 50 km around the eye of the medicane also increase, which can be explained by an intensification of deep convection processes caused by the increased heat fluxes. This deep convection leads to deeper sea level pressure minima and stronger pressure gradients and upper-level warm cores, which occur at the same time, just before the medicanes make landfall and begin to dissipate.

Miglietta et al. (2011) found in a similar study of uniform SST changes that the sensible- and latent-heat fluxes from the sea surface during the transit of the cyclone across the Mediterranean Sea have the effect of modifying the boundary layer and are thus efficient mechanisms for convective destabilization. They concluded that warmer (colder) SSTs produce stronger (weaker) sea-surface fluxes, favoring an earlier (delayed) removal of convective inhibition and enhancing (reducing) the development of convection and the intensification of the cyclone. The results of our study, using ensemble simulations, are in strong agreement with these conclusions. They also concluded that taking $\Delta\mathrm{SST}$ as a control parameter, the critical value for which the atmospheric circulation displays the appearance of the medicane, having the characteristics of the actually observed phenomenon, is about $\Delta\mathrm{SST} = -3$ K. Even though we did not compare our results to the observed phenomenon and the situation they studied is located further south than ours, therefore showing higher SSTs of 1 to 2 °C, we also find that a critical value for the appearance of medicanes is around $\Delta\mathrm{SST} = -3$ K. Pytharoulis (2018) found an almost linear deepening of the medicane and an increasing life-time as the SST anomalies increased from ~~3~~ -3 K to $+1$ K. A non-linearity was, however, found as even warmer SST anomalies were applied: a weaker medicane was simulated and this was mainly attributed to the lack of a well defined upper air warm core. A non-linearity was also found at warmer SSTs in our study, but only for minimum pressure and in the direction of deepening and not weakening.

It is clear that our approach using prescribed SST changes can not fully simulate the impact of SSTs on the development of a medicane, since feedback processes from the medicane to the ocean are not taken into account. In particular, our modelling strategy reflects AMIP-studies, where the complexity of ocean-atmosphere interactions are removed from the modelling process by using prescribed SSTs in global atmospheric general circulation models (Gates, 1992). This allows a clear but rather idealized attribution of the observed effects to the applied SST changes. It should be noted that the inflow into the computational domain is not changed, thus producing a large ~~differences~~ difference between SSTs and air temperatures close to the lateral boundaries. Furthermore, strong gradients are also induced between SSTs and land temperatures. However, the temperatures over land, in particular in the coastal areas, proved to adapt rapidly to the SST changes before the formation of the cyclone. ~~Akhtar et al. (2014)~~ Ricchi et al. (2017) studied the impact of the modelling approach, namely with or without ocean-atmosphere coupling, on simulated medicanes and found the medicane tracks and intensities to exhibit little sensitivity. Akhtar et al. (2014), meanwhile, studied the robustness of COSMO-CLM coupled with a one-dimensional ocean model (1-D NEMO-MED12). They showed that at high resolution, the coupled model is able to not only simulate most ~~of~~ medicane events but also improves the track length, core temperature, and wind speed of simulated medicanes compared to the atmosphere-only simulations, suggesting that the coupled model is more proficient for systematic and detailed studies of historical medicane events. It would be valuable to assess the role of SSTs with such a coupled model.

With climate change, in the last decades of the 21st century (2070-2099), the SSTs of the Meditteranean Sea are projected to increase by 1.73 to 2.97 K relative to 1961-1990 (Adloff et al., 2015). Similarly to Pytharoulis (2018), the results of this study suggest that, if the upper air conditions of the atmosphere remain unchanged, stronger and longer lasting medicanes than today would appear more frequently in the Mediterranean basin. However, the development of medicanes is influenced by additional factors like the presence of baroclinic instability or a cold cut-off low in the upper atmospheric layers. It is likely that climate change will also affect these factors. Romero and Emanuel (2013) and Cavicchia et al. (2014b) both showed that the intensity of medicanes is projected to increase, while their frequency will decrease. Ensemble sensitivity studies, such as that presented here, are thus a valuable tool for offering insights into how the life-cycles of medicanes may differ in a warmer climate.

