Response to reviewers of "How a warmer Mediterranean preconditions the upper-level environment for the development of Medicane Ianos "

We appreciate the time and effort taken by the reviewers to provide a list of insightful comments to improve the paper. A reply to each of their comments is given in blue. Both reviewers coincide in few points, so some replies are cross-referenced. Line and Figure references are for the original manuscript. Figures and equation in the present document and not in the mansucript are refered as "here".

Anonymous Referee #1

General comment

I find the presentation to be mostly descriptive, despite the use of two quantitative diagnostics. Importantly, I was often left wondering about the significance of described observations. While most observations support the authors' main point about the importance of the upper-level low-PV "bubble" well, the presentation of observations without an evident link to theory or conceptual models make for a rather lengthy read. Personally, I would have much appreciated more such links to conceptual or theoretical frameworks of TC-like storm dynamics. I am aware that this comment is very general, but it would take me an unwarranted amount of time to think more thoroughly about Ianos' evolution to make more specific suggestions for improvement. I consider the presentation "ok" for the purpose of the present study, in the sense that the presentation does provide evidence for the main point of the study. I thus leave it to the authors' discretion to improve their manuscript in this respect.
We acknowledge that our original manuscript did not provide enough detail to understand the results in a tropical transition framework. We will incorporate and describe a figure with the Cyclone Phase Space (CPS) diagram of Hart (2003), with results from the IFS analysis and the simulations. The future new figure is shown in Figure 1 here, it shows that Ianos during the period of early intensification (16^{th}) has not attained an axi-symmetric warm-core. Ianos shares similarities with the meridional trough category of subtropical cyclones undergoing Tropical Transitions (Bentley et al., 2017), e.g. quasi-geostrophic forcing and less dependence in bulk stability. We will relate some of our results those found in Tropical Transitions (TT) composites Galarneau et al. (2015), climatologies (McTaggart-Cowan et al., 2008, 2013), metrics (McTaggart-Cowan et al., 2015) and processes (Yanase et al., 2023).

Major comments

1. *QG omega analysis:*

   The importance of the low-PV bubble is well supported from a phenomenological perspective and is of interest in itself. The mechanistic link of how these upper-level changes impact Ianos' evolution, however, is not established sufficiently well by the QG omega inversion analysis. I have several issues with the analysis. First, the signal that the authors present is very weak, and the associated discussion is partly confusing (L465: I do not see the absence of vertical motion described by the authors; L475: I am confused if the authors show omega or w. Equation 3 says omega, but here positive values seem to be referred to as ascent.) Only two out of the six simulations are contrasted. It is thus not possible to say if the weak signal is at least systematic. Second, there is no theoretical or conceptual justification of how the observed small differences would impact the evolution of Ianos. Note that arguments based on the dynamics of (fully) extratropical cyclones can be applied here only partially because Ianos has clearly tropical characteristics. Formation and intensification mechanisms of tropical-like storms thus need to be taken into account also. Third, the authors consider one part of the forcing only. Without evidence that the other forcing term is indeed negligible, I consider the analysis to be incomplete. Finally, the authors should acknowledge

