

Paper wcd-2019-1

“How an uncertain short-wave perturbation on the North Atlantic wave guide affects the forecast of an intense Mediterranean cyclone (Medicane Zorbas)”

Raphael Portmann, Juan Jesús González-Alemán, Michael Sprenger, and Heini Wernli

Reply to the reviewers' comments:

We thank the reviewers for again carefully reading and commenting on the manuscript. All comments have been carefully considered. In particular, the general comment by Reviewer 1 is addressed in detail and led to a corresponding paragraph in the conclusions of the article. The reference to Wikipedia is avoided by using two other references.

Reviewer 1 (Ron McTaggart-Cowan)

Notes for WCD-0001, “How an uncertain short-wave perturbation on the North Atlantic wave guide affects the forecast of an intense Mediterranean cyclone (Medicane Zorbas)” by R. Portmann et al.

Background

This is a massively improved manuscript. The authors have clearly taken the time that they needed to revise their approach to the study and present the material in a clear and logical way. The result is a document that is fun to read and easy to draw conclusions from.

Many thanks for this very positive assessment. We are of course happy that our hard work during the last revisions led to a notable improvement of the manuscript.

I have one general concern regarding the robustness of the storyline for different (primarily earlier) initialization times, and a few specific questions that may require some adjustments to the analysis or text to address (notably Specific Comments # 28, 36, 37 and 59). However, once the authors have completed a set of relatively minor revisions in response to these remaining issues, I look forward to seeing this article in print. I truly appreciate the efforts that the authors have made to bring this manuscript up to a very worthy standard.

Reviewer: Ron McTaggart-Cowan
Recommendation: Minor Revisions

General Comments

1. This detailed analysis is presented for a single initialization time. Do you know if these results are robust for other (primarily earlier) initializations? Does the previous set of ensemble forecasts show a similar range of solutions for the PV streamer that map onto difference cyclone developments? I understand that repeating this analysis for other initializations would be a huge undertaking and make the work much longer than it is. However, can a subjective evaluation of the robustness of the result be made relatively easily and the results noted in the conclusions?

Thank you for this comment. Indeed, it is quite difficult to say if a similar uncertainty propagation and differences in the cyclone evolution occurs for other initializations. We can, however, look at the ensemble spread of geopotential height at 500 hPa at 0000 UTC 27 Sep 2018 for these initializations (see Fig. 1). For the forecast initialized at 0000 UTC 24 Sep 2018, i.e. the initialization considered in the paper, ensemble spread is zonally extended at the tip of the PV streamer, indicative of the zonal position uncertainties discussed in detail in the paper (Fig. 1c). A similar zonally extended spread pattern is visible for the forecast initialized one day earlier (Fig. 1b), However, the enhanced ensemble spread reaches further northeast towards eastern Europe and the Black Sea. This indicates that in this forecast, the overall direction of the PV streamer was mostly uncertain. The forecast initialized two days earlier (Fig. 1a), shows an even more different spread pattern with a meridionally extended region of enhanced ensemble spread poleward of the PV streamer in the operational analysis. This indicates that in this forecast, the reason for the enhanced ensemble spread is not linked to the PV streamer but rather to larger-scale uncertainties in the wave pattern and the onset of the Rossby wave breaking. Based on this analysis, we add a paragraph in the conclusions as requested by the reviewer:

” Finally, we note that this study is based on one particular ensemble initialization time where the occurrence of Rossby wave breaking and cyclone formation was already certain (but not the exact zonal position of the resulting PV streamer). Later initializations are characterized by much lower positional uncertainties of the PV streamer and, hence, strongly reduced ensemble spread of 500 hPa geopotential height (as shown in Fig. 5). In contrast, earlier initializations have even larger ensemble spread with high values extending from the Mediterranean to eastern Europe (not shown), indicating uncertainty in the onset of Rossby wave breaking and the overall orientation of the PV streamer. This implies that the uncertainty patterns discussed in this study are not representative for earlier initializations of the ensemble. While in this study, the ensemble forecast was used to investigate uncertainties in the PV streamer position and the evolution of the Mediterranean cyclone, similar studies with forecasts initialized earlier could shed light on processes that determine uncertainties in the onset of the wave breaking. However, they would then be less suitable for investigating uncertainties in the formation of the medecane.”

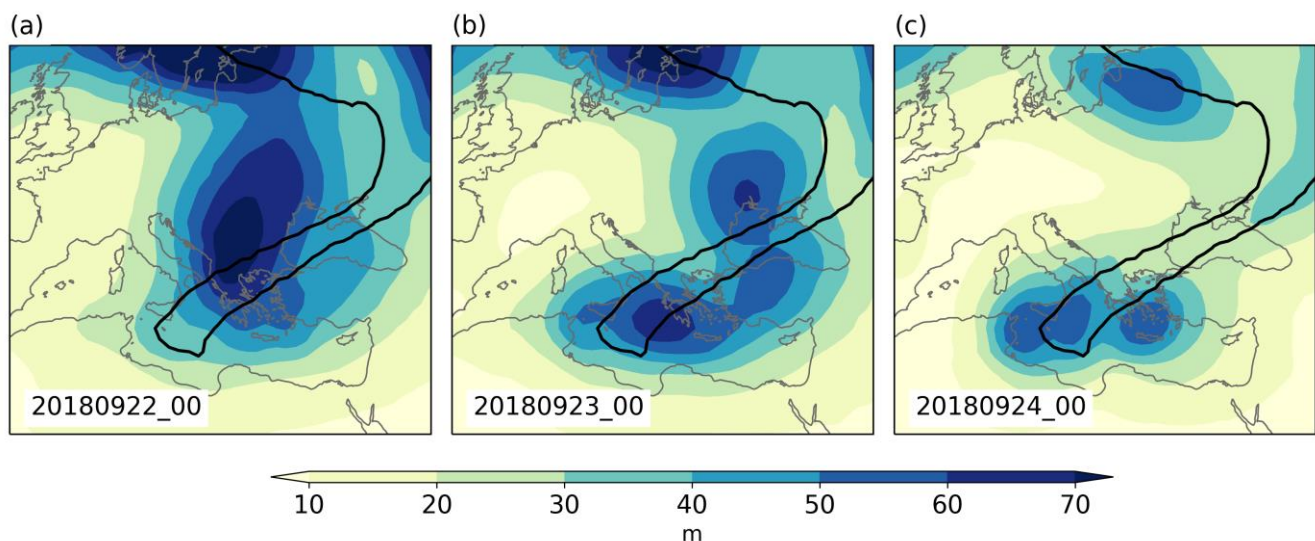


Figure 1: Ensemble spread of geopotential height at 500 hPa over the Mediterranean for initializations at (a) 0000 UTC 22 Sep 2018, (b) 0000 UTC 23 Sep 2018, and (c) 0000 UTC 24 Sep 2018 valid at 0000 UTC 27 Sep 2018. The black line marks the 2 PVU contour at 325 K in the operational analysis

Specific Comments

1. [L10] Suggest “... amplified on the stratospheric side ...”.
2. [L24] Suggest the more direct “... investigates the impact of PV streamer position uncertainty on medecane development”.
3. [L27] Would everyone agree that medicanes are the main meteorological threat in the Mediterranean region? There are other local wind hazards and there’s the flooding on the Alpine south-side that can be pretty intense. I don’t mind if you want to stick with the current wording, but perhaps consider adjusting this to something like, “... are therefore a leading meteorological threat ...”.
4. [L34] Add “... a range of modelling case studies ...” to make it clear that the errors are in a numerical model, not the real atmosphere.
5. [L40] Replace “far equatorward reaching” with “high amplitude” or “meridionally extended”.
6. [L48] Suggest citing Clark et al. (2017) and Keller et al. (2019) when mentioning ET here.

Thanks for these suggestions. All of them have been considered.

7. [L55 and L57] Wikipedia is an unstable reference, so ideally primary material should be cited here instead. If Wikipedia absolutely needs to be cited, then an access date should be provided.

Thanks for this comment. We avoided using Wikipedia and replaced it by two other references.

8. [L57] Suggest simplifying to “This cyclone belonged to a special class ...”.

9. [L62] Suggest “significant damage” as more common.

Thanks, the manuscript has been changed accordingly.

10. [L62] The note that “sometimes they acquire the typical appearance of a hurricane” suggests that sometimes medicanes don’t acquire hurricane-like characteristics. Given that medicanes are typically identified by morphology, this seems unlikely and therefore the statement should be strengthened.

The sentence has been adapted to “They acquire...”

11. [L73] Remove comma after “during ET”.

12. [L97-107] This paragraph is too general to be particularly useful, and contains a defense of the experimental design that would be better placed in a data/methods section. It also disrupts the flow between the “study objectives” paragraph and the “outline” paragraph at the end of the introduction. I think that this paragraph should be removed.

Thanks for pointing this out. We agree that this paragraph is interrupting the flow. Therefore, the first part has been removed and the second part added to the previous paragraph, where it does not interrupt the flow.

13. [L131-L133] The TRMM mission ended in 2015, replaced by the GPM. Are the 2018 data used here processed by the legacy TRMM algorithm or the newer IMERG algorithm? The text here may be completely correct, but please confirm.

The data processed by the original TRMM algorithm is available until 2019: <https://trmm.gsfc.nasa.gov/3b42.html>

14. [L138-L139] The idea of intersection points between a trajectory and a layer is a bit strange. I would ordinarily have thought of a trajectory line intersecting a 2D plane (e.g. the 325 K surface). Doesn’t the use of the 322.5 K lower boundary for the layer simply imply that the points are defined as the locations at which the ascending WCB trajectories cross the 322.5 K surface? The Fig. 1 caption suggests that the simpler 325 K surface definition is used, at odds with the description here. The Fig. 2 caption suggests that the 322.5 K surface is used instead. I realize that the difference between these is relatively small, but consistency is desirable.

Please apologize for this inconsistency. The idea in Fig. 1 is to identify trajectories crossing an isentropic surface in order to see if WCB air parcels are present at that isentropic surface. However, the potential temperature value of the air parcel will mostly not be exactly 325 K, therefore a layer has to be specified in which air parcels are assigned to the 325 K level (i.e. if air parcels are close enough to that level their trajectories are identified as “trajectories crossing the 325K isentropic surface”).

In contrast, in Fig. 2, all air parcels are shown that reach above the 322.5 K level in order to show which air parcels were able to reach high enough to affect the erosion of the PV cutoff (at the 325 K level shown in the plot or even at higher levels). So, the purpose here is slightly different. We changed the description in the data section to make this clearer.

15. [L140] Suggest “around the cyclogenesis position”.

16. [L148] This use of the CPS does not seem to distinguish between convection- and seclusion-induced warm cores. Is there any risk that some of the members classified as medicanes by the CPS are the result of frontal seclusion, a process that is not associated with tropical transition? Might B be useful to distinguish between storms at the early stages of seclusion and those whose warm cores are diabatically generated?

This is indeed possible. In fact it is known that the warm core in some medicanes is actually produced by frontal seclusions (e.g. Fita and Flaounas 2018). We did not look at this in this study and possibly both scenarios occur in the ensemble prediction we used for this paper. The fact that most medicanes in this case are also associated to high precipitation rates and upper level PV erosion could be seen as indication that, here, warm cores are mostly driven by latent heating. However, it would probably require detailed trajectory analyses to properly differentiate between convection and seclusion-induced warm cores. Something that might be addressed in our planned follow up study.

If B is useful to distinguish the different mechanisms producing a warm core is difficult to judge. It would require a classification of the medicanes into these two types, which has, as stated above, not been done.

17. [L172-L182] This is an excellent description of your testing technique: very well done.

Thank you!

18. [L184] Suggest reversing “provides first”.

Done

19. [Fig. 1] The PV streamer has already formed in (d), so the phrase “before the formation of the PV streamer over the Mediterranean” should be removed or replaced with something like, “during the development of the PV streamer”.

It was changed to “before the formation of Medicane Zorbas”

20. [Fig. 2] The contour interval for SLP should be noted in the caption (it looks like 4 hPa). The fact that 500 hPa height is shown in yellow contours should be noted, as should the contour interval used for this field.

21. [Fig. 2] Suggest adding “322.5 K isentropic level” to avoid confusion with the equivalent potential temperature that serves as the departure threshold.

Thanks for carefully reading the caption. Changes have been made accordingly.

22. [L206] Suggest inverting to read, “The PV streamer broke up at the time of cyclogenesis, resulting in the ...”.

23. [L207] Suggest replacing “following” with “subsequent”.

24. [L209] Suggest referring to Fig. 3a for locations to help with this discussion.

25. [L245] “Landfall” is usually written as a single word.

26. [L248] The phrase “about one-day period” is approximate and slightly strange. Was this an 18-h period? The exact length doesn’t matter very much here, so the phrase could simply read “... prior to cyclogenesis, the initial cyclone intensification, and the formation ...”.

Thanks for the above suggestions. Changes have been made accordingly.

27. [Fig. 4] A greyscale bar should be included for the brightness temperatures.

Thanks for this comment. The satellite data is given in radiances and a conversion to brightness temperatures seems rather complicated and, in our opinion, does not provide substantial benefit to the reader. The satellite images are used to show the presence of clouds and their structure and no quantitative conclusions are drawn from it. We could, of course, add a greyscale bar for radiances, but we doubt that this is of benefit to the reader.

28. [L267] To be “substantial” this spread would need to be larger than typical ensemble spread at these lead times. If such a typical spread is known, it would be useful to add this line to Fig. 5 for reference. If it is not (and is not readily computed), then this sentence could be restructured to focus on the decrease in spread in the medium range.

Thanks for this comment. This is a very good idea. Unfortunately, we don’t have access to enough data to calculate the climatological ensemble spread in this region. Therefore, the sentence has been modified accordingly to “The synoptic situation over the Mediterranean was associated to uncertainties in the operational ECMWF ensemble forecasts, which decreased particularly strongly for initialization later than three days prior to genesis of Zorbas.”

29. [L287] Suggest removing “a” before “substantial”.

30. [L288-290] Suggest simplifying to, “To establish the dynamical link between uncertainties in the position (thus thermal structure) of the cyclone and upstream uncertainties ...”.

31. [L290] Suggest “classifies” instead of “allows separating the”.

32. [L292] Suggest “(clusters)” rather than the current subordination.

33. [L297] Suggest a full stop rather than a colon.

34. [L321] Suggest “... and amplification of these uncertainties along the ...”.

35. [L324] This section title would be more complete as “Uncertainty propagation from the North Atlantic jet streak to the Mediterranean PV streamer”.

Thanks for these suggestions, they have been adopted.

36. [L336-L338] I agree that there are no WCB trajectories ending in this region. However, this does not mean that moist diabatic processes are not relevant to the uncertainty. I’ve included a satellite retrieval (Fig. 1 below) that shows extensive high-topped cloud cover in the region. In addition to potential latent heating effects, these clouds will affect the radiative heating profile. If the clouds are handled differently by the members in the different composite groups, they could explain the differences in the solutions rather than “dry upper-tropospheric dynamics” (L338). Imagine, for example, that members in which the local SPPT coefficients suppress the radiative heating tendencies do not amplify the ridge while those in which the coefficients amplify the heating signal create a much more robust ridge. If this is truly the sensitive region for the Mediterranean streamer, this difference in heating could cause the eventual separation of the solutions that is observed. I haven’t demonstrated

that any of this is true, but the analysis in the manuscript does not rule out this possibility despite the assertions in the text.

Thank you for this comment and the attached image. We agree that, given the presence of clouds in the vicinity of the region, where the uncertainty amplifies, moist diabatic processes can not be excluded by our analysis. We apologize for not formulating this part more carefully. We changed the corresponding parts in the manuscript. We now only exclude a substantial contribution of WCBs, but not of moist diabatic processes in general.

37. [L346 and L362-367] This is a very 2D way of describing the tropopause evolution. What if you considered the “approach” of the high-PV contours as a steepening of the tropopause or development of a tropopause fold. This is of course necessarily related to the jet streak, but might give the readers a useful way to conceptualize the process that’s promoting wave amplification in some members. For example, the approach of a northern stream PV perturbation towards the jet seems dynamically similar to the events discussed by Winters and Martin (2017).

Thanks for this perspective. We added a sentence on that “The strengthening of the jet streak in such a situation can also be understood as a steepening of the tropopause in this region (e.g. Winters and Martin, 2017).”

38. [L351] Please avoid parenthetical negation (Robock 2010).

Thanks, sentence has been changed.

39. [L357] This trough is referred to as S2 in Fig. 1d. I think that’s good because it’s definitely a PV streamer rather than a trough at this time; however, the reference needs to be corrected here. Also, there is no S2 in Fig. 1c. Is it possible that the panel references are inverted here?

Thanks for seeing this, indeed, panel references (d and c) were inverted.

40. [L368-370] As in Comment #28, it would be useful to have a spread climatology in Fig. 5 for reference so that it is clear that this spread reduction is larger than would be expected by the decreasing lead time.

We agree that it would be interesting to see how large Z500 ensemble spread (and the spread decrease) is compared to the climatological evolution in this region. However, this would require further analysis with additional data. On a global northern hemispheric average, we know that this evolution is very gradual (e.g. Rodwell et al. 2018). Most likely, this is also the case for the Mediterranean. Hence, it is very likely that the almost step-like evolution in this case cannot be fully explained by a climatological decrease of ensemble spread with lead time. We therefore decide to stick to the current formulation.

Rodwell, M. J., D. S. Richardson, D. B. Parsons, and H. Wernli, 2018: Flow-Dependent Reliability: A Path to More Skillful Ensemble Forecasts. *Bull. Amer. Meteor. Soc.*, 99, 1015–1026, <https://doi.org/10.1175/BAMS-D-17-0027.1>.

41. [L376-L379] There is also a notable difference in streamer tilt, with W more positively tilted and E notably more meridional (note the westward shift of the high-PV region over Eastern Europe in the E cluster). This suggests that the streamer may be in a slightly different stage of its life cycle in the different groups.

Thanks for this observation. We agree that the tilt is different between clusters. However, it is not straightforward to clearly separate differences in the streamers tilt and the position of the streamers tip. The latter is obviously strongly influenced by the former. And as the clustering focuses on the position of the streamer, we decided to stick to the current formulation in order to avoid confusion (as we are not discussing the streamers tilt anywhere else in the article).

42. [Fig. 11] If it doesn't take too much effort, you could consider masking out significance regions that are too small to be meaningful. This would help to clean up the otherwise beautiful plots a bit without any loss of important information.

Thanks for this suggestion. Very small significance regions have been masked out.

43. [L411] Remove comma before "because".

44. [L413] Remove dash after "upper-" (this is not a compound adjective).

Thanks, text has been changed accordingly.

45. [Fig. 12] I really like Fig. 12 and the associated discussion, but the precipitation panel should appear as its own figure (Fig. 13). There is no association of either axis between panels a and b with panel c, so placing them in a single figure is not beneficial.

Thanks for this comment. We agree that the axes of panel c are not associated to the ones of panels a and b. However, the legend is the same for all panels. Also, the discussion of the different panels is strongly connected. Therefore, we decided to keep them within the same Figure. To better avoid potential confusions with the axes of panels a and b, we moved the y-axis labels to the left of panel c.

46. [L427] This sentence could/should be moved to the figure caption.

47. [L436] Suggest replacing "following" with "subsequent".

48. [L439] Consider replacing "crucial role" (which doesn't really fit with the remainder of the sentence) with "necessity".

49. [L439] Replace "... heating and cross-isentropic ..." with "heating, cross-isentropic".

50. [L444] Change "much lower" to "much reduced" to avoid ambiguity with precipitation fluxes in the vertical.

51. [L445] Change "indicating much lower latent heating" to "indicative of a reduction in column-integrated latent heating".

52. [L445-L446] Without more context or an analysis of why this precipitation bias exists, this does not seem like an "interesting side remark". I think that this sentence should be removed to maintain the focus of this discussion.