Code and data availability. Information about the availability of the COSMO-CLM source code can be found at <https://www.clm-community.eu>. The simulation data generated as part of this work have been archived at the DKRZ World Data Center for Climate <https://www.dkrz.de/up/systems/wdcc> and are publicly available under an open access license at <http://cera-www.dkrz.de/WDCC/ui/Compact.jsp?acronym=DKRZ_LTA_961_ds00005>, and citable as Noyelle et al. (2018). Researchers interested in scientific collaboration and/or data usage are asked to contact the authors.

Appendix A: Additional Results

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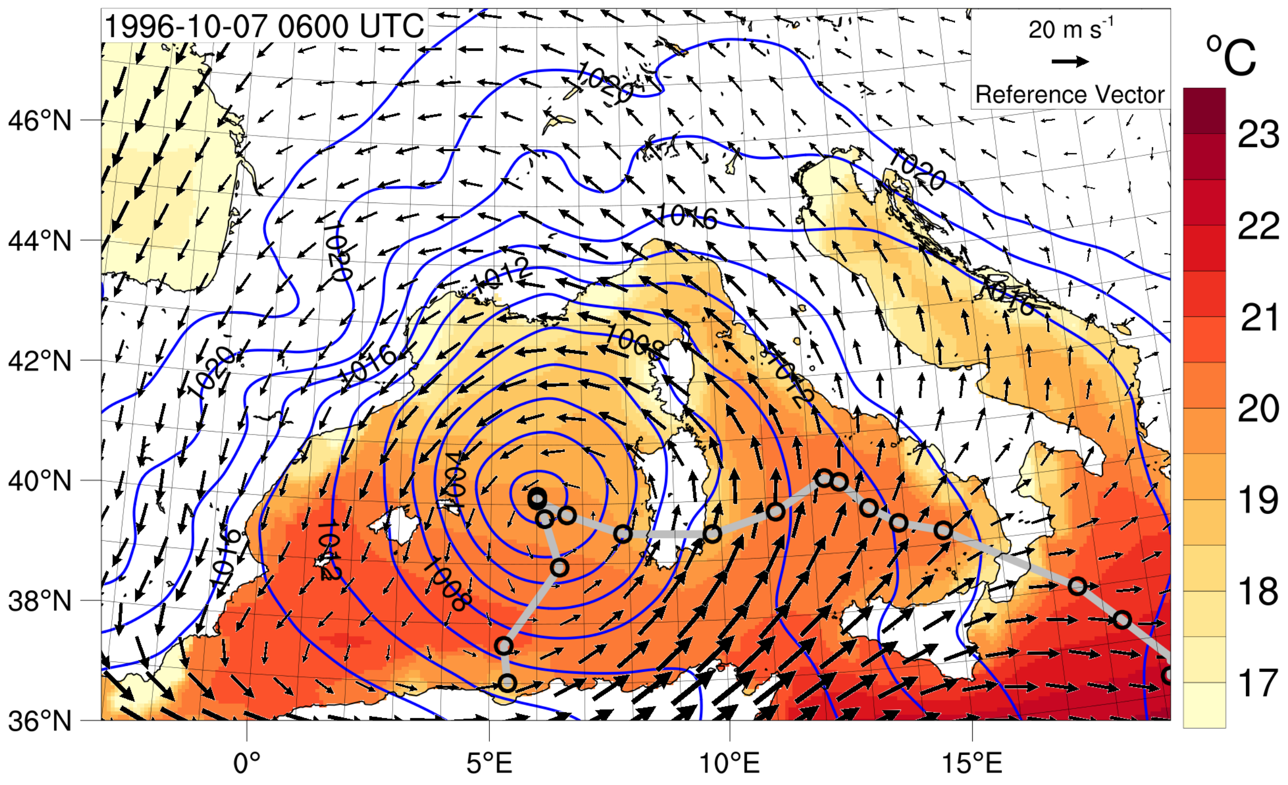