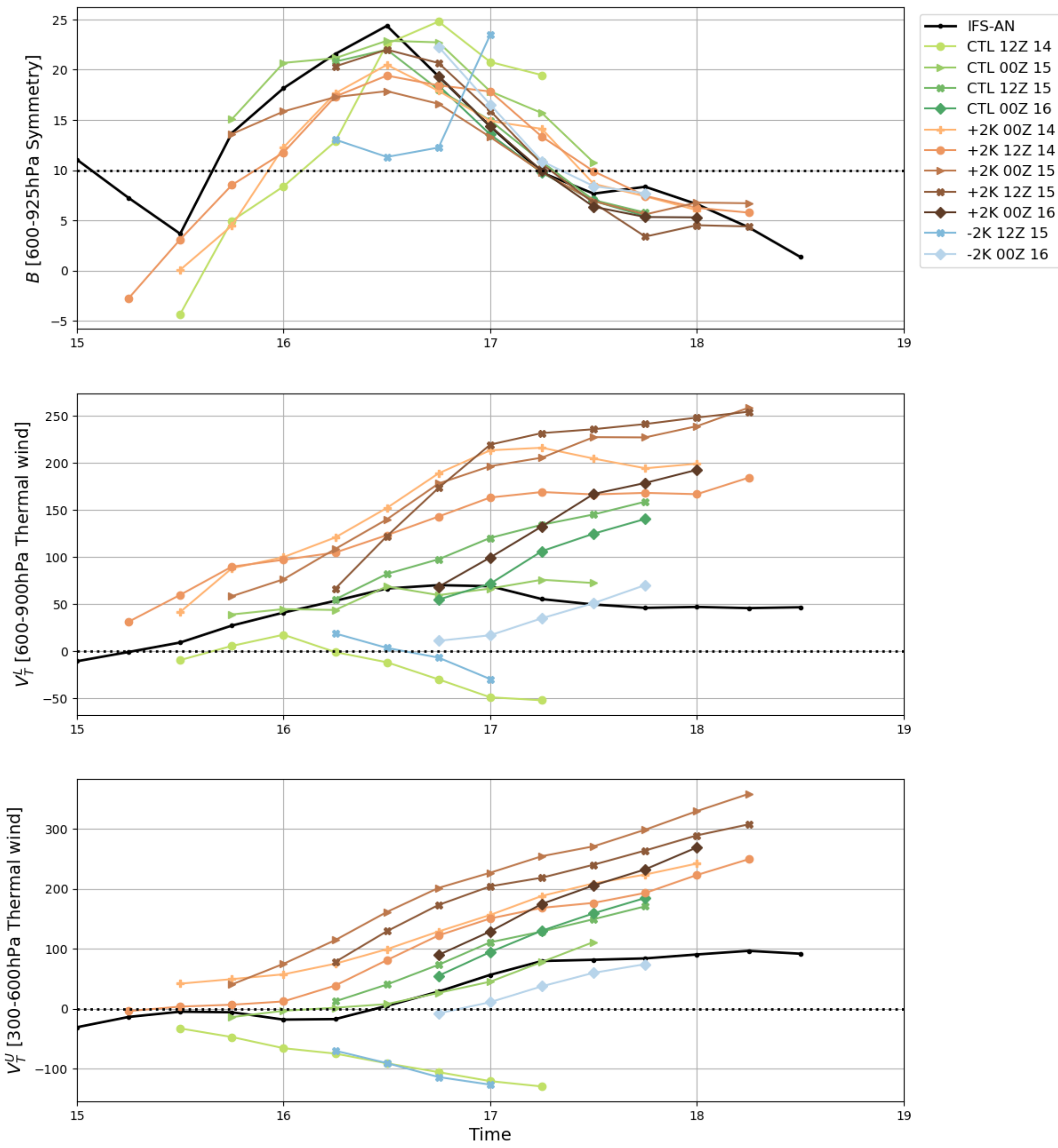

Figure 1: Time-series of (a) thickness asymmetry B between 600–925 hPa (b) V_T^L low-level thermal wind between 600–900 hPa and (c) V_T^L upper-level upper thermal wind between 300–600 hPa. Same colours as in Figure 2,3 and 6 of the manuscript. The CPS metrics are computed with a radius of 400km instead of 500km because of the small size of our domain (only points on the 16^{th} and 17^{th} where captured). The B is computed at 925 hPa level instead of 900 hPa.

the intricacies of a vertical partitioning of forcing in the omega equation, as discussed by Morgan (1999).

(a) We will replace Section 4.6 in the manuscript entirely. the new Figure 15 will show QG ascent forced by the full column. The cross-sections shown in Fig 16 will also include QG ascent forced by the full column and mid-levels.