53. [L447] Suggest changing "pathway" to "evolution".

54. [L447] Unless WCD uses the APA style, I do not think that the word following a colon should be capitalized.

55. [L451] Consider replacing "... this storyline and they are mostly ..." with "... this archetype, mostly ...".

56. [L459] Suggest "... were used to assess how uncertainties originating in a short-wave perturbation on the North Atlantic wave guide influenced a downstream PV stream and, as a result, ...".

57. [L461] Suggest inverting "appeared first" and changing "at" to "on".

Thanks for the above suggestions, they have all been adopted.

58.[L461-463] This summary makes it sound as though the PV differences and the short-wave perturbation happened (by chance) to occur at the same time. Is there not a dynamical link between them? The subsequent sentence suggests that they were both prompted by the high-PV perturbation in the polar stream, but this all seems like a weaker connection than the earlier analysis implied.

Thanks for pointing this out. We changed the sentence to “They were tightly connected to...” to make the connection clearer.

59. [L465 and L491] As noted in Specific Comment #36, I think that the current analysis does not rule out the importance of upper-tropospheric moist processes (cloud formation) and their secondary effects.

See reply to comment #36

60. [L465] The referent of his pronoun (“they”) is unclear.

Thanks, the sentence has been made clearer.

61. [L471] Suggest “... cyclogenesis that affects cyclone ...”.

62. [L478-480] I like this discussion and the context of systematic errors that you cast it in.

Thanks:-)

63. [L482] I think that your analysis (including trajectories) was robust enough to let you conclude using the definite article that “The reason for this ...”.

64. [L483-L484] Recommend putting a full stop after “region” and beginning the next sentence as “This prevented ...”.

65. [L484] Replace “... to be strong enough and reach ...” with “... from being strong enough and reaching ...”.

66. [L488] Suggest adding “the” before “medium-range”.

Thanks, suggestions have been adopted.

67. [L493-L494] I think that I understand what you’re trying to say here, but the concept of “upstream influence” is strange enough that I think that a reformatting of this sentence would help to clarify your conclusion.

Thanks for pointing this out. We simplified the sentence to “...how frequently this mechanism *limits* the medium-range predictability of Mediterranean PV streamers and, as a result, ...

68. [L499] Suggest removing “for example”.

69. [Fig. S4] Please use the full citation method requested at <https://www.lightningmaps.org/about>.

Thanks, we adopted the citation in the manuscript and supplement accordingly.

References

Robock, A. (2010), Parentheses are (are not) for references and clarification (saving Space), Eos Trans.

Winters, A. C., and J. E. Martin, 2017: Diagnosis of a North American Polar–Subtropical Jet Superposition Employing Piecewise Potential Vorticity Inversion. *Mon. Wea. Rev.*, 145, 1853–1873, <https://doi.org/10.1175/MWR-D-16-0262.1>.

Figures

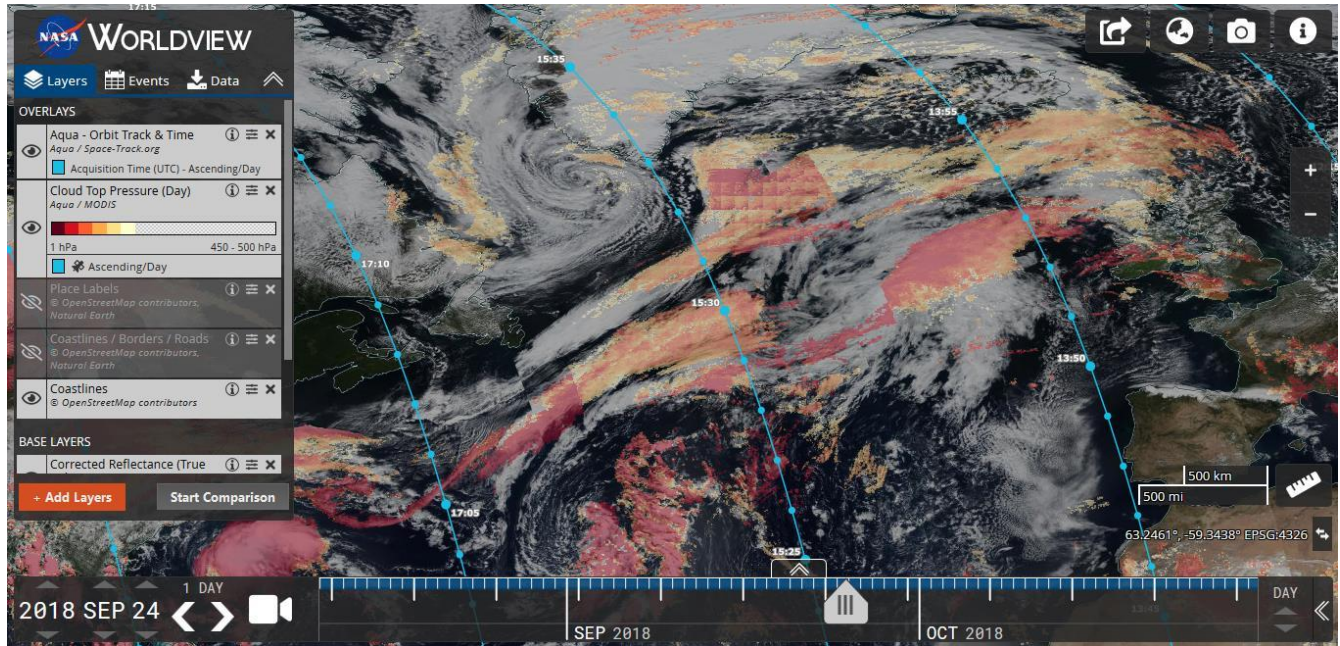


Figure 1: Composite satellite image for 24 September 2018 from NASA Worldview. Aqua/MODIS estimates of cloud top pressure are shown in warm colours for >500 hPa as shown on the colour bar.

Reviewer 2: Florian Pantillon

“How an uncertain short-wave perturbation on the North Atlantic wave guide affects the forecast of an intense Mediterranean cyclone (Medicane Zorbas)” by Raphael Portmann, Juan Jesús González-Alemán, Michael Sprenger, and Heini Wernli

The paper has changed substantially since the last round of reviews. Its scope is now well introduced and its limitations explained, while discussions have gained in clarity and are supported by very illustrative figures. Altogether, the paper highlights the role of remote uncertainties along the upper-level wave guide in the medicane forecast and presents an interesting hypothesis of upper-level PV erosion by latent heating that allows tropical transition to take place. I thus recommend the paper for publication pending minor corrections listed below to further improve clarity.

Specific comments

l. 23–24 could you give a more general statement or perspective to conclude the abstract?

Thanks for this comment. We switched the last two sentences in the abstract and slightly changed them to “This study is the first that explicitly investigates the impact of PV streamer position uncertainty for medicane development. Overall, results extend current knowledge of the role of upstream uncertainties for the medium-range predictability and unsteady forecast behavior of Mediterranean cyclones including medicanes.” In this way, it ends with a more general statement.

l. 27 “the main meteorological threat”: exaggerated, as local high-impact weather is not necessarily related with cyclones (see HyMeX program)

Thanks, this statement has been changed to “leading meteorological threat”, as suggested by reviewer 1.

l. 45 remove “for instance”

l. 52 typo: “causal link s”

Thanks, the manuscript was changed accordingly.

l. 54 “whose formation due to an upper-level PV streamer is the subject of this study”: too much information for this sentence (and not supported by Wikipedia); better keep for the end of the paragraph?

Thanks, we agree that this statement does not really fit here. We removed it completely, because a similar statement is already present at the end of the paragraph.

l. 79 “similar to Maier-Gerber et al., 2019”: explicit “for a tropical transition over the North Atlantic”?

Thanks, reference was changed accordingly.

l. 84–87 this sentence is disconnected from the previous one (no ET in Di Muzio et al. 2019)

It is true that ET is not covered in DiMuzio et al 2019. However, the connection of the sentences is via the topic of the different stages in the cyclone predictability/forecast jumps. We still think that this connection works.

l. 92–96 unclear (it becomes clearer in Section 4)

Unfortunately, without more specific comments about what is unclear, we don't see how we could make this paragraph clearer.

l. 228–230 do you mean that more than half of those parcels actually reach the upper levels? giving the average ascent in km or hPa rather than in K would be easier

Yes, that is what we mean. We provided the heating rate in K because what is relevant for the diabatic erosion is the isentropic level which the air parcels reach, rather than the pressure level or height. We therefore stick to the current formulation.

l. 230–231 “they contributed substantially”: too strong statement

We deleted “substantially”.

l. 231 “Despite limitations of trajectories in convective situations”: detail (convection has not been mentioned yet)

Thanks for this comment. We removed this part of the sentence.

l. 232 “as a result”: why?

Because replacing the upper-level cold core with a warm-core requires to get rid of the positive upper-level PV anomaly (which is necessarily associated to a mid/upper tropospheric cold core).

l. 233–235 the link with the previous sentence (PV erosion) is not straightforward

The previous sentence also contains that low-level air with high THE was important to form a warm core. This is also the case for the coupling index. Therefore, we think that this sequence of sentences is reasonable and stick to the current formulation.

l. 255 typo: “precentile”

Thanks for pointing this out, it was corrected.

l. 278 “only 21 ensemble members predicted a medicane” that's not bad!

We think this judgement strongly depends on the perspective. From a forecaster's perspective, 21 members is less than 50% of the cases, which could be interpreted as “bad”. According to Di Muzio et al. 2019 (their Fig. 4), the evolution of medicane predictability with lead time is very variable. For example, for Ilona, more than 60% of the members forecasted a medicane three days ahead (i.e. a surface cyclone with an upper level warm core), for Trixie more than 60% forecasted no surface cyclone at all with 3 days lead time (and the remaining 40% did mostly not forecast a medicane). In order to cleanly judge if the forecast of a medicane is good or bad, we would need a stable reference, i.e. average forecast skill over many medicanes, which I think we don't have yet. The word “only” was used in this case simply because less than 50% of the members forecasted a medicane.

l. 299 refer to black contour in Fig. 7 for the analysis

Thanks, we adopted this suggestion.

l. 337 unclear in what the region is “clearly stratospheric”: is it associated with $PV > 2$ pvu? It also appears to contradict the “upper-tropospheric” dynamics and forecast uncertainties mentioned below

Thanks, we clarified this by adding that it is in a region with $PV > 2$ PVU and changed “upper-tropospheric” to “tropopause-level”.

l. 350 a westward shift of the wave pattern is apparent rather than a superimposed short-wave pattern

Thanks for this comment. Maybe this is a question of perspective. We would argue that it is definitely not a shift of the large-scale wave pattern, as the troughs over Newfoundland and Europe are pretty much the same in the two clusters at 0000 UTC 25 Sept 2018. In fact, the western flank of the ridge in cluster E is “steeper” (i.e. more meridionally directed) than in cluster W, and vice versa for the western flank. This results in the wave-like shape of the mean 2 PVU contour in cluster W, if cluster E is taken as reference (or also vice versa). Or in other words: It is not possible to bring the two mean 2 PVU contours to cover just by shifting them around, at least to our eyes. We acknowledge your perspective, which is obviously slightly different, but as it still seems to be the best description of the situation to us, we stick to the current formulation.

l. 353–355 emphasize that the negative (positive) difference becomes more and more (less and less) significant?

Thanks for pointing this out, a sentence about this aspect has been added.

l. 367 “large drop” seems exaggerated for a decrease that is steep but continuous

Thanks for pointing this out. We agree and changed it to “substantial reduction”

l. 379 “in these regions”: which ones? Refer to white contours?

Thanks for pointing out this unclarity. We added a reference to the white contours in Fig. 11.

l. 394 Fig 11g

Thanks, this was changed accordingly.

l. 402 84h and 106h lead times are not mentioned before

They are the ones shown in Fig. 6, and are therefore mentioned before, but not explicitly. We changed the sentence structure and added a reference to Fig. 6 to make this clearer.

l. 407–408 refer to Fig. 6 again?

Thanks for this suggestion, we added such a reference.

l. 421 rephrase: the stratospheric PV anomaly is not equivalent to the cyclone thermal structure

Thanks for this comment, we changed this part to “...and thereby the differences in the vertical thermal structure of the cyclones...”

l. 427ff remind which color corresponds to which cluster to help the reader follow the discussion

Thanks, we adopted your suggestion.

l. 465 “they”: the significant differences?

Thanks, this unclarity was resolved by specifically using “these differences”.

l. 496 better “relevance of a PV streamer position for medicane formation” (without uncertain)?

Thanks for this suggestion, we adopted it.

l. 497 indeed, climatological studies have shown that some regions are more prone to medicane formation than others, but what is meant here exactly?

Thanks for pointing out this unclarity, we added a sentence to clarify: “In this case, only members with cyclogenesis in a relatively confined region at the Libyan coast developed a medicane.”

l. 515ff many DOI links are broken due to unwanted characters

We check many links and it seems to us that most of them work fine. For a few, we found that curved brackets around the doi in the bibtex file were a problem. We removed curved brackets for all references and all links should work now.

l. 651 The Wikipedia reference is incomplete (I let the Editor judge whether it is appropriate):
[https://en.wikipedia.org/wiki/Mediterranean_tropical_like_cyclone#Zorbas_\(27_Sep_%E2%80%93_1_Oct_2018\)](https://en.wikipedia.org/wiki/Mediterranean_tropical_like_cyclone#Zorbas_(27_Sep_%E2%80%93_1_Oct_2018))

Thanks for this comment. The Wikipedia reference has been replaced by two other references.

Figure 1 Explain labeled features, or refer to the text?

Thanks for this advice, we added “Labels mark relevant flow features (for details see text)” to the caption.

Figures 8–9 Labeling relevant features as in Figure 1 would be helpful and would strengthen the link between the different Sections

Thanks for this suggestion, we labelled the relevant features in Figures 8 and 9 accordingly.

Figure S5 do clusters 1, 2, 3 refer to C, W, E? The figure should be mentioned somewhere in the text or in the caption of Fig. 11 (or removed otherwise)

Thanks for noting this mistake and the missing reference. The caption of Fig. 11 and the supplement Fig. S5 have been changed accordingly.

Reviewer 3

I have already expressed my positive evaluation of this manuscript in the previous versions, since the results improve our understanding of the mechanisms of development of Medicanes. In the newer version, I repeat my appreciation for this work, evaluating positively the Authors' efforts to further improve the manuscript (very clear the present version of Fig. 12!). I think the paper is really mature for publication, a few comments needed for better clarification are reported below.

Minor points:

- Line 40: please clarify what you mean with “far equatorward reaching PV streamers”;

We changed this according to a suggestion of reviewer 1 to “high amplitude PV streamers”.

- Line 56 and elsewhere: Libya instead of Lybia;
- Line 136: Lagrangian instead of Langrangian;
- Line 173 and elsewhere: (Wilks, 2011) instead of (Wilks, D. S., 2011);
- Line 218: acquired instead of aquired;

Thanks for pointing at these mistakes. The manuscript has been changed accordingly

- Line 222: this suggests that the cyclone belongs to the first category of Medicanes, following Miglietta and Rotunno (2019);

Thanks for making this link. We agree that Zorbas probably fits into the first category. However, we do not analyze the role of baroclinicity and the WISHE mechanism explicitly for Zorbas. Therefore, we think that such a statement should not be made in the article.

- Lines 225-228: Include a reference to better explain this point, e.g. Fig. 9.10 in Holton, IV edition;

Thanks for this suggestion. We added the following sentence to explain this point better: “The larger θ_e of the low level air parcels, the higher they can rise through moist adiabatic ascent (see e.g. Holton (2004) their Fig. 9.10)”

- Line 230: (average ... of about 30K): do you mean that the maximum equivalent potential temperature difference between the parcel and the environment is about 30 K?

No, we mean that they have been heated diabatically by 30 K during their ascent. We changed the phrase in brackets to “(average diabatic heating of about 30 K)”.

- Figure 1 caption: the values of wind speed (white contours) are not indicated;

Thanks for pointing this out. We added it.

- Figure 2 caption: the reason for the white areas in the lower panels is not clear;

Thanks, we added the explanation that it is missing values due to orography.

- Figure 7 caption: the definition of PVav should be included in the caption;

Thanks, the definition has been added to the caption

- Figure 11 caption: the meaning of the small circles and of the bars in the insets is not clear;

Thanks for this remark. The explanation of the circle has been added (they are outliers). The bars show standard box plots (i.e. upper and lower quartile), we added the term “standard” to the description to make this more clear.

- Figure 5S caption: the names of the clusters should be C, E, W not 1, 2, 3.

Thanks for noting this. We changed the names.

How an uncertain short-wave perturbation on the North Atlantic wave guide affects the forecast of an intense Mediterranean cyclone (Medicane Zorbas)

Raphael Portmann¹, Juan Jesús González-Alemán², Michael Sprenger¹, and Heini Wernli¹

¹ETH Zurich, Institute for Atmospheric and Climate Science, Zurich, Switzerland

²University of Castilla-La Mancha, Environmental Sciences Institute, Toledo, Spain

Correspondence: Raphael Portmann (raphael.portmann@env.ethz.ch)

Abstract. Mediterranean cyclogenesis is known to be frequently linked to ridge building over the North Atlantic and subsequent anticyclonic Rossby-wave breaking over Europe. But understanding of how this linkage affects the medium-range forecast uncertainty of Mediterranean cyclones is limited, as previous predictability studies mainly focused on the relatively rare cases of Mediterranean cyclogenesis preceded by upstream extratropical transition of tropical cyclones. This study exploits a European Centre for Medium-Range Weather Forecast (ECMWF) operational ensemble forecast with an uncertain PV streamer position over the Mediterranean that, three days after initialization, resulted in an uncertain development of the Mediterranean tropical-like cyclone (Medicane) Zorbas in September 2018. Later initializations showed substantially lower forecast uncertainties over the Mediterranean. An ad-hoc clustering of the ensemble members according to the PV streamer position in the Mediterranean is used to study the upstream evolution of the synoptic to mesoscale forecast uncertainties. Cluster differences show that forecast uncertainties amplified at-on the stratospheric side of a jet streak over the North Atlantic during the first day of the ensemble prediction. Subsequently, they propagated downstream and further amplified within a short-wave perturbation along the wave guide, superimposed to the large-scale Rossby-wave pattern. After three days, the uncertainties reached the Mediterranean, where they resulted in a large spread in the position of the PV streamer. These uncertainties further translated into uncertainties in the position and thermal structure of the Mediterranean cyclone. In particular, the *eastward* displacement of the PV streamer in more than a third of the ensemble members resulted in a very different cyclone scenario. In this scenario, cyclogenesis occurred earlier than in the other members in connection to a pre-existing surface trough over the Levantine Sea. These cyclones did not develop the deep warm core typical for medicanes. It is proposed that the *eastward* shifted cyclogenesis resulted in reduced values of low-level equivalent potential temperature in the cyclogenesis area. As a result, latent heating was not intense and deep enough to erode the upper-level PV anomaly and allow the formation of a deep warm core. The *westward* displacement lead to surface cyclones than were too weak and a medicane formed in only half of the members. The *central*, i.e. correct, PV streamer position resulted in the most accurate forecasts with a strong medicane in most members. These-This study is the first that explicitly investigates the impact of PV streamer position uncertainty for medicane development. Overall, results extend current knowledge of the role of upstream uncertainties for the medium-range predictability and unsteady forecast behavior of Mediterranean cyclones ~~in general, and medicanes in particular. Moreover, this~~

25 ~~study is the first that explicitly investigates the role of an uncertain PV streamer position for medicane development, including~~
~~medicanes.~~