Figure 1. Inner simulation domain (0.0625° resolution) and medicane in reanalysis. SSTs (shading), sea-level pressure (hPa, blue contours) and 500-hPa wind vectors, representative of the steering flow, are shown for the 7th of October 1996 at 0600 UTC. The cyclone's track is shown with a grey line, marked at 6-hour intervals from 6th October 1996 at 0600 UTC. Plot based on ERA-Interim data.

Figures

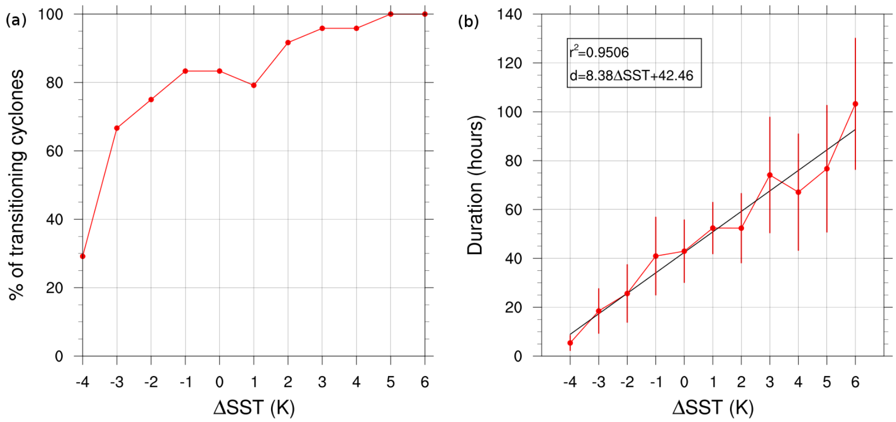

Figure 2. (a) Percentage of cyclones encountering a tropical transition over the 24-member ensembles for different SST changes, using classification criteria based on the cyclone phase space. (b) Mean period of time during which transitioning cyclones are classified as medicanes for different SST changes. Error bars represent standard deviation. The black line is based on a linear regression.

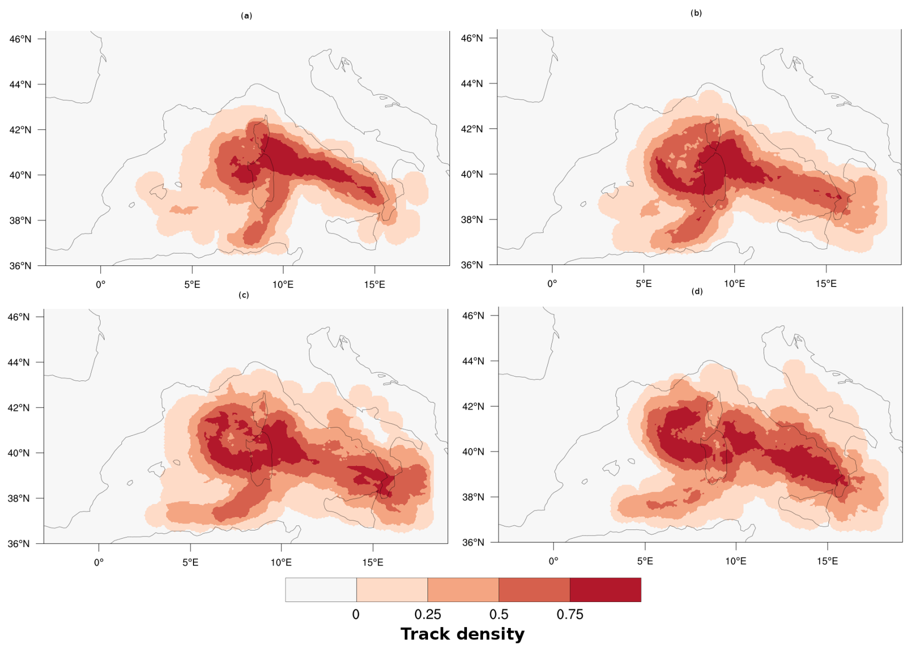

Figure 3. Track densities based on all cyclones for an SST change of a) −3 K, b) 0 K (original SSTs), c) +3 K and d) +6 K.