(b) The methodology section will show equation 3 with the vertical wind component w

(c) The introductory paragraph of the new section 4.6 will provide more detail about why only two simulations with control SST are used instead of the full array of simulations

(d) The new section will include a clearer explanation of the attribution of TA and VA terms to the ascent forced by different levels.

(e) We will compare the low values of QG ascent forced by upper levels in Ianos at $12Z$ 16, with those obtained by Deveson et al. (2002) for a mid-latitude cyclone at the time of maximum intensity. The figure for Ianos supporting this statement is not included in the paper but is included here in Fig. 2 here for reference.

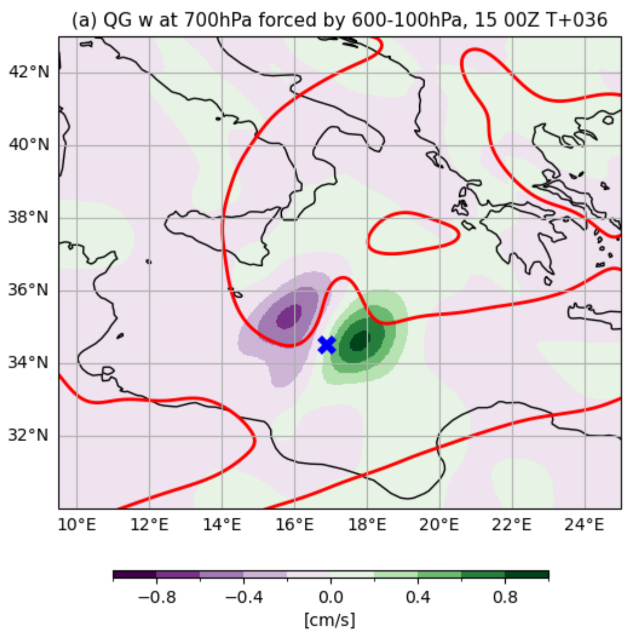

Figure 2: Quasi-Geostrophic ascent at 700hPa forced by the upper levels (600-100hPa) for the "good simulation", initialised at 00Z 15, at 12Z 16 validation time. Note values in the colorbar are higher than in Figure 15.

(f) We will update point (ii) in the abstract with the new results. Additionally we will update the description of the section's results in L518 and the second point in the list of key elements at L526.

(g) The partitioning done in Morgan (1999) attributes the vertical motion to individual PV anomalies, using the distribution of the QG forcing from the Q vector convergence. Our methodology is different. We obtain the QG ascent forced by different level ranges from the inversion of the QG equation with the forcing applied at selected levels.

In addition, there is an alternative plausible hypothesis how the changes to the upper levels impact Ianos: by changes to the vertical wind shear. The authors note this mechanism in the discussion of preconditioning role of preceding convection during tropical transition in L542. The same mechanisms may be at work here, too, and analysis of this aspect would provide much benefit to the manuscript.

We consider that the wind-shear hypothesis is weaker than those presented in the manuscript. The Figure 3 here shows the timeseries of vertical wind Shear (VWS), defined as the magnitude of the wind shear vector between the 200 hPa and 850 hPa levels and spatially averaged in a 3x3 box with the cyclone at the centre. The wind shear drops once the surface weak low goes underneath the trough on the 14^{th}, but it is still above 10m/s in all simulations and the IFS analysis. VWS increases through the cyclone's lifetime in all simulations. The VWS values in those simulations not developing medicane Ianos are not different than those developing it. Very similar results are obtained when averaging VWS with a radius of 150 km around the centre of the cyclone (not shown), as well as a radius around 500 km for IFS-AN (not shown). We will include some comments about wind shear in section 4.1, but without the figure.