1 Introduction

Mediterranean cyclones are major causes of heavy precipitation and strong winds all across the Mediterranean basin and are therefore ~~the main~~ a leading meteorological threat in this region (e.g. Jansa et al., 2001; Pfahl and Wernli, 2012; Raveh-Rubin
30 and Wernli, 2015). Hence, it is of high societal relevance to study uncertainties in their forecasts. It is widely known that Mediterranean cyclones mostly form from elongated equatorward intrusions of stratospheric high potential vorticity (PV), so-called PV streamers, that are the result of anticyclonic Rossby-wave breaking over the North-Atlantic/European region (e.g. Tafferner, 1990; Fita et al., 2006; Tous and Romero, 2013; Flaounas et al., 2015). Often, these PV streamers break up into PV cutoffs, which are typically identified as quasi-circular PV anomalies isolated from the main stratospheric reservoir on an
35 isentropic surface (Appenzeller and Davies, 1992; Wernli and Sprenger, 2007). The dynamical forcing and destabilization by the upper-level PV streamer or cutoff are known to favor strong convection and cyclogenesis. Indeed, a range of modeling case studies established that mesoscale errors in the structure of the upper-level PV streamer or cutoff are relevant sources of errors in the low-level development of Mediterranean cyclones and heavy precipitation events (Fehlmann and Davies, 1997; Fehlmann and Quadri, 2000; Romero, 2001; Homar and Stensrud, 2004; Argence et al., 2008; Chaboureau et al., 2012). Other
40 case studies have shown that intense latent heating in upstream cyclones over the North Atlantic can enhance anticyclonic Rossby-wave breaking and thereby affect the PV streamer formation and, as a result, Mediterranean cyclogenesis and heavy precipitation (e.g. Massacand et al., 2001; Grams et al., 2011; Pantillon et al., 2015). Wiegand and Knippertz (2014) showed that ~~far equatorward reaching~~ high amplitude PV streamers over the North Atlantic and Mediterranean are systematically preceded by latent heating upstream. The basic mechanism behind this link is that intense latent heating results in the transport
45 of low-PV air from low levels to the upper troposphere where it contributes to the build-up or amplification of a ridge and, hence, the formation of a PV streamer downstream. Similar situations also occur in other regions, e.g. the North Pacific (Grams and Archambault, 2016). Such substantial latent heat release often occurs ~~for instance~~ in warm conveyor belts (WCBs), which are coherent, rapidly ascending airstreams within extratropical cyclones (Browning, 1990; Madonna et al., 2014). In a systematic analysis, Raveh-Rubin and Flaounas (2017) found that more than 90% of the 200 strongest Mediterranean cyclones were
50 preceded by North Atlantic cyclones with substantial WCB activity, out of which five were tropical cyclones that underwent extratropical transition (ET, Clark et al., 2017; Keller et al., 2019). Situations with ET result in especially strong WCBs, ridge building, and downstream flow amplification (e.g. Riemer et al., 2008; Torn, 2010; Archambault et al., 2013; Quinting and Jones, 2016). Therefore, in recent years, particular attention has been devoted to cases where the genesis of intense Mediterranean cyclones or heavy precipitation over Europe was preceded by ET in the North Atlantic, thereby establishing a causal
55 link ~~s~~ between the two (e.g. Grams et al., 2011; Chaboureau et al., 2012; Pantillon et al., 2013, 2015; Grams and Blumer, 2015).

Mediterranean cyclone Zorbas in September 2018 ~~, whose formation due to an upper-level PV streamer is the subject of this~~

study, led to considerable damage through severe winds, torrential rainfall, major flooding, and even tornadoes [~~Wikipedia and references therein~~[floodlist.org](https://www.floodlist.org) and [severe-weather.eu](https://www.severe-weather.eu), last access for both: 11 September 2020]. The main affected regions were Tunisia and Libya Libya in the early stages and southern Greece and Turkey later on [~~Wikipedia and references therein~~[floodlist.org](https://www.floodlist.org), last access: 11 September 2020]. ~~A specialty of this cyclone was that it~~ This cyclone belonged to a special class of Mediterranean cyclones that develop visual and structural similarities to tropical cyclones in a process similar to tropical transition [for further details on tropical transition see Davis and Bosart (2004)]. These cyclones are often called medicanes (Mediterranean hurricanes; Emanuel, 2005; Tous and Romero, 2013; Cavicchia et al., 2014) or Mediterranean tropical-like cyclones (Miglietta et al., 2013). Medicanes are often associated with strong horizontal pressure gradients, wind, and rainfall, which may result in large-significant damage, although medicanes rarely attain hurricane intensity. ~~Sometimes they~~ They acquire the typical appearance of a hurricane, with convective cloud bands wrapped around a cloud-free central eye and a typical size of the associated cloud clusters on the order of 300 km in diameter, i.e. smaller than typical hurricanes (Emanuel, 2005). There is not yet a clear definition of medicanes. A common property seems to be the development of a (symmetric) warm-core structure throughout the whole troposphere, often called deep warm core. The deep warm core of medicanes is not necessarily produced directly by convection but can, especially at lower levels, be promoted by horizontal advection and the seclusion of warm air in the cyclone centre (Fita and Flaounas, 2018). The relative role of the positive upper-level PV anomaly and air-sea interaction for the intensification of medicanes is currently debated. In most cases the positive upper-level PV anomaly seems to be important for the initial intensification (Miglietta et al., 2017). This study focuses on uncertainties related to the PV streamer that lead to genesis and initial intensification of Medicanes Zorbas.

Using ECMWF operational ensemble forecasts, Pantillon et al. (2013) investigated the predictability of a medicane that was preceded by upstream ET. They found that ensemble members that appropriately forecasted the cyclone track during ET ~~re-~~correctly reproduced ridge building and the resulting PV streamer over the Mediterranean, while ridge building was reduced and the PV streamer was absent in the ensemble members that wrongly predicted a southward deflection of the tropical cyclone. At the same time, only few of the ensemble members with a PV streamer forecasted a downstream medicane, showing that the predictability of the medicane was still strongly limited, even when the representation of upstream ET was roughly correct and a PV streamer was forecasted. This indicates that other synoptic-scale aspects related to the PV streamer, for example uncertainty in its position, shape, or intensity limited the predictability of the medicane (similar to Maier-Gerber et al., 2019 [for a tropical transition over the North Atlantic](#)). The existence of several ‘stages’ in cyclone predictability is consistent with the systematic analysis of the predictability of recent medicanes by Di Muzio et al. (2019), which showed that such “forecast jumps” occur at different lead times for different forecast parameters. For example, rapid increases in the probability of cyclone occurrence can be found at longer lead times (4-7 days before the mature phase of the medicane) than rapid decreases of the spread of cyclone position (2-5 days) and of the strength of the upper-level warm core (initializations after cyclogenesis). While the dynamical link between uncertain upstream ET and uncertainties in the occurrence of Mediterranean cyclones and heavy precipitation is well established, Raveh-Rubin and Flaounas (2017) showed that only a small percentage of the most intense Mediterranean cyclones is preceded by ET in the North Atlantic. Therefore current understanding of the role of upstream processes for uncertainties and jumps in the forecasts of intense Mediterranean cyclones in general, and medicanes in particular,

is limited.

The present study addresses this knowledge gap by presenting a chain of dynamical processes linking ensemble forecast uncertainties in the North Atlantic to an uncertain PV streamer position over the Mediterranean, and subsequently to an uncertain position and thermal structure of Medicane Zorbas. It is also one of the first studies that explicitly documents the role of an uncertain PV streamer position for uncertainties in the forecast of a medicane. To this aim, it investigates the ECMWF ensemble prediction initialized 84 h before cyclogenesis of Medicane Zorbas, which was the last initialization before a rapid decrease in ensemble spread of geopotential height at 500 hPa over the Mediterranean (i.e. a forecast jump) the day before cyclogenesis. This suggests that this particular ensemble forecast provides valuable information about the dynamics related to the forecast jump. ~~Many previous medicane studies have used high-resolution, convection-permitting models to study small-scale processes like air-sea interaction and convection involved in the transition to and during the tropical-like phase (Fita et al., 2007; Davolio et al., 2009; Mazza et al., 2017; Fita and Flaounas, 2018; Miglietta and Rotunno, 2019). In this study, forecasts of the comparably coarse ECMWF operational ensemble forecast model with parametrized convection are used to study synoptic to mesoscale forecast uncertainties before cyclogenesis and during the initial 24-hour period of cyclone intensification. This data is valuable because the model is able to reproduce medicanes adequately (Pantillon et al., 2013; Di Muzio et al., 2018). Additionally, other studies have~~ Previous studies have shown that a detailed analysis of ensemble forecasts, especially of different scenarios in a particular ensemble prediction, can be highly rewarding for better understanding the involved dynamics and predictability limits. As an example, such scenarios have already been used to identify key dynamical elements limiting the predictability of medicanes (Pantillon et al., 2013), but also tropical cyclones (Torn et al., 2015; Pantillon et al., 2016; Gonzalez-Aleman et al., 2018; Maier-Gerber et al., 2019) and atmospheric blocking (Quandt et al., 2017).

The remainder of this article is structured as follows. After a description of the data and methods in Sect. 2, an overview of the large-scale situation prior to cyclogenesis and the synoptic evolution of Zorbas is given in Sect. 3. In Sect. 4, uncertainties of Zorbas in the operational ensemble forecast are discussed and a pragmatic clustering is introduced that uses the uncertainty in the PV streamer position to separate the ensemble forecast into three distinct PV streamer scenarios. Sect. 5 discusses the origin and the dynamical pathway of the forecast uncertainty that lead to the three PV streamer scenarios and, as a result, uncertain position and thermal structure of the Mediterranean cyclone. Finally, the main conclusions are summarized in Sect. 6.

2 Data and methods

2.1 Data

The basic data for this study are from the ECMWF Integrated Forecasting System (IFS, Cycle 45r1; ECMWF, 2018). Operational ensemble forecasts with 50 perturbed members initialized at 0000 UTC 22 - 27 Sep 2018 and the operational analysis are used. The ECMWF operational ensemble forecast is based on perturbed initial conditions as well as stochastic perturbations of model physics (for details see ECMWF, 2018). The spectral resolution of the operational ensemble is TCO639 (about 18 km) on 91 model levels, and the resolution of the operational analysis is TCO1279 (about 9 km) on 137 model levels. The data are

available every 6 h and have been interpolated to a regular grid with a horizontal resolution of 1° . For the initialization at 0000 UTC 24 Sep 2018, PV on isentropic surfaces (every 5 K) and equivalent potential temperature (θ_e) on pressure levels (every 25 hPa) are additionally computed from the standard variables. As a measure for forecast skill, anomaly correlation coefficients (ACC) are calculated for geopotential height at 500 hPa for each ensemble member of the forecasts initialized at 0000 UTC 24 Sep 2018 and 0000 UTC 27 Sep 2018. As a reference, the daily mean ERA-Interim climatology from 1979-2014 is used (for details see supplementary material S4). Anomalies of θ_e at 900 hPa were computed with respect to the September/October ERA-Interim climatology from 1979-2017.

In addition, observational data are used from satellite imagery: the infrared channel 9 ($10.8\ \mu\text{m}$) of MSG SEVIRI provided by the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT), and the satellite-based 3-hourly rainfall intensity estimate Tropical Rainfall Measuring Mission (TRMM) level 3 version 7 on a 0.25° regular grid. Accumulated rainfall over a nine-hour period is computed using the average intensity (in mm h^{-1}) over three subsequent 3-hourly time intervals, consistent with the computation of the daily accumulated TRMM rainfall estimate.

2.2 Trajectory computation and identification of WCBs

Computing trajectories provides insight into the Lagrangian history of air parcels. In this study, the ~~Langrangian~~-Lagrangian analysis tool LAGRANTO (Wernli and Davies, 1997; Sprenger and Wernli, 2015) is used to identify WCB trajectories in the operational analysis (ascent rate larger than 600 hPa in 48 h, see e.g. Madonna et al., 2014). Intersection points of WCBs with the 325 K level are identified, considering trajectories present within the 322.5 and 327.5 K isentropic layer ~~are identified~~. Additionally, LAGRANTO was used to compute 24 h forward trajectories of low-level air parcels in the 850-950 hPa layer (every 25 hPa) and in a circle with 250 km radius around the cyclogenesis position.

2.3 Cyclone phase space and cyclone tracking

The cyclone phase space (CPS; Hart, 2003) is a useful tool to diagnose the thermal structure of cyclones throughout their life cycle. The CPS uses three parameters to define the thermal structure: lower-tropospheric horizontal thermal asymmetry (B), which measures the across-track 900-600 hPa thickness gradient, i.e. frontal nature; and thermal winds in the lower ($-V_T^L$; 900-600 hPa) and upper troposphere ($-V_T^U$; 600-300 hPa), which measure the vertical thermal structure. In this three-dimensional parameter space, cyclones can be classified as frontal ($B > 10$) or non-frontal ($B \leq 10$), cold-core ($-V_T^L < 0$ and $-V_T^U < 0$), hybrid ($-V_T^L > 0$ and $-V_T^U < 0$), or deep warm-core ($-V_T^L > 0$ and $-V_T^U > 0$). In this study, cyclones that at least once in their life cycle fulfill the deep warm-core criterion are classified as medicanes. As the frontal nature of the cyclone is not in the focus of this study, the symmetry parameter B is not considered.

Cyclone tracks at six-hourly temporal resolution are obtained for each of the 50 ECMWF ensemble members and the operational analysis using the cyclone detection and tracking method described by Picornell et al. (2001). This method was specifically designed to study mesoscale cyclones in the Mediterranean Sea, including medicanes (Gaertner et al., 2018). More specifically, six-hourly SLP fields are used to identify pressure minima after applying a Cressman filter (radius of 200 km;

Sinclair, 1997) to smooth out noisy features and small cyclonic structures. Weak cyclones are then filtered with a SLP gradient threshold of 0.5 hPa per 100 km. Cyclone tracks are identified with the aid of the horizontal wind field at 700 hPa, which is considered the steering level for cyclone movement. For one member (member 32) the cyclone track showed an unrealistically large jump during the first 6 h and therefore the first track point was removed. The CPS is calculated every 6 h based on the track positions and the CPS values at each time are smoothed using a running-mean filter with a 24-h window. Due to the small size of medicanes, a radius of 150 km is used to calculate the CPS values, consistent with previous studies (e.g. Gaertner et al., 2018).

2.4 Normalized PV differences

Ensemble members will be grouped into clusters (see Sect. 4.2). To compare PV of two ensemble clusters at different lead times, it is useful to compute normalized cluster-mean differences (see e.g. Torn et al., 2015):

$$\Delta PV_{AB} = \frac{\overline{PV}_A - \overline{PV}_B}{\sigma_{PV}} \quad (1)$$

where σ_{PV} is the standard deviation of the full ensemble. Hence, ΔPV_{AB} becomes large when the cluster-mean difference of PV between clusters A and B at a given location is much larger than the ensemble standard deviation at the same location, i.e. when the two clusters contain the members of the ensemble that are most different from each other. Additionally, it allows different lead times to be easily compared. For example, if ΔPV_{AB} increases with lead time, the cluster differences grow faster than the ensemble standard deviation, which means that the clusters become increasingly distinct from each other relative to the full ensemble.

2.5 Statistical significance

In order to be confident that the differences between two ensemble clusters are robust, a two-sided Wilcoxon rank-sum test (Wilks, 2011) for each cluster pair and considered field was applied. With such a test, the null hypothesis is investigated that it is equally likely that at a certain grid point the value of a randomly picked ensemble member in one cluster is larger or smaller than in a randomly picked ensemble member of the other cluster. When applying such a statistical test to a field, the false discovery rate should be controlled in order to avoid over-interpretation of the results (Wilks, 2016). This can be done by correcting the p -values of the statistical test taking into account the number of tests. For this study we are only interested in a domain covering the North Atlantic and the Mediterranean and consider a box from 30 to 70°N and 80°W to 30°E. Therefore, a number of 4400 tests are used for the correction. As suggested by Wilks (2016), a Benjamini-Hochberg correction is used in this study and the false discovery rate is set to a rather conservative value of $\alpha_{fdr} = 0.1$ for all analyses. Regions where the null hypothesis is rejected on this level of α_{fdr} can then be used to identify where and when robust differences in the clusters emerge in the ensemble forecast.

3 Synoptic overview

This section ~~provides first~~ first provides an overview of the synoptic situation over the Euro-Atlantic region prior to cyclogenesis of Medicane Zorbas. Then cyclogenesis and the initial intensification of Zorbas are discussed, during which it acquired a deep warm core. A particular focus is given to the link between the evolution of low-level θ_e and upper-level PV, and how it affected the formation of a deep warm core. This is followed by an overview of the full cyclone track and its evolution in the CPS diagram. The section ends with a discussion of satellite-based observations of clouds and precipitation.

The period prior to cyclogenesis was initially, at 0000 UTC 24 Sep 2018 (Fig. 1a), characterized by a large-scale situation with a low-amplitude Rossby-wave pattern in the Euro-Atlantic region including: a large-scale trough (T), a zonally oriented jet maximum (J) over Newfoundland, and a weak ridge (R) and trough (T2) pattern over northern Europe. In the following three days, the wave pattern strongly amplified and anticyclonic Rossby-wave breaking resulted in a pronounced PV streamer (S2) over the Mediterranean at 0000 UTC 27 Sep 2018 (Fig. 1d). In greater detail, this transition can be split into different phases. First, the trough over Newfoundland and the weak ridge / trough pattern over Europe amplified and the jet maximum moved over the North Atlantic and became directed north-eastward towards Iceland (Fig. 1b). Subsequently, the trough (T) elongated into a PV streamer (S), then interacted with Hurricane Leslie (L) resulting in substantial WCB activity over the central North Atlantic (black crosses in Fig. 1c,d). At the same time, anticyclonic wave breaking downstream over Europe was accompanied by a strongly amplified ridge and a narrowing of the trough (T2) over eastern Europe. This narrowing trough finally elongated to a PV streamer (S2) reaching the central Mediterranean Sea at 0000 UTC 27 Sep 2018 (see Fig. 1d). Note that in this case the anticyclonic wave breaking over Europe occurred clearly before the inflow of WCB air masses into the upstream ridge, indicating that the ridge amplification was not driven by the WCB related to Leslie. Hence, even if the presence of an upstream tropical cyclone and enhanced WCB activity are reminiscent of situations with Mediterranean cyclogenesis documented in previous studies (e.g. Pantillon et al., 2013; Raveh-Rubin and Flaounas, 2017), the temporal sequence in this case differs from the evolution documented in these studies.

The formation of the PV streamer over the Mediterranean was followed by cyclogenesis of Zorbas at the PV streamer's south-eastern flank (Fig. 2a-c). ~~At The PV streamer broke up at~~ the time of cyclogenesis, ~~the PV streamer broke up~~ resulting in the formation of a PV cutoff (Fig. 2b). In the ~~following subsequent~~ 24 h, the cyclone intensified rapidly and at the same time the PV cutoff was eroded, indicating the presence of intense diabatic processes. Shortly before cyclogenesis, the large mean sea level pressure gradient between a surface high pressure system over eastern Europe and a surface low pressure area over the Levantine Sea resulted in strong low-level advection of air with low θ_e across the Aegean Sea (Fig. 2a,d, for geographical locations see Fig. 3a). Air with anomalously high θ_e was present over ~~Lybia~~ Libya and at cyclogenesis in immediate proximity of the cyclone centre (hatched regions in Fig. 2d,e). A detailed trajectory analysis (see supplementary material S1 and Figs. S1, S2, and S3) shows that the low-level air in the 850-950 hPa layer and within a radius of 250 km around the cyclone centre at the time of genesis (1200 UTC 27 Sep 2018) originated from the Aegean and Black Sea and was substantially moistened by sea-surface fluxes as it traveled across the Aegean Sea. This is consistent with the direction of low-level winds (Fig. 2d,e). The relevance of strong advection of cold and dry air and moistening by surface fluxes over the Mediterranean has already been

pointed out for medicane formation in the western Mediterranean (Miglietta and Rotunno, 2019). A day after cyclogenesis, a low-level θ_e maximum was present in the cyclone centre (Fig. 2f) and, as diagnosed by the CPS, Zorbas had acquired a deep warm core at this time (Fig. 3b). The system acquired an equivalent barotropic structure, i.e. the surface cyclone, the minimum of geopotential height at 500 hPa, and the upper-level PV maximum were vertically aligned (Fig. 2c,f). The upper-level PV cutoff had decayed and the small-scale PV maximum with values around 2 PVU above the cyclone centre at 1200 UTC 28 Sep 2018 marked the upper end (at around 400 hPa) of a vertically extended diabatic PV maximum above the cyclone centre that was disconnected from the stratospheric high PV reservoir (not shown). The presence of a mid- and low-tropospheric PV maximum and an upper-tropospheric PV minimum are characteristic for many medicanes (Miglietta et al., 2017).