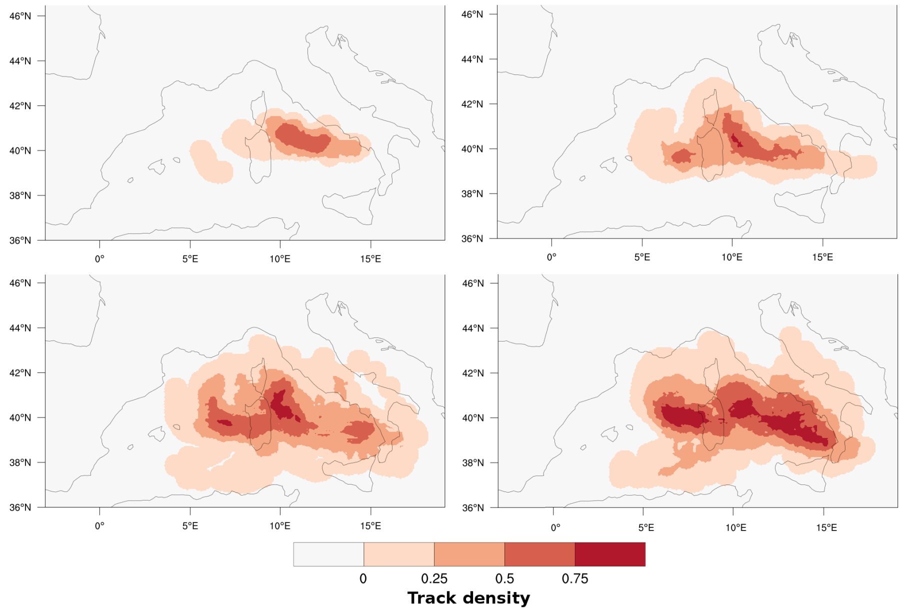

Figure 4. Track densities based on all cyclones classified as medicanes for an SST change of a) -3 K, b) 0 K (original SSTs), c) $+3$ K and d) $+6$ K.

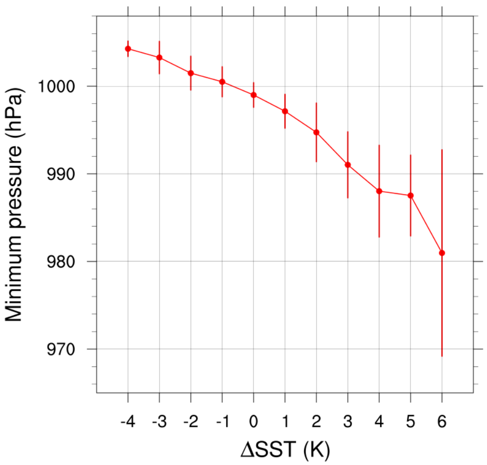

Figure 5. Dependence of composite minimum pressure on SST change. The error bars represent standard deviation.