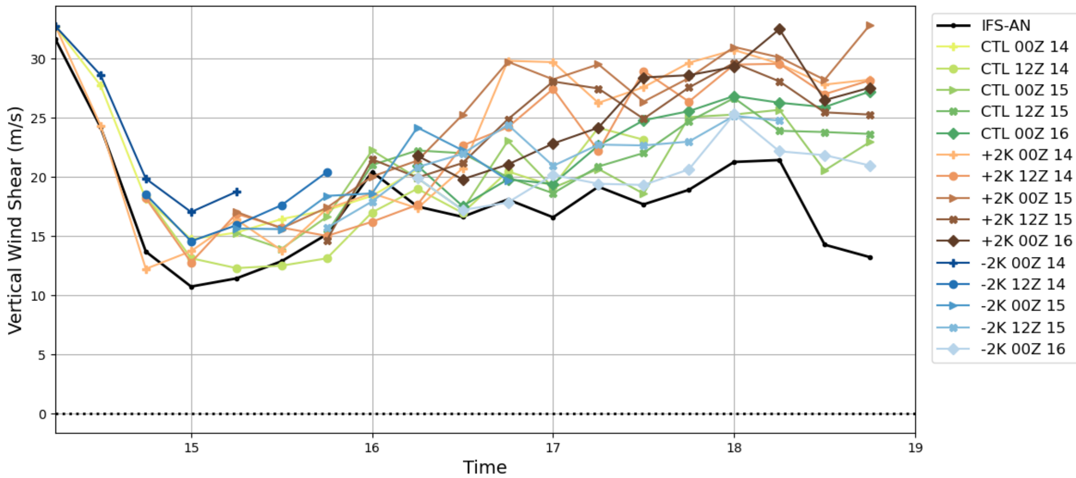

Figure 3: Time-series of vertical wind shear around the cyclone, see text above for details.

2. *Title:* I fully agree with the authors that convection preceding Ianos can be considered as a preconditioning of subsequent evolution. Warmer SST makes this preconditioning more robust in the model simulations of this specific case. I'd argue, however, that the preconditioning is still by the preceding convection and not by the warmer SST. It is hard to make a general case about the preconditioning role of SST from this single case. I think that it is thus warranted to adjust the title accordingly.
   The following title is suggested: The impact of preceding convection in the development of Medicane Ianos and the role of sea surface temperature
   We would like to keep a reference to the SST, as this paper is the result of the journey we undertook to understand how the predictability of Ianos improved in the simulations with warmer SST experiments. The experiments are very sensitive to SST and the paper's points on the preceding precipitation, low-PV bubble and diabatic heating align well with warmer or cooler SST.

3. *Reference to tropical transition:* At a few points in the manuscript the authors refer to the evolution of Ianos as tropical transition. Is there evidence that Ianos indeed started as a (distinct) midlatitude cyclone? The authors argument in L520 that baroclinic forcing alone was insufficient for strong cyclogenesis speaks against a distinct baroclinic origin of Ianos. An alternative interpretation could consider the observed evolution more akin to tropical cyclogenesis. I believe that clarification or a more explicit discussion of tropical transition vs. tropical cyclogenesis would be beneficial to the manuscript because the underlying mechanism differ distinctly between these pathways.
   Yes, Ianos did not have a symmetric warm core during its first day (Figure 1 here). L520 will be rewritten to make clearer that diabatic processes were important during Ianos intensification like in intense mid-latitude cyclones or sub-tropical cyclones.

Minor comments

L118: single-moment scheme: Please clarify which hydrometeors are represented. Is there ice? The presentation suggests that there is rain only. More generally, please add a brief discussion on how the simplistic one-moment scheme affects the representation of convection.

Details can be found in the "microphysics" section in RAL2M's reference paper Bush et al. (2023) cited in the manuscript. It includes the snow size distribution parameterization of Field Field et al. (2007), which will be referenced in the new version of the manuscript.

Broadening the point on model deficiencies, we will add description of the main setbacks of the RAL2M configuration, mostly precipitation biases at high and low intensity. Note, RAL2M was an established regional configuration at the time we run our simulations, it was operational in the MetOffice and the National Institute of Water and Atmospheric Research (NIWA) for regional domains over UK and New Zealand.