In order for the latent heating to reach high enough and result in the erosion of the upper-level PV anomaly, sufficiently moist and warm air has to be present in the lower troposphere. The larger θ_e of the low level air parcels, the higher they can rise through moist adiabatic ascent (see e.g. Holton (2004), their Fig. 9.10). In this case, values of θ_e at 900 hPa in the cyclogenesis area exceeded 330 K. This value provides the approximate maximum isentropic level to which these air masses can ascend upon the release of latent heat. In fact, more than half of the low-level air parcels with $\theta_e > 322.5$ K between 850 and 950 hPa and within a radius of 250 km around the cyclone centre experienced strong diabatic heating and rapid cross-isentropic ascent (average $\Delta\theta$ -diabatic heating of about 30 K) to levels above 322.5 K during the first 24 h after cyclogenesis (black crosses in Fig. 2c). Hence, they contributed ~~substantially~~ to the erosion of the PV cutoff. ~~Despite limitations of trajectories in convective situations, this~~ This is a strong indication that air with high θ_e at low levels was a crucial prerequisite for the erosion of the stratospheric PV anomaly and, as a result, the formation of a deep warm core. In fact, the difference between θ_e at 850 hPa and tropopause potential temperature is a measure of bulk stability and has shown to be a suitable predictor for the occurrence of tropical transition (so-called coupling index, McTaggart-Cowan et al., 2015). The formation of a deep-warm core system with an equivalent barotropic structure as result of high θ_e values at low tropospheric levels and strong latent heating will become relevant again towards the end of this article when cyclone evolutions in the ensemble members are discussed.

The full track of Medicane Zorbas and the CPS diagram are shown in Fig. 3. Zorbas formed at 1200 UTC 27 Sep 2018 close to Benghazi, moved into the central Mediterranean and then sharply turned eastward and moved over Greece into the Aegean Sea, where it finally decayed four days after its formation. According to the CPS (Fig. 3b), Zorbas formed as a cold-core cyclone and within 18 h acquired a deep warm core that was sustained for more than three days. This is comparable to the January 1982 case investigated by Picornell et al. (2014), but substantially longer than for all eight recent medicane cases investigated by Di Muzio et al. (2019) using the same dataset. Zorbas reached its maximum intensity (992 hPa) already 12 h after cyclogenesis.

Note that the ECMWF reported a substantial underestimation of the cyclone intensity in the operational analysis in the later stage of its life cycle and estimated the real central pressure at ~~land-fall~~ landfall to below 990 hPa (ECMWF, 2019). Satellite images indicate the formation of an eye-like feature shortly before Zorbas reached Greece on 29 Sep 2018. However, this aspect of the life cycle is beyond the scope of this study. Instead, we focus on the synoptic aspects prior to cyclogenesis, and the subsequent ~~about one-day~~ period of initial cyclone intensification and the formation of a deep warm core.

An observational perspective on this period is given in Fig. 4a. Shortly after cyclogenesis, intense rainfall was observed north-west of the cyclone centre (Fig. 4a). The dense cloud patch and lightning activity (see supplementary material S2 and Fig. S4)

at this location are indicative of strong latent heating and the presence of deep convection, which helps to explain the rapid diabatic erosion of the PV cutoff (see e.g. Wirth, 1995; Portmann et al., 2018). At the time when the deep warm core was well established, precipitation was weaker and mainly located near the cyclone centre (Fig. 4b). The cloud structure indicates that well-defined fronts were absent, i.e. Zorbas acquired a more tropical-like appearance. According to TRMM, Zorbas lead to extreme daily rainfall (>99th ~~pre~~centilepercentile, reference period 1998-2018) in several regions in ~~Lybia~~Libya, the central Mediterranean, and Greece (not shown).

The evolution of Zorbas in the first day of its life cycle to some extent agrees well with the climatological evolution found for the strongest Mediterranean cyclones around their time of maximum intensity (Flaounas et al., 2015), in particular considering the shape and cyclone-relative position of the upper-level PV anomaly. Remarkable in this case were the anomalously high values of low-level θ_e . Further, the evolution bears similarities to the first phase of tropical transition events of strong extratropical cyclones as discussed in Davis and Bosart (2003, 2004). In particular, this is true for the enhanced rainfall to the west of the cyclone centre, the diabatic erosion of the stratospheric PV anomaly, the emergence of a tropospheric PV maximum above the storm centre, and the formation of an equivalent barotropic vortex.

270

4 ECMWF ensemble forecasts

4.1 Ensemble spread and uncertainties in the formation of the Mediterranean cyclone

The synoptic situation over the Mediterranean was associated to ~~substantial~~uncertainties in the operational ECMWF ensemble forecasts~~until three days before~~, which decreased particularly strongly for initialization later than three days prior to genesis of Zorbas. This is shown by the evolution of the ensemble spread of geopotential height at 500 hPa averaged over the Mediterranean at 0000 UTC 27 Sep 2018 for different initializations (Fig. 5). For initializations until 0000 UTC 24 Sep 2018, the spread decreases only marginally, but it does so very rapidly for later initializations, indicating a forecast jump. For the initialization at 0000 UTC 24 Sep 2018, all ensemble members develop a surface cyclone but uncertainties related to cyclone position and its thermal structure were substantial (Fig. 6, ignore colors for this paragraph). While several members forecasted the cyclone approximately at the correct location over ~~Lybia-Libya~~ at 1200 UTC 27 Sep 2018, some forecasted it too far to the west and some too far north-east in the Aegean Sea (Fig. 6a). This zonal position uncertainty was still present 24 h later, and in four members the cyclone already disappeared (Fig. 6b). At this time, the uncertainty in the position of the cyclone ranged from the coast of Tunisia to the Aegean Sea. Interestingly, in the members where the cyclone formed too far to the north-east, genesis occurred more than 12 h before cyclogenesis in the operational analysis. In addition, only 21 ensemble members predicted a medicane (markers with white centres), and among the medicanes differences in their strength (as defined by the maximum $-V_T^U$ value, see marker size) were substantial. Also there was a clearly preferred region for medicanes to form near the ~~Lybian~~Libyan coast, indicating a link between cyclone position and thermal structure. Considering these large uncertainties associated with the prediction of the surface cyclone and the timing of the forecast jump we focus in the following on the 0000 UTC 24 Sep 2018 initialization. The rest of this article aims to show that these uncertainties in the Mediterranean cyclone evolution

285

290 can be traced back to a short-wave perturbation in the wave guide over the North Atlantic initiated during the first day of the forecast, and that they were tightly linked to uncertainties in the position of the Mediterranean PV streamer.

4.2 Ensemble clustering according to the position of the PV streamer

In the 0000 UTC 24 Sep 2018 forecast, the ensemble spread at 0000 UTC 27 Sep was mainly enhanced because of a substantial uncertainty in the position of the Mediterranean PV streamer. To establish the dynamical link between ~~on the one~~
295 ~~hand, the~~ uncertainties in the position ~~and thermal structure~~ (and thus the thermal structure) of the cyclone and ~~on the other~~
~~hand,~~ upstream uncertainties along the North Atlantic wave guide, a pragmatic clustering procedure is presented that ~~allows~~
~~separating~~ classifies the ensemble members of the 0000 UTC 24 Sep 2018 initialization into three clusters based on the position of the Mediterranean PV streamer (S2 in Fig. 1d), at day 3 of the forecast. The three identified PV streamer scenarios ~~i.e.~~
~~clusters~~ (clusters), are the basis for all remaining analyses. For the clustering, a box is defined around the PV streamer identified
300 at 0000 UTC 27 Sep 2018 in the operational analysis (Mediterranean box, 5-30°E, 30-45°N, see black box in Fig. 7). The clustering uses vertically averaged PV between 320 and 330 K, hereafter called PV_{av} . Before averaging, all PV values with $PV < 2$ PVU are set to zero to remove the contribution of the variability of tropospheric PV values. Hence, PV_{av} is high in areas where the stratospheric PV streamer is strong and deep, and low where it is weak and shallow. The pragmatic clustering is then based on two different steps~~:-~~. First, from all 50 ensemble members the ones are identified for which the area with
305 $PV_{av} \geq 2$ PVU in the box has more than 75% overlap with the corresponding area in the analysis ~~:-~~ (black contour in Fig. 7). In these 19 members, the streamer has a similar location as in the analysis, i.e. a central position in the ensemble, and is therefore referred to as cluster C (see blue shading in Fig. 7). The remaining members are separated into two clusters depending on whether the maximum PV_{av} is shifted to the west (cluster W, 12 members, green shading in Fig. 7) or east (cluster E, 18 members, red shading in Fig. 7) relative to the analysis. There is one ensemble member that cannot be attributed to one of the
310 three clusters because its overlap is less than 75% but the maximum of PV_{av} is located at the same longitude as in the analysis. The histogram of the longitude where the maximum of PV_{av} occurs between 36-37°N (inset in Fig. 7) shows three clearly distinct peaks, one for each cluster, validating the simple clustering approach. There are a few borderline members but they do not affect the main results of this study.

The meaningfulness of this clustering for studying the predictability of this case is further supported by the fact that it helps
315 to explain the temporal development of the ACC averaged in the Mediterranean box. As shown in Fig. 8a, the ACC of geopotential height at 500 hPa in the Mediterranean starts to decrease in the majority of the ensemble members at the time when the PV streamer reaches the Mediterranean on 26 Sep 2018 and even more after cyclogenesis occurs, while it remains high (close to 1) until 29 Sep 2018 for most members of cluster C (blue lines in Fig. 8a). After the decrease from 1 to around 0.8 the median ACC (red line) remains fairly constant until 29 Sep 2018. In comparison, for the ensemble forecast initialized at
320 0000 UTC 27 Sep 2018, i.e. at the time when the PV streamer has developed, the ACC remains high in all members during the intensification and deepest phase of Zorbas, decreasing only after 29 Sep 2018 (Fig. 8b), likely due to errors associated with a second PV streamer reaching the Mediterranean in the northern part of the box (not shown). It can be concluded that

errors in the position of the PV streamer limited the large-scale predictability as measured by the ACC of geopotential height on 500 hPa in the Mediterranean, and that cluster C contains the members with the most accurate forecasts.

325 5 Propagation of forecast uncertainties along the North Atlantic wave guide to the Mediterranean cyclone

In the following the chain of dynamical processes is described that enabled the propagation and amplification of forecast uncertainties (here considered as significant differences between cluster means) from the North Atlantic to the Mediterranean cyclone. In a first step, the propagation and amplification of these uncertainties along the North Atlantic wave guide to the Mediterranean PV streamer is considered. Subsequently, the effect of the uncertain PV streamer position on the cyclone position
330 and thermal structure is discussed.

5.1 ~~Propagation~~ Uncertainty propagation from the North Atlantic jet streak to the Mediterranean PV streamer

To investigate the first part of the uncertainty propagation, normalized PV differences (see Sect. 2.4) on 325 K between clusters E and W (ΔPV_{EW}) are analyzed, as these are the clusters that deviate the most in terms of the PV streamer position. During the first day after initialization a short-wave pattern of positive and negative PV differences emerges on the North
335 Atlantic wave guide from an initially very spotty difference field (Fig. 9 and Fig. 10a). At 1800 UTC 24 Sep 2018 (Fig. 9d), a positive ΔPV_{EW} with an amplitude larger than 1.5 standard deviations appears on the stratospheric side of the strengthening jet streak (yellow contour, marked as J in Fig. 1b six hours later) over the North Atlantic. This ΔPV_{EW} is statistically significant (as indicated by the white contours in Fig. 9d; see Sect. 2.5 for the testing procedure). Visually, it seems that this ΔPV_{EW} emerges from a small positive ΔPV_{EW} that propagates from the Gulf of Saint Lawrence at initial time (Fig. 9a) along the wave
340 guide into the North Atlantic and amplifies (indicated by the grey boxes in Fig. 9). However, these differences early in the forecast are not statistically significant and other sources of the amplified ΔPV_{EW} at 1800 UTC 24 Sep 2018 could be relevant. ~~However, a~~ A substantial contribution of ~~moist diabatic processes and~~ WCBs can be excluded. ~~There, as there~~ is no WCB activity in the area indicated by the grey boxes (as shown in Fig. 1a,b) and precipitation is weak (not shown). ~~Furthermore, the positive ΔPV_{EW} is located in a region that is clearly stratospheric, i.e. where strong moist diabatic processes are mostly~~
345 ~~absent. Hence, it is most likely dry upper-tropospheric dynamics associated to the jet streak that drives the amplification of the initial condition differences until 1800 UTC 24 Sep 2018.~~ This is in contrast to studies that showed the relevance of the diabatic low-PV outflow of WCBs for the emergence of upper-tropospheric forecast uncertainties and subsequent downstream propagation (e.g. Pantillon et al., 2013; Grams et al., 2018), ~~but in agreement with studies emphasizing the important role of non-linear (barotropic) upper-tropospheric dynamics.~~ However, diabatic processes could still be relevant for the amplification
350 of ~~forecast error and ensemble spread (Baumgart et al., 2018; Baumgart and Riemer, 2019).~~ An the forecast uncertainties in this case. Further, an analysis of geostrophic and ageostrophic wind differences between the two clusters and PV gradients in the jet streak region suggests that differences in the ageostrophic circulation are important for this amplification (not shown). A physically plausible cause of the strengthening of the jet streak and the initiation of a wave-like perturbation at the tropopause at 1800 UTC 24 Sep 2018 could be the band of high stratospheric PV that is approaching the tropopause region (green contours

355 in Fig. 9d).

After the emergence of the prominent positive ΔPV_{EW} at 1800 UTC 24 Sep 2018, there is a clear downstream propagation as a short-wave perturbation along the wave guide into the Mediterranean (Fig. 10). First, the positive ΔPV_{EW} further amplifies and a negative ΔPV_{EW} emerges downstream over the North Sea (Fig. 10a). The deviation of the 2 PVU contours shows an increasingly clear short-wave pattern superimposed onto the large-scale Rossby-wave pattern, which is particularly pronounced in cluster W (dashed contour). The positive ~~(negative)~~ ΔPV_{EW} are associated with cyclonic ~~(anticyclonic)~~ difference winds and the negative ones with anticyclonic difference winds, resulting in a westward phase speed of the ΔPV_{EW} relative to the mean flow. During the propagation, the maximum amplitude of the ΔPV_{EW} pattern increases and moves downstream, consistent with an eastward group speed. For example, at 0000 UTC 25 Sep 2018, the negative ΔPV_{EW} has a smaller amplitude than the positive ΔPV_{EW} (Fig. 10a), while 12 hours later, the opposite is the case (Fig. 10b). Also, while the negative ΔPV_{EW} becomes increasingly significant, the significance of the positive ΔPV_{EW} decreases after 1200 UTC 25 Sep 2018. The downstream development of the ΔPV_{EW} -wave subsequently results in a more progressed anticyclonic Rossby-wave breaking in cluster W compared to cluster E (Fig. 10c,d). Ultimately, this leads to a zonally shifted tip of the narrow trough (T2 in Fig. 1d), and later, the PV streamer (S2 in Fig. 1e), as seen in Fig. 10d and consistent with Fig. 7.

Similar wave-like patterns of PV errors that emerge from a localized PV error and result in downstream development have been shown for example by Davies and Didone (2013) and Baumgart et al. (2018) for time scales of several days. Here such a pattern is shown for significant PV differences between ensemble clusters with a particularly fast propagation from 40°W to 20°E in less than two days. The initiation of the short-wave perturbation by a stratospheric PV anomaly is consistent with results of idealized studies looking at the effect of an isolated vortex approaching a strong isentropic PV gradient from the stratospheric side (e.g. Schwierz et al., 2004) and of a climatological analysis of precursor perturbations of Rossby-wave initiation events (Röthlisberger et al., 2018, their Fig. 13). ~~If~~ The strengthening of the jet streak in such a situation can also be understood as a steepening of the tropopause in this region (e.g. Winters and Martin, 2017). This situation is also reminiscent of the ~~situation depicted~~ depiction by Davies and Didone (2013), in which a lower-stratospheric PV anomaly approaches the wave guide, initiates a wave train at the tropopause, and results in forecast error growth. In our case, this initiation occurs around 1800 UTC 24 Sep 2018, consistent with the ~~large drop~~ substantial reduction of ensemble spread over the Mediterranean from the 0000 UTC 24 Sep to the 0000 UTC 25 Sep 2018 initializations (Fig. 5). This indicates that, once the short-wave perturbation was captured properly, the forecast uncertainties associated with the formation of the PV streamer were substantially reduced.

5.2 How the uncertain PV streamer position affects the cyclone's position and thermal structure

In the previous section the dynamical pathway leading to the uncertainty in the position of the PV streamer at day 3 of the ensemble forecast was analyzed. In the following, it is investigated how this uncertainty affects the position and thermal structure of the resulting Mediterranean cyclone.

First, the effect of the PV streamer position on the subsequent PV cutoff formation and surface cyclogenesis is discussed based on synoptic composites for the three clusters (Fig. 11). At 1200 UTC 26 Sep 2018, the position and shape of the PV streamer in cluster C is still very close to the analysis, whereas in cluster W the tip of the streamer is thinner and extends more to the

west, and in cluster E it is shifted to the east (Fig. 11a,d,g), consistent of course with the previous discussion of Fig. 10d. In these regions, clusters W and E significantly differ from cluster C ~~-(indicated by the white contours in Fig. 11a,g)~~. This is not surprising as the clustering was specifically designed to focus on these differences. One day later, at the time of cyclogenesis in the analysis, a PV cutoff has formed in all clusters (Fig. 11b,e,h) and the differences in the scenarios over the Mediterranean are very prominent. While in cluster C the cutoff is located south of Italy in the Central Mediterranean (in excellent agreement with the analysis), cluster W exhibits a much weaker cutoff further to the west over Tunisia, and cluster E shows a stronger cutoff shifted to the east. In all clusters the developing surface cyclones are located slightly east of the cutoff (cyclone centres of individual ensemble members are shown by black dots). Hence, in cluster C the cyclones are located close to Benghazi (as in the analysis, indicated by the teal star), in cluster W too far west close to Tripoli, and in cluster E too far east over Crete. One day later (Fig. 11c,f,i), the PV cutoff in the analysis has decayed into smaller patches. In cluster C, the cutoff has clearly weakened (PV values < 3 PVU), in cluster W it has fully decayed, and in cluster E it is still very prominent and strong (PV values > 6 PVU), indicating substantial differences in the diabatic modification of the PV cutoff. In cluster W, the absence of clear structures at 1200 UTC 28 Sep 2018 in both upper-level PV and SLP is partially due the large variability within this cluster at this time. Note again that the cyclone positions in cluster C agree well with the analysis whereas cyclones in the other clusters have typical position errors of about 400 km.