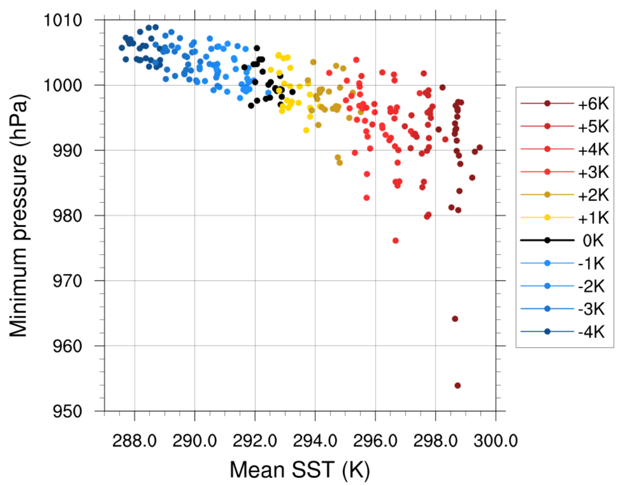

Figure 6. Dependence of minimum pressure on mean SST in a radius of 150 km, as encountered by the cyclone from from -20 h before MWCT until MWCT. Colors represent global SST change. Note that this plot is based on all cyclones and is not a composite average.

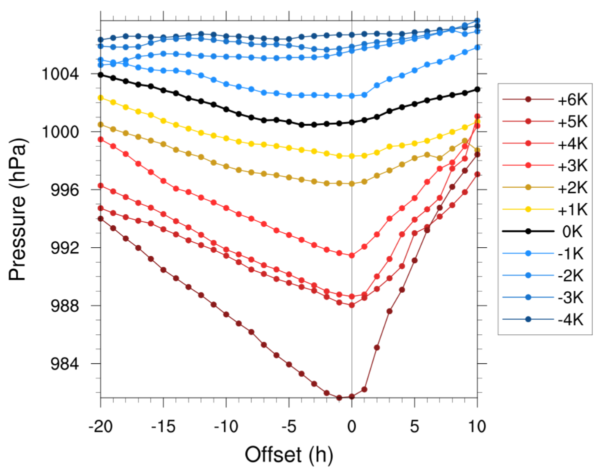

Figure 7. Composite time series of minimum pressure from -20 h before until $+10$ h after MWCT for each SST change.

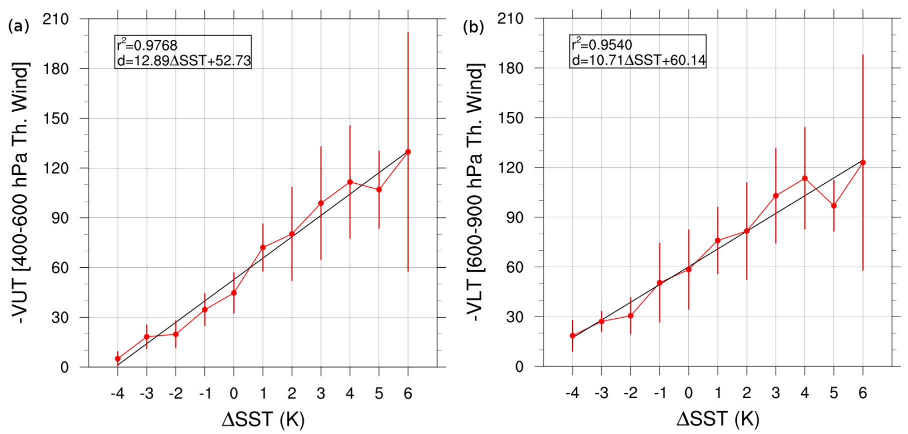

Figure 8. Dependence of composite of (a) $-\mathrm{V}_T^U$ and (b) $-\mathrm{V}_T^L$ at MWCT on SST change. The error bars represent standard deviation.