L281: I do not see an indication of dipole structure in the figure and thus this explanation seems mere speculation. Alternatively, and more simply, the observed tropospheric PV values at upper-levels could simply be due to vertical transport (cross-isentropic as well as adiabatic) of PV from the lower troposphere.
The PV dipoles appeared earlier on when the low-PV bubble is forming at $6Z$ 14/9 over the areas of high convective activity, as shown in Figure 4 here. It is clearer in the MetUM simulations, whose resolution is higher than the IFS-Analysis and in which convection is not parametrized. The low-valued PV could be vertically advected from below and/or generated aloft. We do not aim to resolve such question in the manuscript (e.g. see L523). We will detail that the PV dipoles appear earlier and are not shown in Figure 14.a

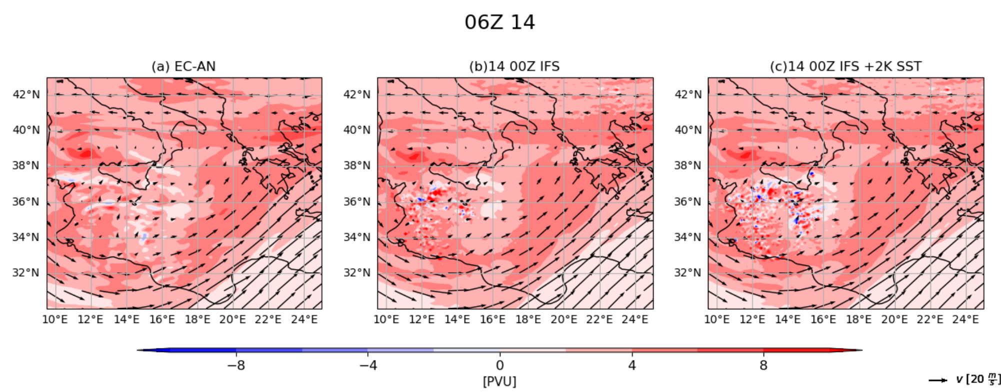

Figure 4: Upper-level PV and horizontal winds as Figures 7,9 and 10 but at the 14/9/2020 06Z validation time for (a) IFS-Analysis (b) control SST and (c) +2K SST, both init. at $00Z$ 14.

L303: "horizontal gradients": Did the authors evaluate different contributions to PV or is this speculation? Usually, diabatic heating generates PV anomalies by generating stability anomalies, i.e., changing the vertical gradient of theta.
No, we did not evaluate the vertical or horizontal contribution to the PV production, we will clarify this point in the new revision of the manuscript

Fig 14: I am confused: Is this a Hovmoeller diagram for which the meridional location is adjusted at each time step to match the meridional position of Ianos? I have a hard time understanding this rather unconventional and complex plot and thus suggest further improving the description/ introduction of the format. Or is there a simpler way to depict the relevant information?
Yes, it is a Hovmoeller diagram where the meridional location is the validation time of the simulation, and each point in the zonal is a location of the Ianos' track. We believe the figure's format is often employed to show local changes before and after the passage of a TC, in particular the cold-wake in SST, e.g. see Fig 20 of Thompson et al. (2019). We will rewrite the relevant sentence in the caption and the second sentence of the paragraph introducing the figure at L403.

L526: The authors did not study the adjustment process and thus I recommend not emphasizing this process in the conclusions.
The development of the geostrophic circulation on the western side of the low-PV bubble will not be associated to the geostrophic adjustment.

Editorial comments

L10: "bubble" I think it is fine to use this term in the main text (L285) in quotation marks and when supported by a figure. For the purpose of the abstract, I recommend rewording.
The "low-PV bubble" element is quite central in our analysis and in the description of our results. Thus we will improve its definition in the abstract, and use it few times in it to avoid duplication.

L15: The sentence reads as if the divergent outflow aloft sustains Ianos' development. Is this the causality that the authors mean to imply. Or isn't the outflow at this point during the development rather a consequence of Ianos' sustained development? Please clarify.
Point (iii) only applies to Ianos intensification during the 16^{th}. It is missing in earlier simulations with -2K SST. The whole list is rewritten to improve its readability and separate the three elements with clearer text.