The surface cyclones in cluster E show a very different behavior than in clusters W and C. First, cyclogenesis occurs earlier and takes place in a pre-existing low pressure area over the Levantine Sea (Fig. 10l,g). At 1200 UTC 26 Sep 2018, 9 out of 18 members in this cluster have a cyclone identified in the Levantine Sea close to Cyprus, whereas in clusters W and C most cyclones form later in the southern part of the Central Mediterranean Sea, in immediate proximity to the PV cutoff. Second, cyclones in cluster E are on average much weaker than in clusters W and C (see box plots in the individual panels of Fig. 11). The pre-existing cyclones over the Levantine Sea deepen slightly when they interact with the PV cutoff but – with the exception of two cases – weaken again afterwards. It can be concluded that the eastward shift of the PV streamer (cluster E) leads to a particularly strong non-linear response of the cyclogenesis process and the intensity evolution of the surface cyclone. The westward shift (cluster W) also results in weaker surface cyclones than in cluster C and in the analysis, some with very short life times. Hence, the uncertain surface cyclone positions ~~after-at the time of cyclogenesis and after one day of intensification~~ (i.e. after 84 h and 106 h ~~lead time~~ of the forecast, ~~i.e. at the time of cyclogenesis and after one day of intensification~~ see Fig. 6), can be clearly attributed to the uncertain PV streamer position and the cluster with the best representation of the PV streamer position (cluster C) results in the best forecast of the cyclone position and intensity. This is also supported by Fig. 6, now referring the colors. They indicate the cluster to which each cyclone belongs, in full agreement with the aforementioned conclusion.

Interestingly, cluster E also results in the lowest fraction of medicanes (i.e. cyclones with a deep warm core, 2 out of 18 members, ~~see also Fig. 6~~), followed by cluster W (6 out of 19 members) and cluster C (15 out of 19 members). Hence, uncertainties in the cyclone's position are also tightly linked to uncertainties in its thermal structure. Because this link is not straightforward, the final part of this section sketches a potential pathway of how the uncertainties of the positions of the PV streamer and cyclogenesis affect the cyclone's thermal structure. This analysis will not be complete ~~because~~, as uncertainties

reach the mesoscale, we approach the limits of the dataset and methods used in this study. Nonetheless, key elements of this link can be identified by focusing on mesoscale differences at ~~upper-upper~~ and lower levels between cyclones in the three clusters during the 24 h period after cyclogenesis in the operational analysis. As shown in Fig. 11f,i, in both clusters C and E, the upper-level PV cutoff and the surface cyclone are vertically aligned at 1200 UTC 28 Sep 2018, i.e. they have an equivalent barotropic structure. Despite this similarity, the vertical thermal structure of the vortices strongly differs between the clusters. As diagnosed by the CPS, most cyclones in cluster E have an upper-level cold core, whereas most cyclones in cluster C have an upper-level warm core. In essence, this means that the stratospheric PV anomaly in cluster C is eroded (as in the operational analysis, see Sect. 3), while it remains strong in cluster E (consistent with Fig. 11f,i). In the operational analysis, the erosion of the stratospheric PV anomaly was linked to low-level air masses with high θ_e values near the cyclone centre. Here, we investigate the hypothesis that the differences in the modification of the stratospheric PV anomaly in cluster C and E ~~, i.e. and~~ thereby the differences in the vertical thermal structure of the cyclones, are linked to differences in low-level θ_e values. To this aim, θ_e between 850 and 950 hPa is averaged within a 250 km radius around the cyclone centre (as shown for the analysis in Fig. 2e), to quantify low-level θ_e values for each cyclone. Then, the 50% grid points with the highest PV values on 325 K within a radius of 750 km around the cyclone centre are averaged to quantify the amplitude of the upper-level PV anomaly. The larger radius is chosen because the highest values of upper-level PV are usually expected west of the cyclogenesis area. Each cyclone can now be positioned in a diagram of low-level θ_e vs. upper-level PV ~~. Figure (Fig. 12a,b shows such diagrams with the same markers and for the same times as the geographical maps in Fig. 6.)~~. At cyclogenesis time in the operational analysis, cluster C ~~and W~~ (blue) and W (green) are positioned at moderate upper-level PV values around 2-3 PVU and high low-level θ_e values between 320 and 330 K (Fig. 12a). Cluster W (red) cyclones tend to have slightly lower upper-level PV and low-level θ_e values than cluster C. The operational analysis (black marker) is positioned fairly well within cluster C, albeit with relatively high upper-level PV. Cluster E cyclones exhibit higher upper-level PV values around 3-5 PVU and much lower low-level θ_e values around 310-315 K. These values are most likely lower because cyclogenesis occurred closer to the northern coast of the Mediterranean and as a result, the low-level air parcels were less exposed to the sea surface and therefore less strongly moistened by latent heat fluxes compared to the operational analysis (for a discussion of the Lagrangian history of the low-level air parcels at cyclogenesis in the operational analysis, see supplementary material S1 and Figs. S1, S2, and S3). Within the ~~following subsequent~~ 24 h period of initial intensification and deep warm core formation in the operational analysis, cyclones in cluster C and W are associated with substantial precipitation in their centres (Fig. 12c) and a reduction of upper-level PV by about 1 PVU and of low-level θ_e by about 3-5 K (Fig. 12b), similar to the operational analysis. This behavior is consistent with the ~~crucial role necessity~~ of low-level air with high θ_e values for strong latent heating ~~and~~ cross-isentropic upward transport and the resulting erosion of the upper-level PV anomaly as observed in the operational analysis (see Sect. 3). Cyclones in cluster E experience an increase in low-level θ_e and, most importantly, little change in upper-level PV. The slight increase in upper-level PV values in some members might be related to the vertical alignment of the upper-level PV anomaly and the surface cyclone, such that a larger fraction of the upper-level PV anomaly is located within the 750 km radius around the cyclone. Precipitation in the cyclone centre is much ~~lower-reduced~~ indicative of a reduction in column-integrated latent heating. ~~As an~~

interesting side remark, we note that also cluster C underestimates the precipitation in the cyclone centre compared to TRMM rainfall along the cyclone track in the operational analysis.

In summary, the results of this analysis are consistent with the following pathway evolution of the forecast uncertainties: ~~In~~ in some members, the eastward displacement of the PV streamer position resulted in a strongly north-eastward shifted cyclogenesis position, leading to a reduced supply of low-level air with high θ_e in the cyclogenesis region. This resulted in weaker and shallower latent heating and no diabatic PV destruction on the 325 K level. Hence, the PV anomaly was not eroded and no upper-level warm core could form. There are a few ensemble members that deviate from this ~~storyline and they are~~ archetype, mostly the ones where the PV streamer position is on the borders between the clusters.

6 Summary and conclusions

The basis of this study was an ECWMF operational ensemble forecast, which, after three days, showed large uncertainties in the position of a PV streamer over the Mediterranean and the subsequent development of Medicane Zorbas in September 2018. These uncertainties were substantially smaller for later forecast initializations, motivating the use of this forecast to gain insight into the dynamics behind this rapid decrease in forecast uncertainty. The ensemble members were clustered into three distinct scenarios according to the position of the PV streamer at day 3 of the forecast. The differences between these scenarios were used to ~~present a dynamical pathway of forecast uncertainties from~~ assess how uncertainties originating in a short-wave perturbation in the North Atlantic wave guide ~~to the~~ influenced a downstream PV streamer and, as a result, the position and thermal structure of the Mediterranean cyclone.

Significant PV differences between clusters ~~appeared first~~ first appeared after 18 h forecast time ~~at on~~ on the stratospheric side of a strengthening jet streak over the North Atlantic. ~~At the same time, They were tightly connected to the initiation of~~ a short-wave perturbation superimposed to the large-scale Rossby-wave pattern ~~was initiated. The initiation of the short-wave perturbation~~ . This initiation and the strengthening of the jet streak was likely linked to a stratospheric high-PV filament approaching the tropopause region. A significant ~~moist diabatic contribution~~ contribution of WCBs to the emergence of these significant differences between ensemble clusters could be excluded. To some extent, ~~they~~ these differences could be traced back to differences in the initial conditions on the stratospheric side of the upper-level jet streak over the Gulf of Saint Lawrence. Subsequently, the differences further amplified and propagated along the wave guide across the Atlantic into the Mediterranean, where large-scale anticyclonic Rossby-wave breaking occurred and triggered the formation of Zorbas. The propagation and amplification of the upstream PV differences resulted in substantial differences in the position of the PV streamer between the three clusters. The shift in the position of the PV streamer resulted in a shift of cyclogenesis ~~and it that~~ that affected cyclone intensity and the diabatic modification of the upper-level PV anomaly. Ensemble members with the central (i.e. correct) PV streamer position produced cyclones most similar to the operational analysis, while the westward shift of the PV streamer resulted in slightly weaker cyclones too far to the west. In both cases, the upper-level PV anomaly was eroded. The eastward shift of the PV streamer led to a particularly different evolution. In this scenario, the cyclones formed too far north-east and more than 12 h earlier from a pre-existing surface trough in the Levantine Sea. The cyclones remained much weaker and the upper-level PV

anomaly much stronger than in the operational analysis and most other ensemble members. The non-linear response of the eastward shift of the PV streamer is particularly interesting as a comprehensive analysis of the predictability of PV streamers over the North Atlantic and the Mediterranean in the ECWMF ensemble forecasts showed that there is a tendency for eastward displacement in the forecasts compared to the analysis (Wiegand and Knippertz, 2014).

The central PV streamer position provided the best synoptic conditions for the formation of a strong medicane, while the eastward shift resulted in conditions that were most unfavorable for medicane formation. ~~A~~ The reason for this was that the eastward shifted cyclogenesis resulted in significantly reduced low-level equivalent potential temperatures in the cyclogenesis region, ~~which~~ This prevented latent heating ~~to be from being~~ strong enough and ~~reach~~ reaching high enough to erode the upper-level PV anomaly and form an upper-level warm core.

These results extend our understanding of the role of upstream uncertainties for the formation of Mediterranean cyclones in general, and medicanes in particular. It also provides new insight into the dynamics behind forecast jumps as identified by Di Muzio et al. (2019). Previous studies investigating medium-range predictability of Mediterranean cyclones mainly focused on the role of upstream uncertainties related to extratropical transition over the North Atlantic and the associated strong diabatic outflow (e.g. Pantillon et al., 2013). This study showed that the uncertainties limiting the predictability of Medicane Zorbas a few days ahead were ~~mainly linked to dry dynamics in the tropopause region. It highlights the key role of~~ linked to a short-wave perturbation superimposed to the large-scale Rossby-wave pattern that was initiated in a jet streak over the North Atlantic. Further research is needed to quantify how frequently this mechanism ~~leads to an upstream influence on~~ limits the medium-range predictability of Mediterranean PV streamers and, as a result, Mediterranean cyclogenesis.

Building on studies that document the relevance of upper-level PV anomalies for medicane development (e.g. Miglietta et al., 2017), this study also provides the first analysis of the relevance of ~~an uncertain a~~ PV streamer position for ~~uncertain~~ medicane formation and supports the hypothesis that certain regions are more conducive to medicane development than others (Di Muzio et al., 2019). In this case, only members with cyclogenesis in a relatively confined region at the Libyan coast developed a medicane. However, once the uncertainties reach the mesoscale, other factors can play an important role that were not analyzed in this study, such as ~~for example~~ vertical wind shear and mid-tropospheric humidity (Tous and Romero, 2013), or the details of the convective processes. In a subsequent study we plan to investigate how these factors limit the predictability of Zorbas' life cycle after cyclogenesis has occurred.

Finally, we note that this study is based on one particular ensemble initialization time where the occurrence of Rossby wave breaking and cyclone formation was already certain (but not the exact zonal position of the resulting PV streamer). Later initializations are characterized by much lower positional uncertainties of the PV streamer and, hence, strongly reduced ensemble spread of 500 hPa geopotential height (as shown in Fig. 5). In contrast, earlier initializations have even larger ensemble spread with high values extending from the Mediterranean to eastern Europe (not shown), indicating uncertainty in the onset of Rossby wave breaking and the overall orientation of the PV streamer. This implies that the uncertainty patterns discussed in this study are not representative for earlier initializations of the ensemble. While in this study, the ensemble forecast was used to investigate uncertainties in the PV streamer position and the evolution of the Mediterranean cyclone,

similar studies with forecasts initialized earlier could shed light on processes that determine uncertainties in the onset of the wave breaking. However, they would then be less suitable for investigating uncertainties in the formation of the medicane.

Data availability. All data is available from the authors upon request

530 *Author contributions.* JJGA sparked this work by discovering the uncertain forecast of Zorbas. RP and JJGA designed the basic idea for the study. JJGA carried out the analyses that required the computation of the CPS and RP all remaining analyses. MS and HW helped with the data access and handling and gave important guidance and useful inputs during the whole project. HW provided important guidance and support during the review process. RP and JJGA prepared the manuscript and all authors gave critical feedback that helped to improve the article.

Competing interests. The authors declare that they have no conflict of interest.

535 *Acknowledgements.* We thank the reviewers Ron McTaggart-Cowan, Florian Pantillon, and one anonymous reviewer for their detailed feedback that helped to improve the manuscript. RP acknowledges funding from the ETH research grant ETH-0716-2. JJGA has been funded through the PhD-grants BES-2014-067905, EEBB-I-18-12841 for short research stays, and by grant CGL2017-89583-R by the Spanish Ministry of Science, Innovation and University, and co-funded by the European Social and Regional Development Funds. We thank Andries de Vries (ETH Zürich) for providing support with the TRMM data and assessing the extremeness of precipitation. RP thanks Emmanouil
540 Flaounas (ETH Zürich) for insightful discussions about medicanes.

References

- Appenzeller, C. and Davies, H. C.: Structure of stratospheric intrusions into the troposphere, *Nature*, 358, 570–572, <https://doi.org/10.1038/358570a0>, 1992.
- Archambault, H. M., Bosart, L. F., Keyser, D., and Cordeira, J. M.: A climatological analysis of the extratropical flow response to recurving western North Pacific tropical cyclones, *Mon. Weather Rev.*, 141, 2325–2346, <https://doi.org/10.1175/MWR-D-12-00257.1>, 2013.
- Argence, S., Lambert, D., Richard, E., Chaboureaud, J.-P., and Soehne, N.: Impact of initial condition uncertainties on the predictability of heavy rainfall in the Mediterranean: a case study, *Q. J. Royal Meteorol. Soc.*, 134, 1775–1788, <https://doi.org/10.1002/qj.314>, 2008.
- Baumgart, M. and Riemer, M.: Processes governing the amplification of ensemble spread in a medium-range forecast with large forecast uncertainty, *Q. J. Royal Meteorol. Soc.*, 145, 3252–3270, <https://doi.org/10.1002/qj.3617>, 2019.
- Baumgart, M., Riemer, M., Wirth, V., Teubler, F., and Lang, S. T. K.: Potential vorticity dynamics of forecast errors: A quantitative case study, *Mon. Weather Rev.*, 146, 1405–1425, <https://doi.org/10.1175/MWR-D-17-0196.1>, 2018.
- Browning, K.: Organization of clouds and precipitation in extratropical cyclones, in: *Extratropical cyclones: The Erik Palmen memorial volume*, edited by Newton, C.W. and Holopainen, E.O., pp. 129–153, American Meteorological Society, Boston, MA, https://doi.org/10.1007/978-1-944970-33-8_8, 1990.
- Cavicchia, L., von Storch, H., and Gualdi, S.: A long-term climatology of medicanes, *Clim. Dyn.*, 43, 1183–1195, <https://doi.org/10.1007/s00382-013-1893-7>, 2014.
- Chaboureaud, J.-P., Pantillon, F., Lambert, D., Richard, E., and Claud, C.: Tropical transition of a Mediterranean storm by jet crossing, *Q. J. Royal Meteorol. Soc.*, 138, 596–611, <https://doi.org/10.1002/qj.960>, 2012.
- Clark, E., Wood, K. M., Aberson, S. D., Archambault, H. M., Milrad, S. M., Bosart, L. F., Corbosiero, K. L., Davis, C. A., Dias Pinto, J. R., Doyle, J., Fogarty, C., Galarneau, Thomas J., Grams, C. M., Griffin, K. S., Gyakum, J., Hart, R. E., Kitabatake, N., Lentink, H. S., McTaggart-Cowan, R., Perrie, W., Quinting, J. F. D., Reynolds, C. A., Riemer, M., Ritchie, E. A., Sun, Y., and Zhang, F.: The extratropical transition of tropical cyclones. Part I: Cyclone evolution and direct impacts, *Monthly Weather Review*, 145, 4317–4344, <https://doi.org/10.1175/MWR-D-17-0027.1>, 2017.
- Davies, H. C. and Didone, M.: Diagnosis and dynamics of forecast error growth, *Mon. Weather Rev.*, 141, 2483–2501, <https://doi.org/10.1175/MWR-D-12-00242.1>, 2013.
- Davis, C. A. and Bosart, L. F.: Baroclinically induced tropical cyclogenesis, *Mon. Weather Rev.*, 131, 2730–2747, [https://doi.org/10.1175/1520-0493\(2003\)131<2730:BITC>2.0.CO;2](https://doi.org/10.1175/1520-0493(2003)131<2730:BITC>2.0.CO;2), 2003.
- Davis, C. A. and Bosart, L. F.: The TT problem: Forecasting the tropical transition of cyclones, *Bull. Amer. Meteorol. Soc.*, 85, 1657–1662, <https://doi.org/10.1175/BAMS-85-11-1657>, 2004.
- Davolio, S., Miglietta, M. M., Moscatello, A., Pacifico, F., Buzzi, A., and Rotunno, R.: Numerical forecast and analysis of a tropical-like cyclone in the Ionian Sea, *Nat. Hazards Earth Syst. Sci.*, 9, 551–562, <https://doi.org/10.5194/nhess-9-551-2009>, 2009.
- Di Muzio, E., Riemer, M., Fink, A., and Maier-Gerber, M.: Assessing the predictability of medicanes in ECMWF ensemble forecasts using an object-based approach, *Q. J. Royal Meteorol. Soc.*, 145, 1202–1217, <https://doi.org/10.1002/qj.3489>, 2019.
- ECMWF: Tech. rep., <https://www.ecmwf.int/en/publications/ifs-documentation>, last access: 28 April 2020, 2018.
- ECMWF: Severe event catalogue: Zorbas, <https://confluence.ecmwf.int/display/FCST/201809+-+Rainfall+-+Zorbas>, last access: 28 April 2020, 2019.