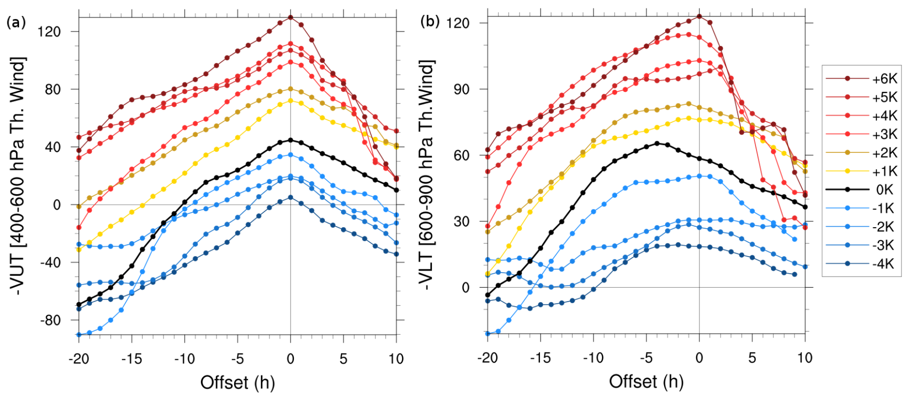

Figure 9. Composite time series of (a) $-\mathrm{V}_T^U$ and (b) $-\mathrm{V}_T^L$ from -20 h before to $+10$ h after MWCT for each SST change~~(for the meaning of each colour see 7)~~.

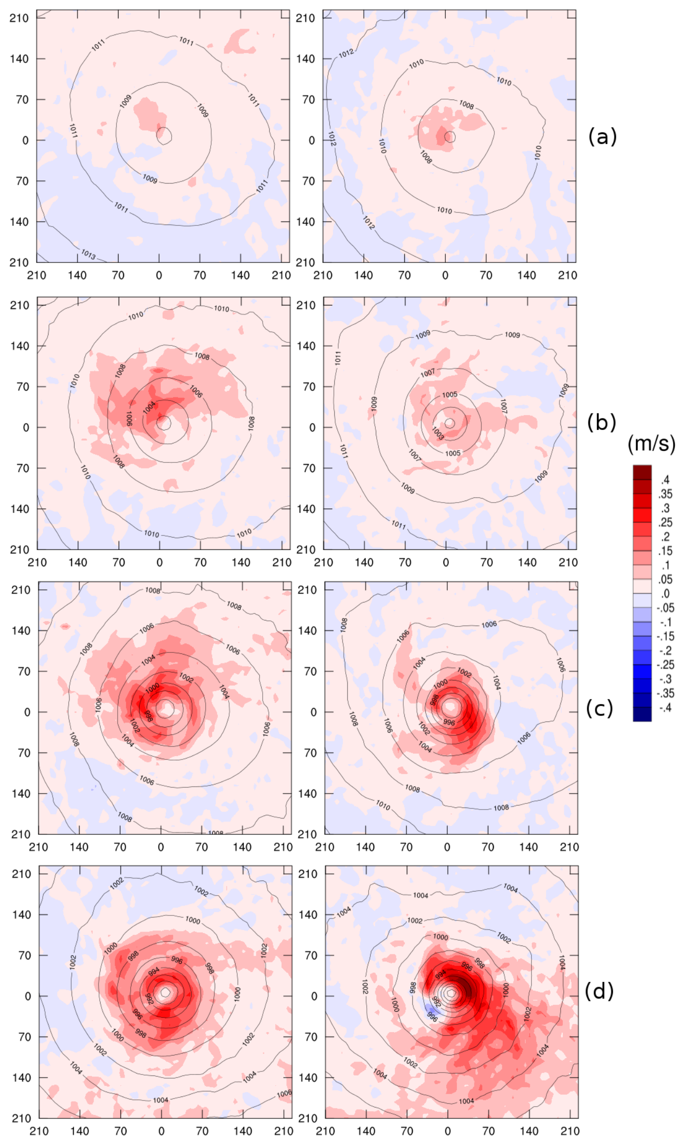

Figure 10. 10 h mean of composite vertical wind speed at 500 hPa for an SST change of a) −3 K, b) 0 K (original SSTs), c) +3 K and d) +6 K (colors) and composite mean sea level pressure (contours) between MWCT−20 h and MWCT−10 h (first column), and between MWCT−10 h and MWCT (second column). The values at the x- and y-axis indicate the distance from the center of the medicane in km.