- Emanuel, K.: Genesis and maintenance of "Mediterranean hurricanes", *Adv. Geosci.*, 2, 217–220, <https://doi.org/10.5194/adgeo-2-217-2005>, 2005.
- Fehlmann, R. and Davies, H.: Misforecasts of synoptic systems: Diagnosis via PV retrodiction, *Mon. Weather Rev.*, 125, 2247–2264, [https://doi.org/10.1175/1520-0493\(1997\)125<2247:MOSSDV>2.0.CO;2](https://doi.org/10.1175/1520-0493(1997)125<2247:MOSSDV>2.0.CO;2), 1997.
- Fehlmann, R. and Quadri, C.: Predictability issues of heavy Alpine south-side precipitation, *Meteorol. Atmos. Phys.*, 72, 223–231, <https://doi.org/10.1007/s007030050017>, 2000.
- Fita, L. and Flaounas, E.: Medicanes as subtropical cyclones: the December 2005 case from the perspective of surface pressure tendency diagnostics and atmospheric water budget, *Q. J. Royal Meteorol. Soc.*, 144, 1028–1044, <https://doi.org/10.1002/qj.3273>, 2018.
- 585 Fita, L., Romero, R., and Ramis, C.: Intercomparison of intense cyclogenesis events over the Mediterranean basin based on baroclinic and diabatic influences, *Adv. Geosci.*, 7, 333–342, <https://doi.org/10.5194/adgeo-7-333-2006>, 2006.
- Fita, L., Romero, R., Luque, A., Emanuel, K., and Ramis, C.: Analysis of the environments of seven Mediterranean tropical-like storms using an axisymmetric, nonhydrostatic, cloud resolving model, *Nat. Hazards Earth Syst. Sci.*, 7, 41–56, <https://doi.org/10.5194/nhess-7-41-2007>, 2007.
- 590 Flaounas, E., Raveh-Rubin, S., Wernli, H., Drobinski, P., and Bastin, S.: The dynamical structure of intense Mediterranean cyclones, *Clim. Dyn.*, 44, 2411–2427, <https://doi.org/10.1007/s00382-014-2330-2>, 2015.
- floodlist.org: <http://floodlist.com/europe/greece-medicane-zorba-september-2018>, last access: 11 September 2020.
- Gaertner, M. A., Jesus Gonzalez-Aleman, J., Romera, R., Dominguez, M., Gil, V., Sanchez, E., Gallardo, C., Marcello Miglietta, M., Walsh, K. J. E., Sein, D. V., Somot, S., Dell’Aquila, A., Teichmann, C., Ahrens, B., Buonomo, E., Colette, A., Bastin, S., van Meijgaard, E.,
- 595 and Nikulin, G.: Simulation of medicanes over the Mediterranean Sea in a regional climate model ensemble: impact of ocean-atmosphere coupling and increased resolution, *Clim. Dyn.*, 51, 1041–1057, <https://doi.org/10.1007/s00382-016-3456-1>, 2018.
- Gonzalez-Aleman, J. J., Evans, J. L., and Kowaleski, A. M.: Use of ensemble forecasts to investigate synoptic influences on the structural evolution and predictability of Hurricane Alex (2016) in the midlatitudes, *Mon. Weather Rev.*, 146, 3143–3162, <https://doi.org/10.1175/MWR-D-18-0015.1>, 2018.
- 600 Grams, C. M. and Archambault, H. M.: The key role of diabatic outflow in amplifying the midlatitude flow: A representative case study of weather systems surrounding western North Pacific extratropical transition, *Mon. Weather Rev.*, 144, 3847–3869, <https://doi.org/10.1175/MWR-D-15-0419.1>, 2016.
- Grams, C. M. and Blumer, S. R.: European high-impact weather caused by the downstream response to the extratropical transition of North Atlantic Hurricane Katia (2011), *Geophys. Res. Lett.*, 42, 8738–8748, <https://doi.org/10.1002/2015GL066253>, 2015.
- 605 Grams, C. M., Wernli, H., Boettcher, M., Campa, J., Corsmeier, U., Jones, S. C., Keller, J. H., Lenz, C.-J., and Wiegand, L.: The key role of diabatic processes in modifying the upper-tropospheric wave guide: a North Atlantic case-study, *Q. J. Royal Meteorol. Soc.*, 137, 2174–2193, <https://doi.org/10.1002/qj.891>, 2011.
- Grams, C. M., Magnusson, L., and Madonna, E.: An atmospheric dynamics perspective on the amplification and propagation of forecast error in numerical weather prediction models: A case study, *Q. J. Royal Meteorol. Soc.*, 144, 2577–2591, <https://doi.org/10.1002/qj.3353>,
- 610 2018.
- Hart, R.: A cyclone phase space derived from thermal wind and thermal asymmetry, *Mon. Weather Rev.*, 131, 585–616, [https://doi.org/10.1175/1520-0493\(2003\)131<0585:ACPSDF>2.0.CO;2](https://doi.org/10.1175/1520-0493(2003)131<0585:ACPSDF>2.0.CO;2), 2003.
- Holton, J. R.: An introduction to dynamic meteorology, vol. 88 of *International geophysics series*, Elsevier Academic Press, Amsterdam, 4th edn., 2004.

- 615 Homar, V. and Stensrud, D.: Sensitivities of an intense Mediterranean cyclone: Analysis and validation, *Q. J. Royal Meteorol. Soc.*, 130, 2519–2540, <https://doi.org/10.1256/qj.03.85>, 2004.
- Jansa, A., Genoves, A., Picornell, M. A., Campins, J., Riosalido, R., and Carretero, O.: Western Mediterranean cyclones and heavy rain. Part 2: Statistical approach, *Meteorological Applications*, 8, 43–56, <https://doi.org/10.1017/S1350482701001049>, 2001.
- Keller, J. H., Grams, C. M., Riemer, M., Archambault, H. M., Bosart, L., Doyle, J. D., Evans, J. L., Galarneau, Thomas J., J., Griffin, K.,
620 Harr, P. A., Kitabatake, N., McTaggart-Cowan, R., Pantillon, F., Quinting, J. F., Reynolds, C. A., Ritchie, E. A., Torn, R. D., and Zhang, F.: The extratropical transition of tropical cyclones. Part II: Interaction with the midlatitude flow, downstream impacts, and implications for predictability, *Mon. Weather Rev.*, 147, 1077–1106, <https://doi.org/10.1175/MWR-D-17-0329.1>, 2019.
- Madonna, E., Wernli, H., Joos, H., and Martius, O.: Warm conveyor belts in the ERA-Interim dataset (1979–2010). Part I: Climatology and potential vorticity evolution, *J. Clim.*, 27, 3–26, <https://doi.org/10.1175/JCLI-D-12-00720.1>, 2014.
- 625 Maier-Gerber, M., Riemer, M., Fink, A. H., Knippertz, P., Di Muzio, E., and McTaggart-Cowan, R.: Tropical transition of Hurricane Chris (2012) over the North Atlantic ocean: A multiscale investigation of predictability, *Mon. Weather Rev.*, 147, 951–970, <https://doi.org/10.1175/MWR-D-18-0188.1>, 2019.
- Massacand, A., Wernli, H., and Davies, H.: Influence of upstream diabatic heating upon an Alpine event of heavy precipitation, *Mon. Weather Rev.*, 129, 2822–2828, [https://doi.org/10.1175/1520-0493\(2001\)129<2822:IOUDHU>2.0.CO;2](https://doi.org/10.1175/1520-0493(2001)129<2822:IOUDHU>2.0.CO;2), 2001.
- 630 Mazza, E., Ulbrich, U., and Klein, R.: The tropical transition of the October 1996 Medcane in the western Mediterranean Sea: A warm seclusion event, *Mon. Weather Rev.*, 145, 2575–2595, <https://doi.org/10.1175/MWR-D-16-0474.1>, 2017.
- McTaggart-Cowan, R., Davies, E. L., Fairman, J. G., Galarneau, T. J., and Schultz, D. M.: Revisiting the 26.5°C sea surface temperature threshold for tropical cyclone development, *Bull. Amer. Meteorol. Soc.*, 96, 1929–1943, <https://doi.org/10.1175/BAMS-D-13-00254.1>, 2015.
- 635 Miglietta, M. M. and Rotunno, R.: Development mechanisms for Mediterranean tropical-like cyclones (medicanes), *Q. J. Royal Meteorol. Soc.*, 145, 1444–1460, <https://doi.org/10.1002/qj.3503>, 2019.
- Miglietta, M. M., Laviola, S., Malvaldi, a., Conte, D., Levizzani, V., and Price, C.: Analysis of tropical-like cyclones over the Mediterranean Sea through a combined modeling and satellite approach, *Geophys. Res. Lett.*, 40, 2400–2405, <https://doi.org/10.1002/grl.50432>, 2013.
- Miglietta, M. M., Cerrai, D., Laviola, S., Cattani, E., and Levizzani, V.: Potential vorticity patterns in Mediterranean “hurricanes”, *Geophys. Res. Lett.*, 44, 2537–2545, <https://doi.org/10.1002/2017GL072670>, 2017.
- 640 Pantillon, F., Chaboureaud, J.-P., and Richard, E.: Remote impact of North Atlantic hurricanes on the Mediterranean during episodes of intense rainfall in autumn 2012, *Q. J. Royal Meteorol. Soc.*, 141, 967–978, <https://doi.org/10.1002/qj.2419>, 2015.
- Pantillon, F., Chaboureaud, J.-P., Mascart, P. J., and Lac, C.: Predictability of a Mediterranean tropical-like storm downstream of the extratropical transition of Hurricane Helene (2006), *Mon. Weather Rev.*, 141, 1943–1962, <https://doi.org/10.1175/MWR-D-12-00164.1>, 2013.
- 645 Pantillon, F., Chaboureaud, J.-P., and Richard, E.: Vortex-vortex interaction between Hurricane Nadine (2012) and an Atlantic cut-off dropping the predictability over the Mediterranean, *Q. J. Royal Meteorol. Soc.*, 142, 419–432, <https://doi.org/10.1002/qj.2635>, 2016.
- Pfahl, S. and Wernli, H.: Quantifying the relevance of cyclones for precipitation extremes, *J. Clim.*, 25, 6770–6780, <https://doi.org/10.1175/JCLI-D-11-00705.1>, 2012.
- Picornell, M., Jansa, A., Genoves, A., and Campins, J.: Automated database of mesocyclones from the HIRLAM(INM)-0.5 degrees analyses
650 in the western Mediterranean, *Int. J. Climatol.*, 21, 335–354, <https://doi.org/10.1002/joc.621>, 2001.
- Picornell, M. A., Campins, J., and Jansà, A.: Detection and thermal description of medicanes from numerical simulation, *Nat. Hazards Earth Syst. Sci.*, 14, 1059–1070, <https://doi.org/10.5194/nhess-14-1059-2014>, 2014.

- Portmann, R., Crezee, B., Quinting, J., and Wernli, H.: The complex life-cycles of two long-lived potential vorticity cutoffs over Europe, *Q. J. Royal Meteorol. Soc.*, 144, 701–719, <https://doi.org/10.1002/qj.3239>, 2018.
- 655 Quandt, L.-A., Keller, J. H., Martius, O., and Jones, S. C.: Forecast variability of the blocking system over Russia in summer 2010 and its impact on surface conditions, *Wea. Forecasting*, 32, 61–82, <https://doi.org/10.1175/WAF-D-16-0065.1>, 2017.
- Quinting, J. F. and Jones, S. C.: On the impact of tropical cyclones on Rossby wave packets: A climatological perspective, *Mon. Weather Rev.*, 144, 2021–2048, <https://doi.org/10.1175/MWR-D-14-00298.1>, 2016.
- Raveh-Rubin, S. and Flaounas, E.: A dynamical link between deep Atlantic extratropical cyclones and intense Mediterranean cyclones, *Atmos. Sci. Lett.*, 18, 215–221, <https://doi.org/10.1002/asl.745>, 2017.
- 660 Raveh-Rubin, S. and Wernli, H.: Large-scale wind and precipitation extremes in the Mediterranean: a climatological analysis for 1979–2012, *Q. J. Royal Meteorol. Soc.*, 141, 2404–2417, <https://doi.org/10.1002/qj.2531>, 2015.
- Riemer, M., Jones, S. C., and Davis, C. A.: The impact of extratropical transition on the downstream flow: An idealized modelling study with a straight jet, *Q. J. Royal Meteorol. Soc.*, 134, 69–91, <https://doi.org/10.1002/qj.189>, 2008.
- 665 Romero, R.: Sensitivity of a heavy-rain-producing western Mediterranean cyclone to embedded potential-vorticity anomalies, *Q. J. Royal Meteorol. Soc.*, 127, 2559–2597, <https://doi.org/10.1002/qj.49712757805>, 2001.
- Röthlisberger, M., Martius, O., and Wernli, H.: Northern Hemisphere Rossby wave initiation events on the extratropical Jet—A climatological analysis, *J. Clim.*, 31, 743–760, <https://doi.org/10.1175/JCLI-D-17-0346.1>, 2018.
- Schwierz, C., Dirren, S., and Davies, H.: Forced waves on a zonally aligned jet stream, *J. Atmos. Sci.*, 61, 73–87, [https://doi.org/10.1175/1520-0469\(2004\)061<0073:FWOAZA>2.0.CO;2](https://doi.org/10.1175/1520-0469(2004)061<0073:FWOAZA>2.0.CO;2), 2004.
- 670 [severe-weather.eu: https://www.severe-weather.eu/event-analysis/medicane-aftermath-in-greece-and-turkey-severe-winds-torrential-rainfall-major-flood](https://www.severe-weather.eu/event-analysis/medicane-aftermath-in-greece-and-turkey-severe-winds-torrential-rainfall-major-flood)
last access: 11 September 2020.
- Sinclair, M.: Objective identification of cyclones and their circulation intensity, and climatology, *Wea. Forecasting*, 12, 595–612, [https://doi.org/10.1175/1520-0434\(1997\)012<0595:OIOCAT>2.0.CO;2](https://doi.org/10.1175/1520-0434(1997)012<0595:OIOCAT>2.0.CO;2), 1997.
- 675 Sprenger, M. and Wernli, H.: The LAGRANTO Lagrangian analysis tool - version 2.0, *Geosci. Model Dev.*, 8, 2569–2586, <https://doi.org/10.5194/gmd-8-2569-2015>, 2015.
- Tafferner, A.: Lee cyclogenesis resulting from the combined outbreak of cold air and potential vorticity against the Alps, *Meteorol. Atmos. Phys.*, 43, 31–47, <https://doi.org/10.1007/BF01028107>, 1990.
- Torn, R. D.: Diagnosis of the downstream ridging associated with extratropical transition using short-term ensemble forecasts, *J. Atmos. Sci.*, 67, 817–833, <https://doi.org/10.1175/2009JAS3093.1>, 2010.
- 680 Torn, R. D., Whitaker, J. S., Pegion, P., Hamill, T. M., and Hakim, G. J.: Diagnosis of the source of GFS medium-range track errors in Hurricane Sandy (2012), *Mon. Weather Rev.*, 143, 132–152, <https://doi.org/10.1175/MWR-D-14-00086.1>, 2015.
- Tous, M. and Romero, R.: Meteorological environments associated with medicane development, *Int. J. Climatol.*, 33, 1–14, <https://doi.org/10.1002/joc.3428>, 2013.
- 685 Wernli, H. and Davies, H. C.: A Lagrangian-based analysis of extratropical cyclones.1. The method and some applications, *Q. J. Royal Meteorol. Soc.*, 123, 467–489, <https://doi.org/10.1256/smsqj.53810>, 1997.
- Wernli, H. and Sprenger, M.: Identification and ERA-15 climatology of potential vorticity streamers and cutoffs near the extratropical tropopause, *J. Atmos. Sci.*, 64, 1569–1586, <https://doi.org/10.1175/JAS3912.1>, 2007.
- Wiegand, L. and Knippertz, P.: Equatorward breaking Rossby waves over the North Atlantic and Mediterranean region in the ECMWF
690 operational ensemble prediction system, *Q. J. Royal Meteorol. Soc.*, 140, 58–71, <https://doi.org/10.1002/qj.2112>, 2014.

- Wikipedia: https://en.wikipedia.org/wiki/Mediterranean_tropical-like_cyclone/, last access: 29 April 2020.
- Wilks, D. S.: Statistical Methods in the Atmospheric Sciences, vol. 100, Academic Press, 3 edn., 2011.
- Wilks, D. S.: “The stippling shows statistically significant grid points”: How research results are routinely overstated and overinterpreted, and what to do about it, *Bull. Amer. Meteorol. Soc.*, 97, 2263–2273, <https://doi.org/10.1175/BAMS-D-15-00267.1>, 2016.
- 695 Winters, A. C. and Martin, J. E.: Diagnosis of a North American Polar–Subtropical Jet Superposition Employing Piecewise Potential Vorticity Inversion, *Monthly Weather Review*, 145, 1853–1873, <https://doi.org/10.1175/MWR-D-16-0262.1>, 2017.
- Wirth, V.: Diabatic heating in an axisymmetrical cutoff cyclone and related stratosphere-troposphere exchange, *Q. J. R. Meteorol. Soc.*, 121, 127–147, <https://doi.org/10.1002/qj.49712152107>, 1995.

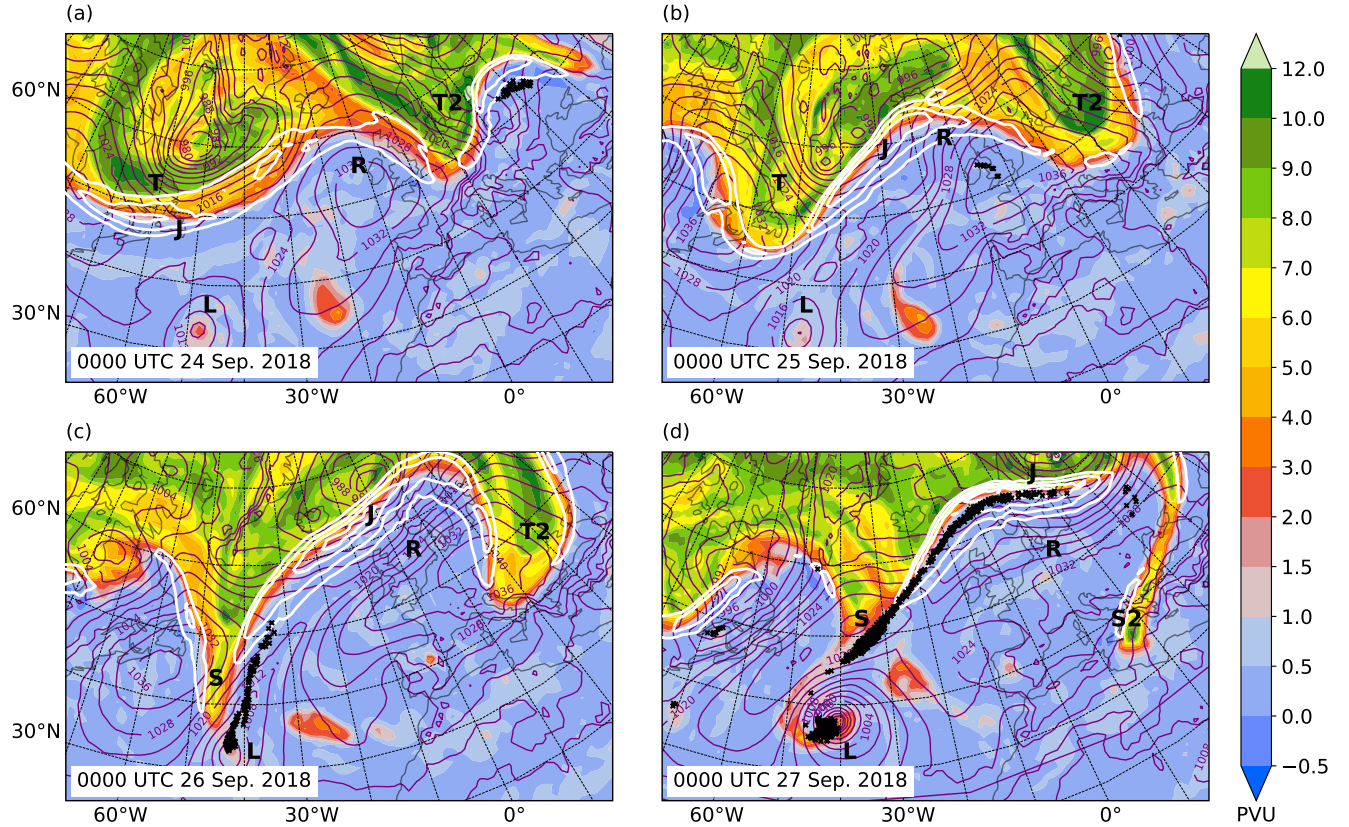


Figure 1. Synoptic situation over the Euro-Atlantic sector before the formation of [the PV streamer over the Mediterranean](#) [Medicane Zorbas](#). PV (shaded, in PVU) and wind speed (white contours, [in 50, 60, 70, 80 m s⁻¹](#)) on 325 K, intersection points of warm conveyor belts (ascent rate of more than 600 hPa in 48 h) with the 325 K isentrope (black crosses), and sea level pressure (purple contours, [in every 4 hPa](#)) at (a) 0000 UTC 24 Sep 2018, (b) 0000 UTC 25 Sep 2018, (c) 0000 UTC 26 Sep 2018, and (d) 0000 UTC 27 Sep 2018. [Labels mark relevant flow features \(for details see text\)](#).

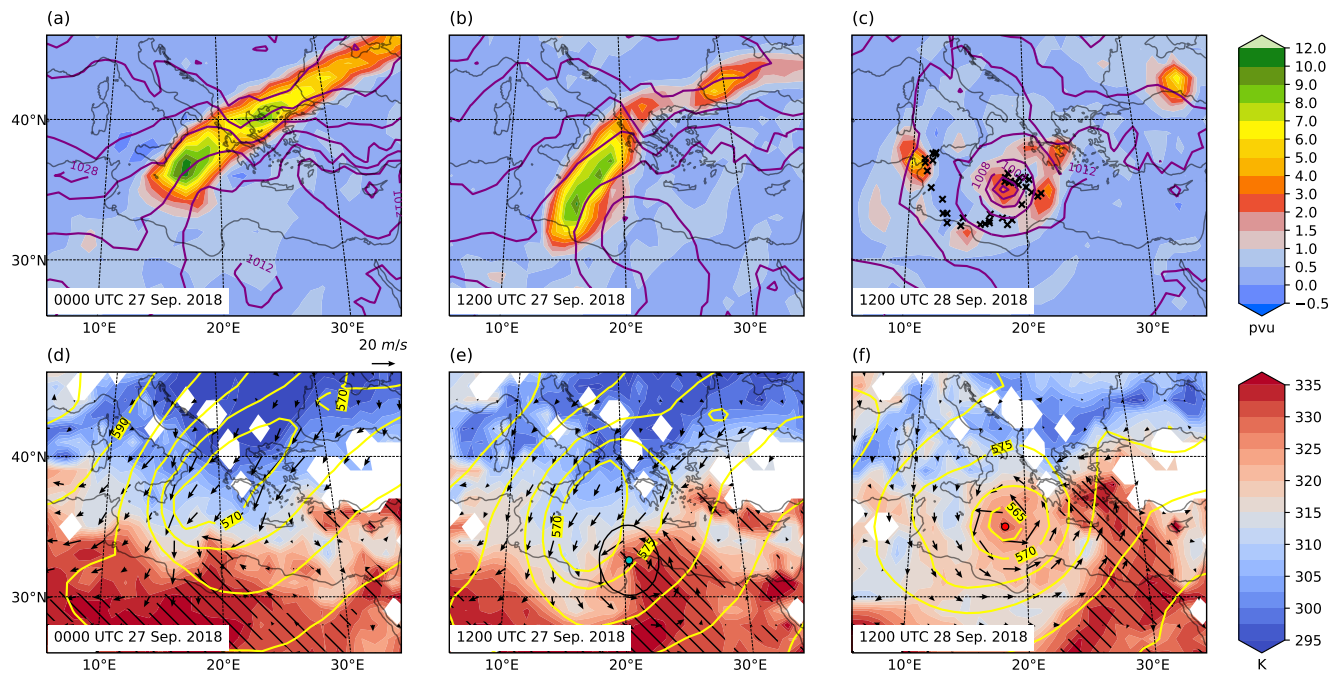


Figure 2. Synoptic situation over the Mediterranean after the formation of the PV streamer at (a,d) 0000 UTC 27 Sep 2018, (b,e) 1200 UTC 27 Sep 2018, and (c,f) 1200 UTC 28 Sep 2018. (a-c) PV on 325 K (shaded, in PVU; this level corresponds approximately to the 300-350 hPa pressure levels in this region), sea-level pressure (purple contours, in every 4 hPa); (d-f) equivalent potential temperature (θ_e , shaded, in K, white areas are missing values due to orography) and wind vectors (black arrows, reference vector above panel d) on 900 hPa, and geopotential height on 500 hPa (yellow contours, every 5 gpm). The hatched areas in (d-f) show regions where θ_e on 900 hPa is anomalously high (at least one standard deviation larger than climatology) with respect to the Sep-Oct ERA-Interim climatology for the period 1979 – 2017. In panel (e), the black circle denotes the circle with radius 250 km from which forward trajectories were started for air parcels with $\theta_e > 322.5$ K and black crosses in panel (c) show the position of these air parcels 24 h later if they reached above the 322.5 K isentropic level.

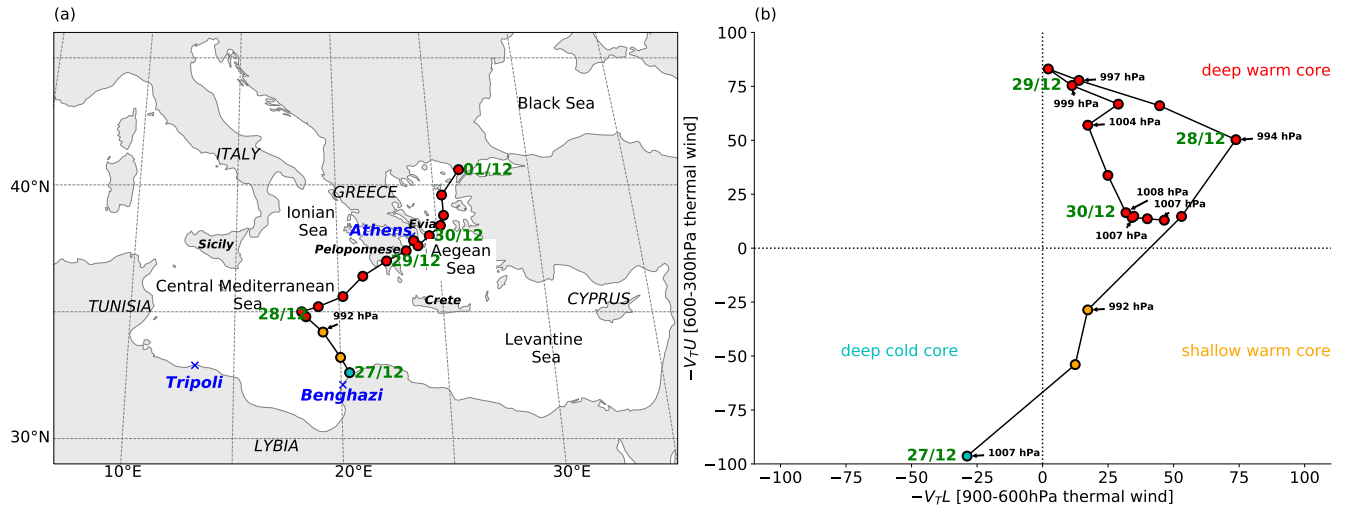


Figure 3. (a) Track of Medicane Zorbas (circles and black line) and (b) cyclone phase space diagram derived from the ECMWF operational analyses at six-hourly intervals in each panel. Cyclone positions are colored according to the quadrant in the CPS diagram (blue: cold core, orange: shallow warm core, red: deep warm core). Black numbers indicate the minimum sea-level pressure (hPa) of the cyclone at this particular time of its life cycle and green numbers the day (in Sep 2018) and time (hours UTC) .

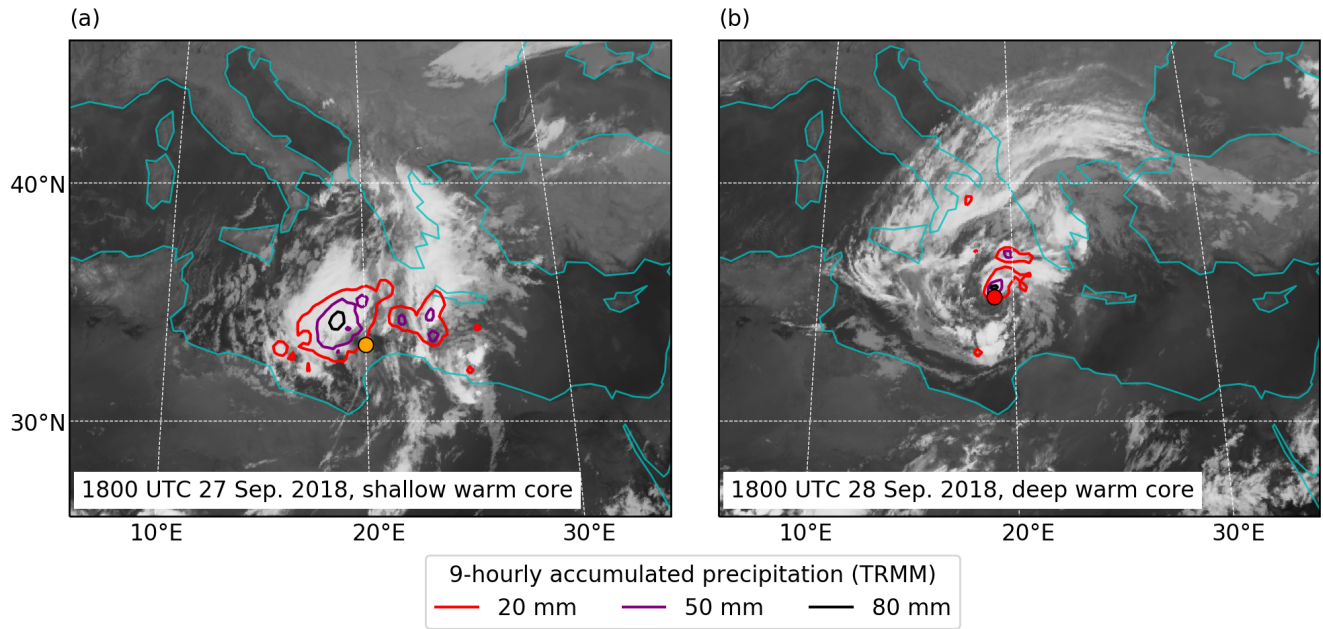


Figure 4. Infrared channel 9 ($10.8 \mu\text{m}$) of MSG SEVIRI provided by EUMETSAT (grey shading) and 9-hourly accumulated TRMM precipitation during the period centered at the indicated time (colored contours) at (a) 1800 UTC 27 Sep 2018 and (b) 1800 UTC 28 Sep 2018. Cyclone positions based on the ECMWF operational analysis are marked with circles and colored according to the thermal structure of the cyclone (as in Fig. 3).

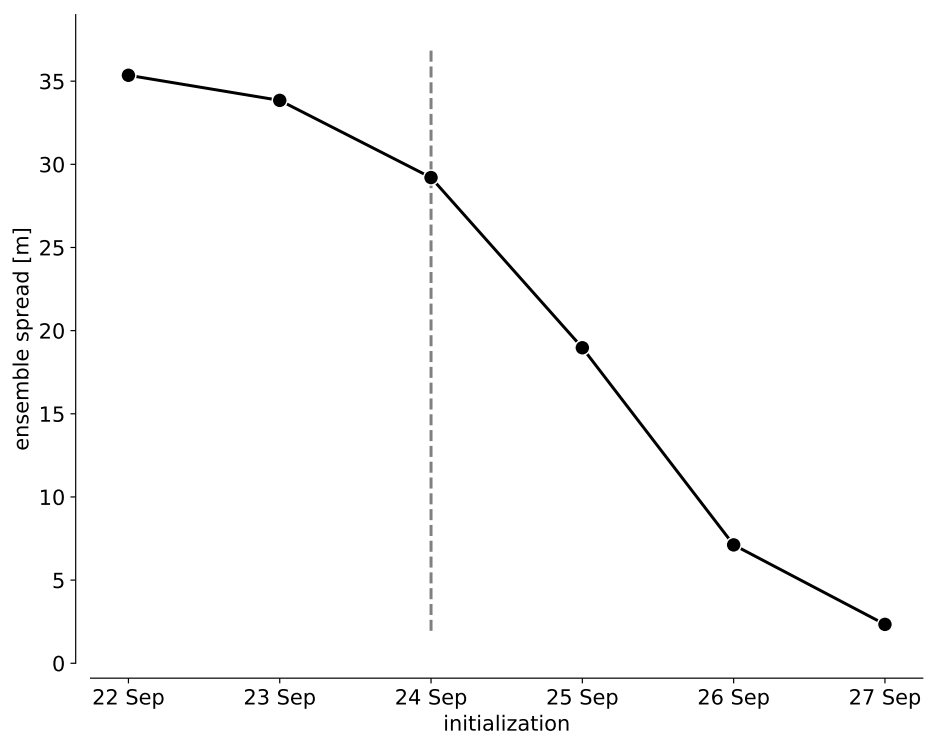


Figure 5. Area-averaged ensemble spread of geopotential height at 500 hPa at 0000 UTC 27 Sep 2018 in a box over the Mediterranean (5-30°E, 30-45°N, see black box in Fig. 7) for initializations at 0000 UTC 22 Sep to 27 Sep 2018 (black dots and line). The initialization used in this study (0000 UTC 24 Sep 2018) is indicated by the dashed line.

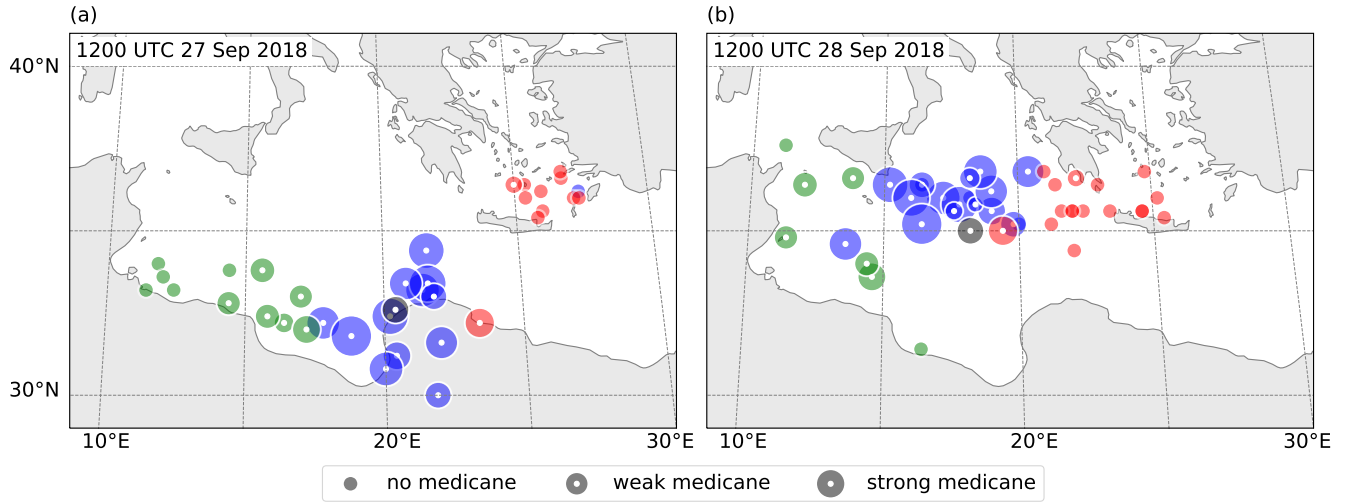


Figure 6. Geographical maps of cyclone positions in all ensemble members and the operational analysis at (a) 1200 UTC 27 Sep 2018 and (b) 1200 UTC 28 Sep 2018. For medicanes (markers with white centre), the size of the markers is proportional to the maximum intensity of the upper-level warm core (see legend for comparison, no medicane: $-V_T^U \leq 0$, weak medicane: $-V_T^U = 50$, strong medicane: $-V_T^U = 100$). Marker colors indicate the cluster to which the cyclone belongs (W: green, C: blue, E: red, analysis: black; discussed in Sect. 5.2)

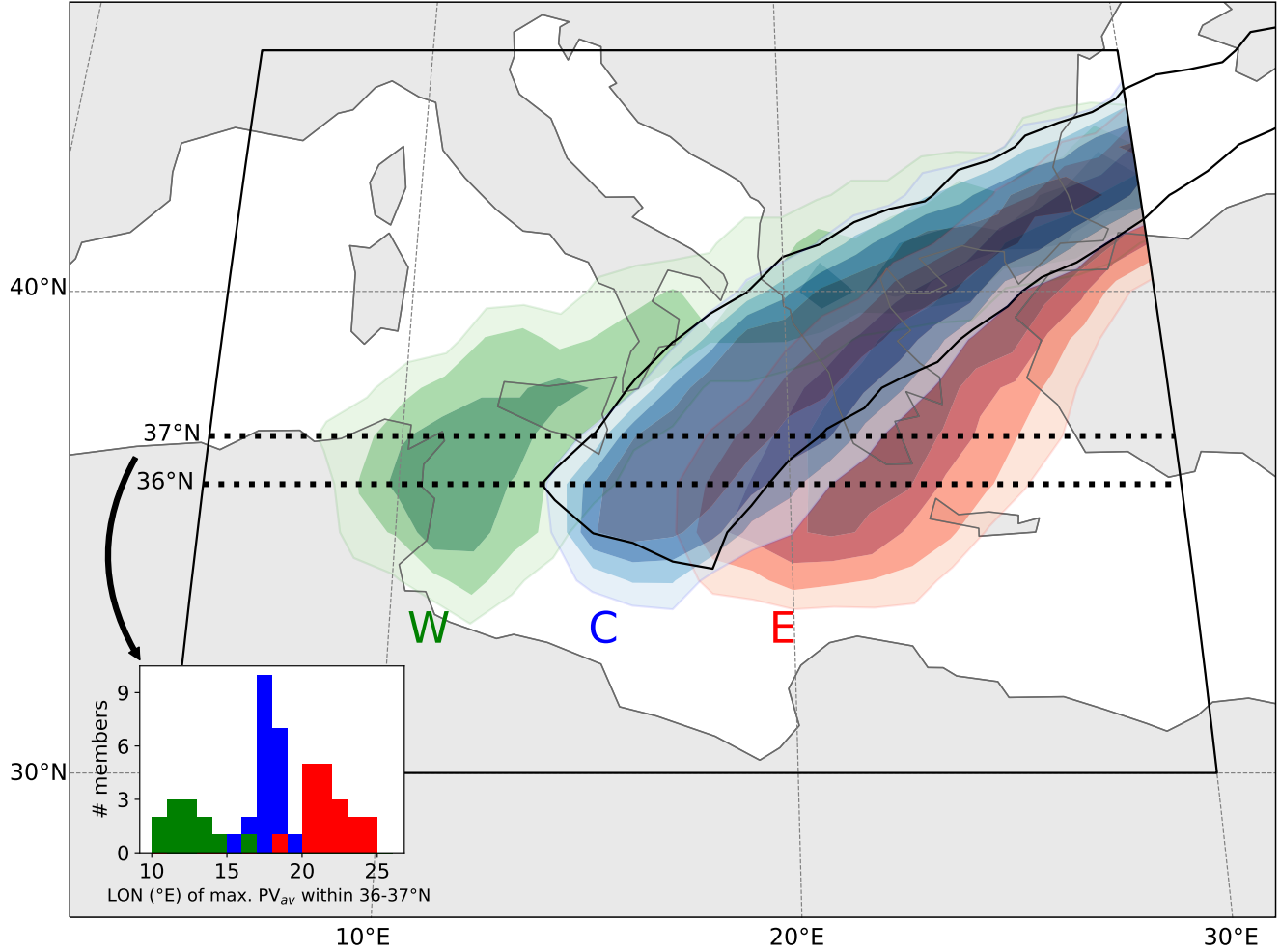


Figure 7. Clustering of ensemble members (initialized at 0000 UTC 24 Sep 2018) according to the position of the upper-level PV streamer in the Mediterranean at 0000 UTC 27 Sep 2018. Colors show frequencies of $PV_{av} \geq 2$ PVU (shading, every 20%,) for each cluster (blue: cluster C, green: cluster W, red: cluster E) and the black line the contour where $PV_{av} = 2$ PVU in the operational analysis. The region considered for the clustering is shown by the black box. PV_{av} denotes vertically averaged PV between 320 and 330 K with PV values below 2 PVU set to zero (see text for details).