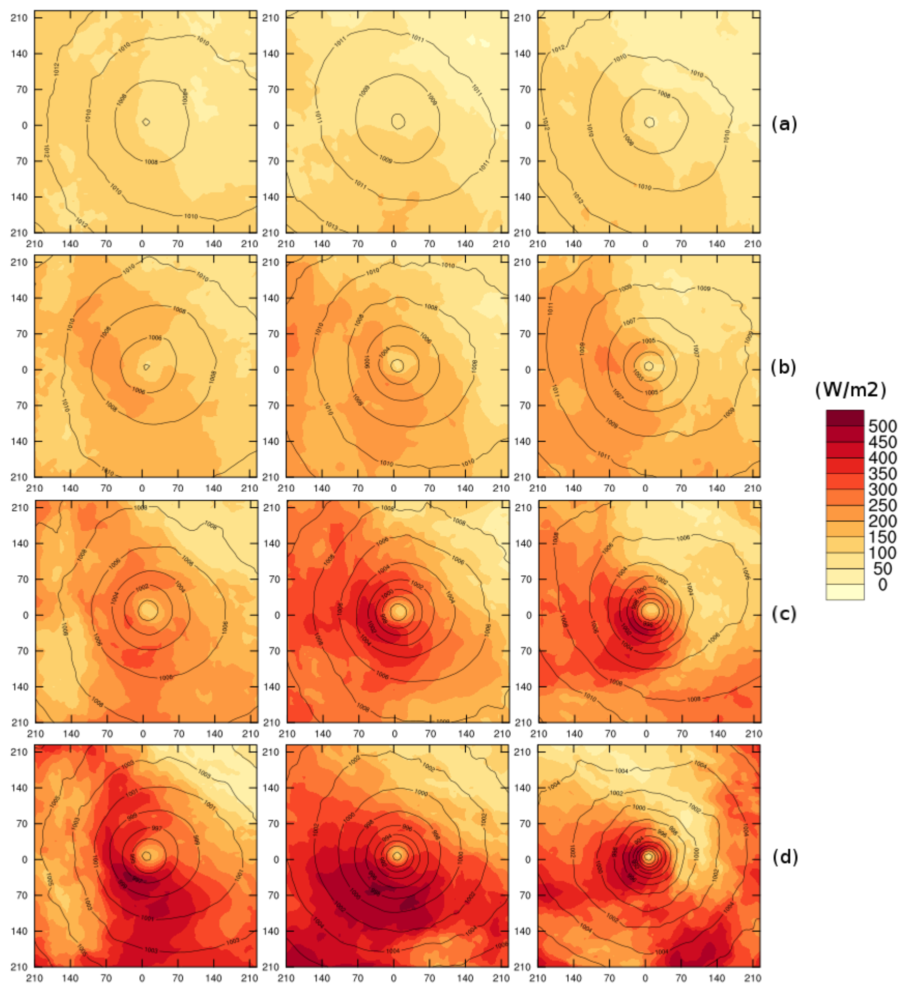

Figure 11. Composite latent heat fluxes from the sea for an SST change of a) −3 K, b) 0 K (original SSTs), c) +3 K and d) +6 K (colors) and composite mean sea level pressure (contours) at MWCT−20 h (first column), MWCT−10 h (second column) and MWCT (third column). The values at the x- and y-axis indicate the distance from the center of the medicane in km.