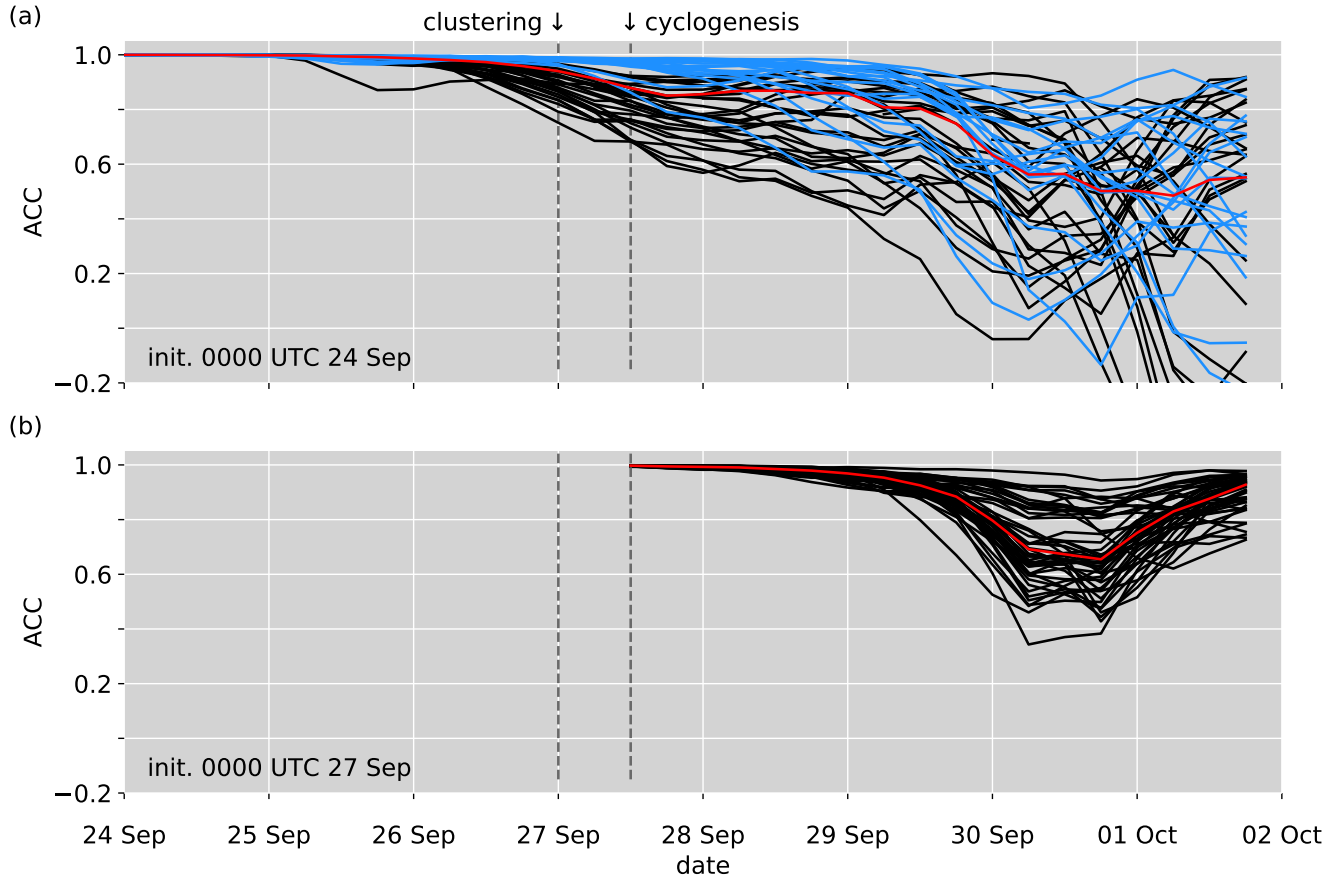


Figure 8. Temporal evolution of the anomaly correlation coefficient of geopotential height at 500 hPa in the Mediterranean box (see Fig. 7) for each ensemble member (black lines) and the median (red line) of the ensemble forecasts initialized at (a) 0000 UTC 24 Sep 2018 (blue lines show members of cluster C) and (b) 0000 UTC 27 Sep 2018.

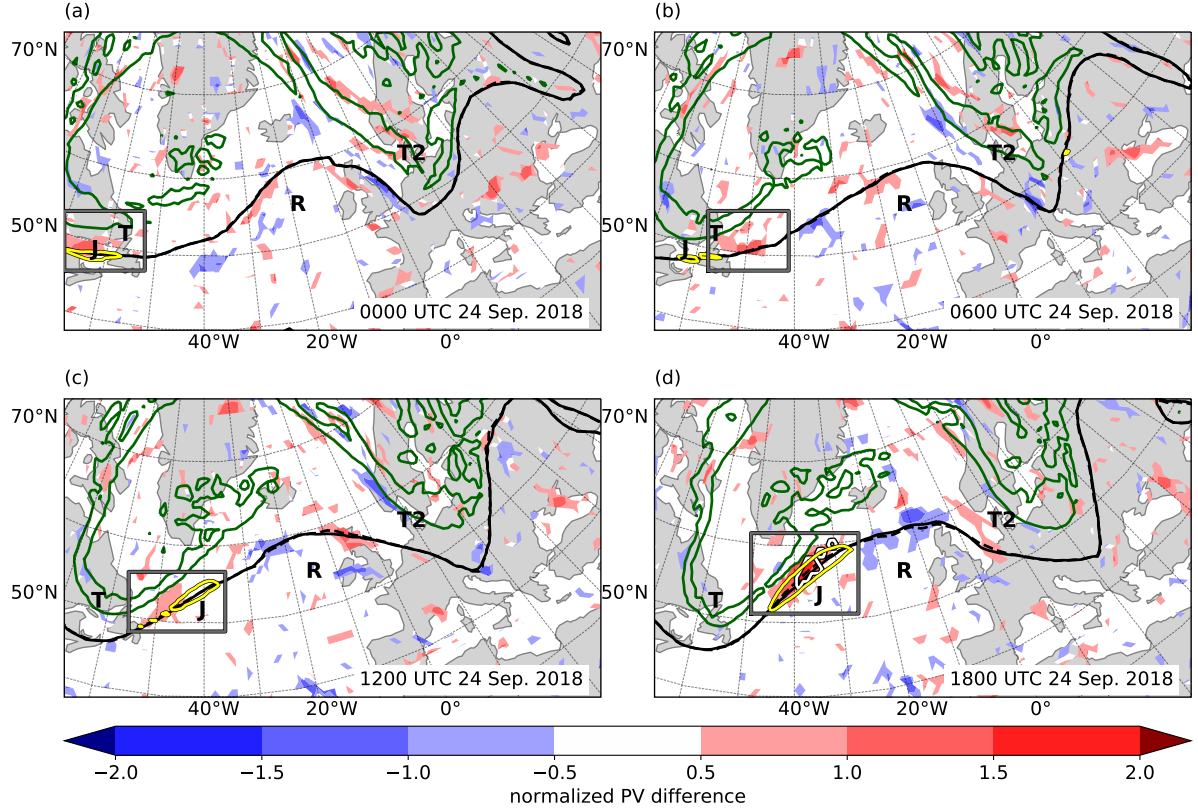


Figure 9. Normalized PV differences between clusters E and W (ΔPV_{EW} , shaded), 2 PVU contour (black lines) of clusters E (solid) and W (dashed), 9 PVU contour (green lines) and wind speed (yellow lines, 70 m s⁻¹) in the operational analysis at 325 K from 0000 UTC 24 Sep to 1800 UTC 24 Sep 2018, every 6 hours. Regions with statistically significant PV differences ($\alpha_{fdr} < 0.1$, [single isolated significant grid points are removed](#)) are marked with white contours and grey boxes mark the regions of interest (for details see text).

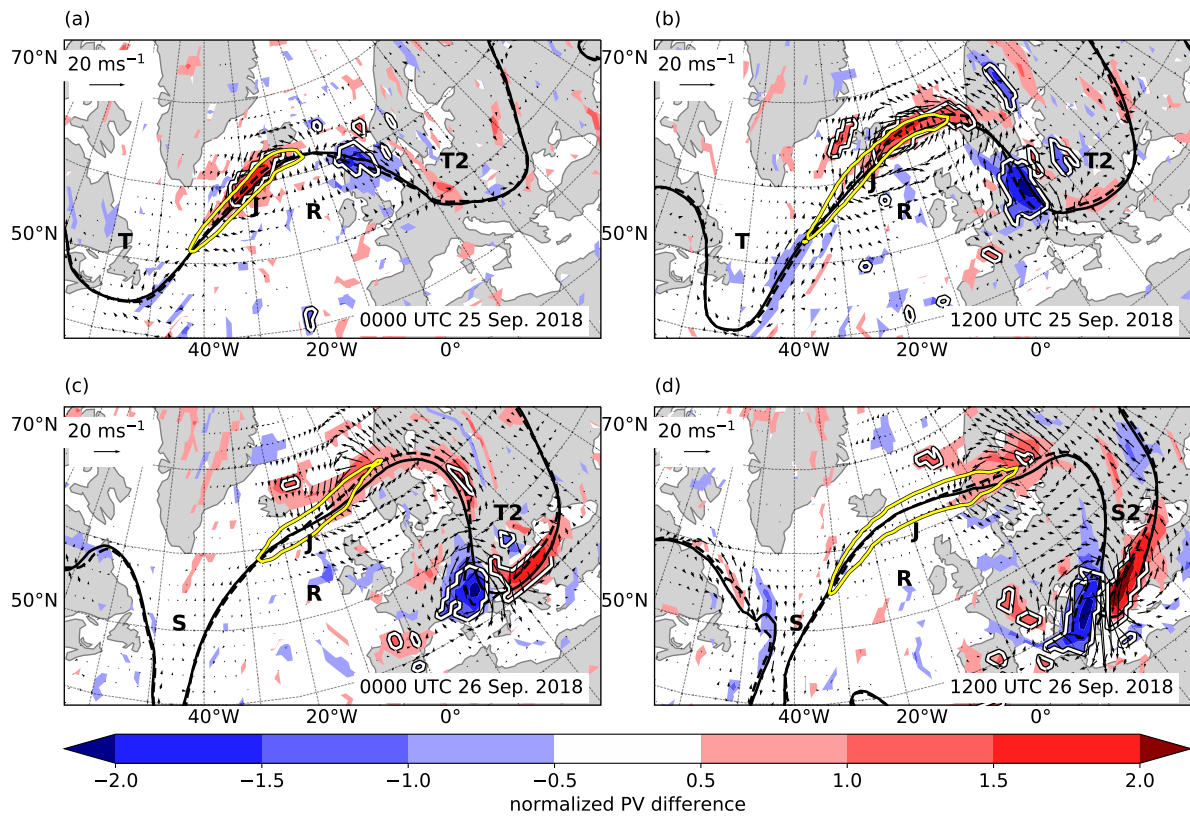


Figure 10. As Fig. 9 but with difference winds (arrows, only if larger than 1 m s^{-1} , reference vectors is in top left of panels), without 9 PVU contours and from 0000 UTC 25 Sep to 1200 UTC 26 Sep every 12 hours.

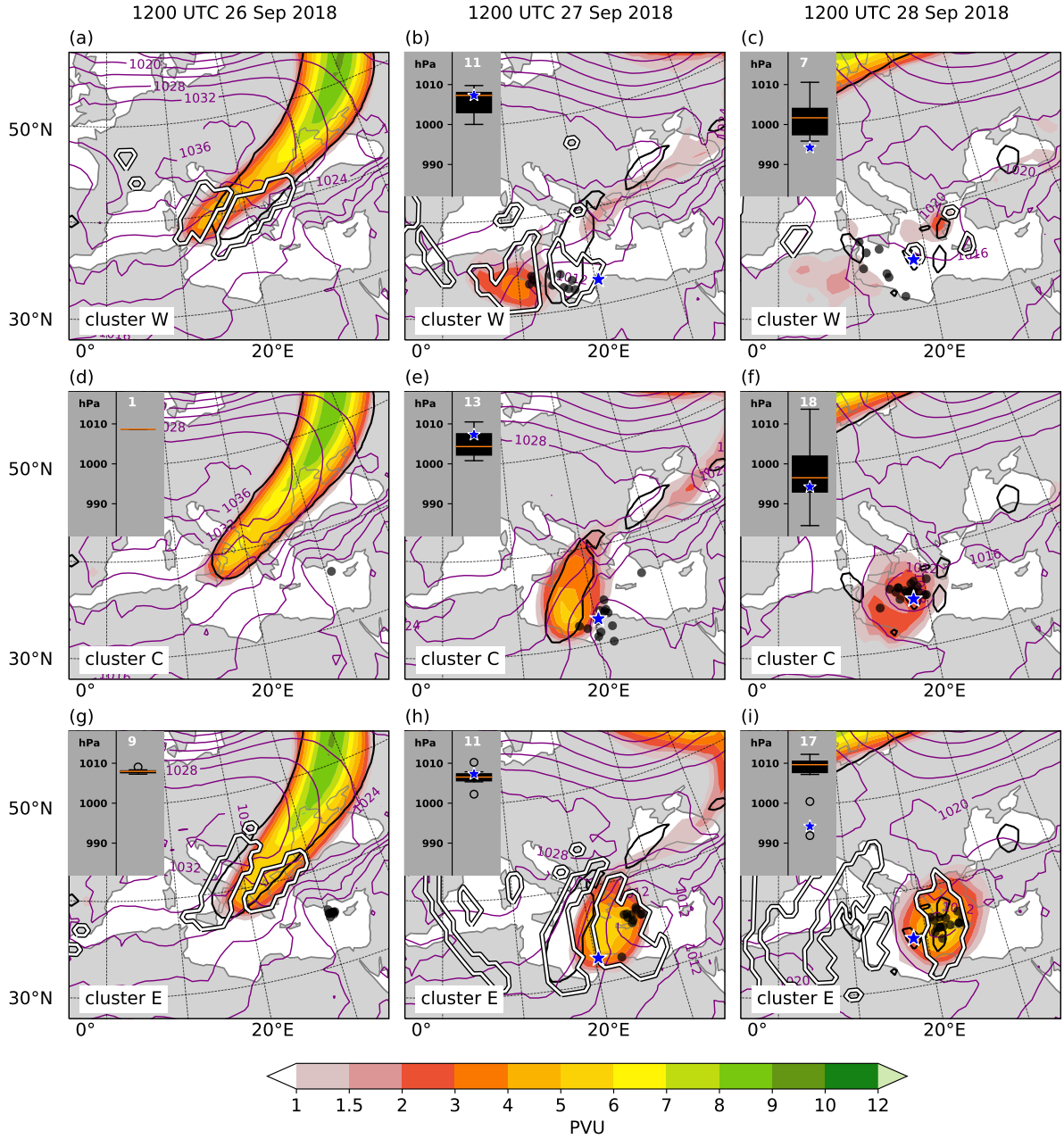


Figure 11. Cluster-mean PV on 325 K (shaded, in PVU), cluster-mean sea level pressure (purple contours, every 4 hPa), analysis 2 PVU contour on 325 K (black), cyclone positions (as identified with the method described in Sect. 2.3) in each ensemble member (black dots), and in the operational analysis (blue star) for clusters W, C, and E (panels a-c, d-f, and g-i) from 1200 UTC 26 Sep to 1200 UTC 28 Sep 2018 every 24 h. Insets at the top left of the panels show [standard](#) box plots ([circles denote outliers](#)) of minimum sea level pressure of the cyclones in each cluster and the value in the operational analysis (blue star); white numerals indicate the number of cyclones. Regions where the differences to cluster C of the PV field on 325 K are statistically significant on the $\alpha_{fdr}=0.1$ level are shown for clusters W and E as white contours (panels a-c, g-i, [single isolated significant grid points are removed](#)). [The statistical significance for differences in sea level pressure are shown in the supplementary material S3 \(Fig. S1\).](#)

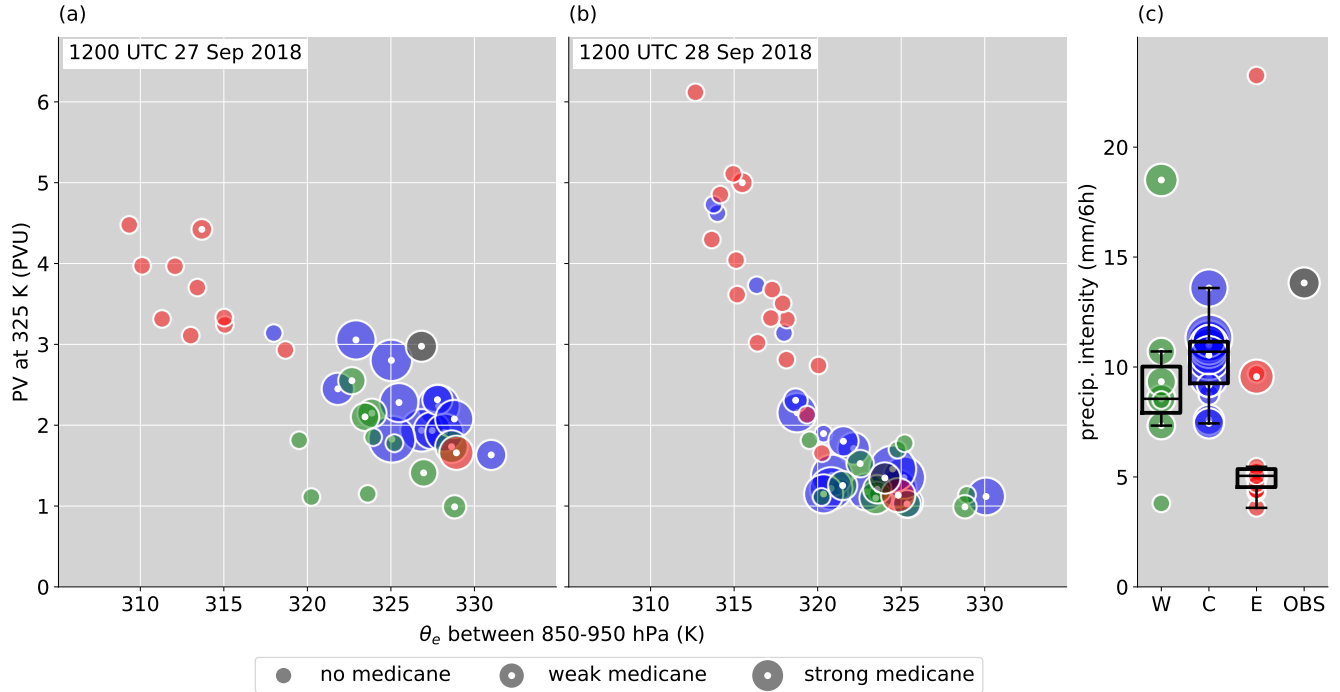


Figure 12. (a,b) Diagram of low-level θ_e vs. upper-level PV for all ensemble members with a cyclone and for the operational analysis at (a) 1200 UTC 27 Sep 2018 and (b) 1200 UTC 28 Sep 2018; markers and times are as in Fig. 76. (c) Average precipitation intensity within a 250 km radius around the cyclone centre between 1200 UTC 27 Sep and 1200 UTC 28 Sep 2018 for all cyclones present during the full 24 h period as individual data points (colored markers) and standard box plots (black). The observation (OBS) is based on TRMM rainfall data along the track in the operational analysis.