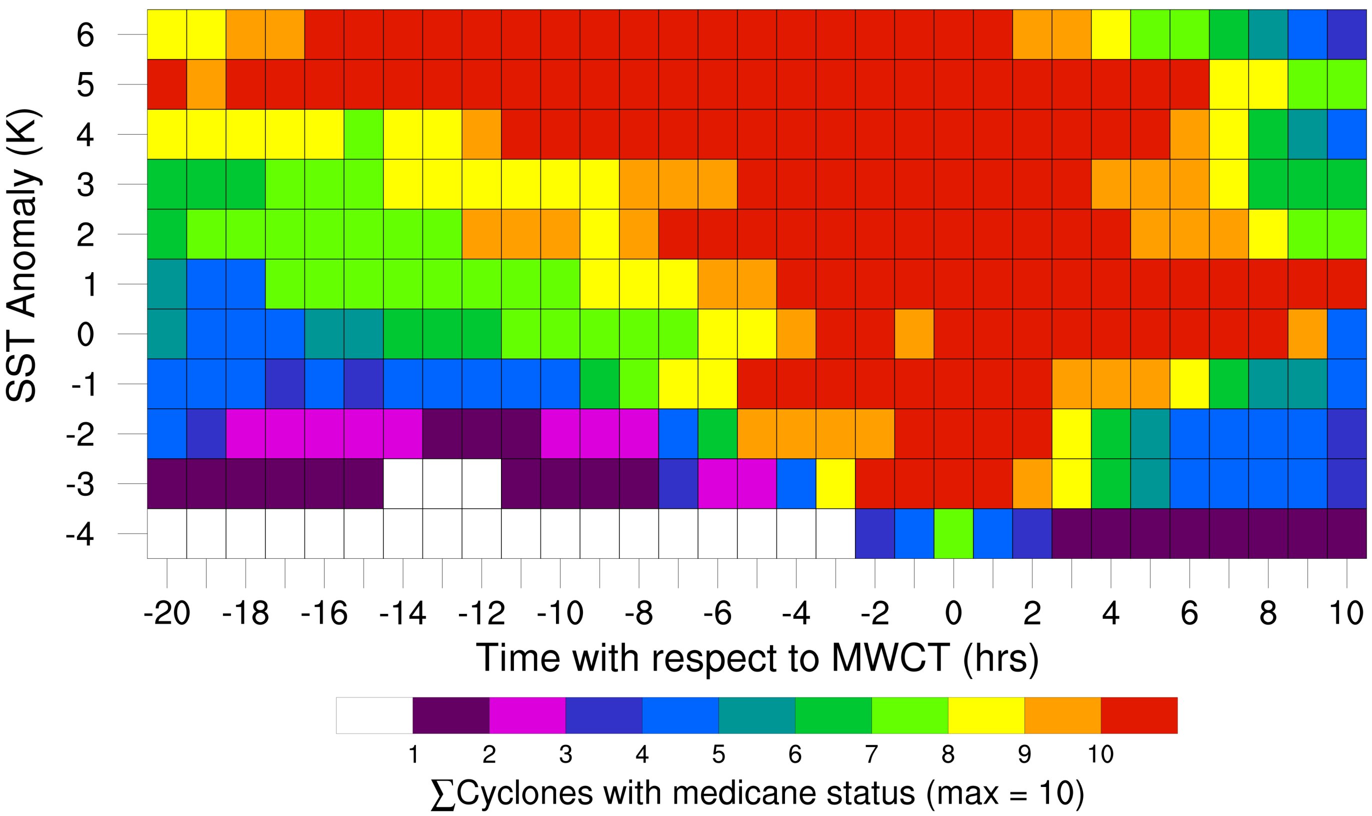

Figure A1. ~~10 h mean~~ Number of medicanes in each composite ~~vertical wind speed at 500 hPa for an~~ (one composite per SST ~~change of a) −3 K, b~~state; y-axis) ~~0~~which have medicane status at a given time relative to MWCT. Note that each composite contains 10 ~~K (original SSTs)~~members, ~~c) +3 K and d) +6~~except for the -4 K ~~(colors) and~~ anomaly SST composite~~mean sea level pressure (contours) between MWCT−20 h and MWCT−10 h (first column)~~, ~~and between MWCT−10 h and MWCT (second column). The values at the x- and y-axis indicate the distance from the center of the medicane in km~~which contains only 7 members as only 7 members underwent transition.