L105: What is the medium-complexity model for surface fluxes? Or do you imply that surface fluxes fully control the diabatic processes analysed with Semi-Geotriptic inversion tool? Please clarify. It is the latter, the text will be rewritten to explicitly relate diabatic processes to surface fluxes and SST changes.

L116: change "resolve" to "represent"
it will be included in the future version of the manuscript

L116: The eye is not a process. Please reword.
"Process" will be replaced by "feature"

L128: The use of the term "trajectory" is not entirely clear to me here.
It means the simulated trajectory of an air parcel by MetUM that is consistent with the maintenance of geostrophic and hydrostatic balance. The text will be rewritten to make this term more explicit

L138: Does this sentence make sense?
No, it is missing the verb! It will be fixed as "The Matrix Q **is** shown ..."

L152 Please note in the following discussion if the SGT inversion is linear.
The SGT inversion is not linear, replacing the wind vector $\vec{u}$ with the continuity equation in equation 1 yields an elliptic equation for the pressure tendency $\partial\phi/\partial t$, shown in eq. 1 here. See sect. 2.3 of Sánchez et al. (2020) for further details. Nevertheless, the residual between the full solution and the sum of both ($NO-HEAT + HEAT-ONLY$") is very small (1%). The residual of the case shown in the manuscript's Figure 12 is shown in Figure 5.d here, and given its marginal values we do not consider it is worth including it in Figure 12.

$$\nabla \cdot \mathbf{Q^{-1}} \nabla \Big(\frac{\partial \phi}{\partial t} \Big) = \nabla \cdot \mathbf{Q^{-1}H} + \nabla \cdot \vec{u}_g \qquad (1)$$

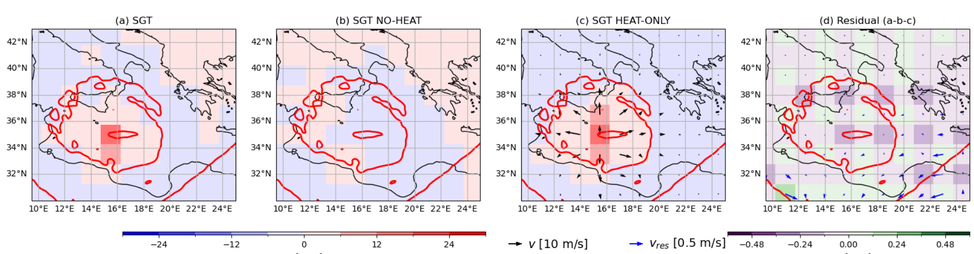

Figure 5: As Figure 12 in the manuscript but including (d), the residual for w (colour) and $\mathbf{v}_{ag}$ (vector). The residual is the difference between the "total" solution (panel a) minus the sum of no heat (panel b) plus the diabatic only (panel c) solutions.

L155: What is your estimate of the Rossby radius of deformation? 0.32° deg would be a rather small estimate. Why do you choose this length scale?
We first filter the MetUM fields to scales equivalent to the global operational models of 0.32°

employed by Sánchez et al. (2020) and Hardy et al. (2023), where the SGT inversion tool was successfully applied. Then a second step is performed where fields are bi-linearly regridded to a grid resolution of 1.5°×1.5°. This procedure allows reasonable computational accuracy in computing scales of 500km or greater (Cullen, 2018). The text will be adapted accordingly.

L208: This statement is not strictly correct because the relation is not monotonic. Please revise.
The text will be rewritten to highlight that the maximum intensity of Ianos is higher in the +2 K SST simulations initialised at the three earliest times, than in the latest two.

L213: "trajectory" (here and elsewhere): "track" is the common term used for tropical-like storms. I suggest revising to avoid confusion.
It will be included in the future version of the manuscript.

L315: Titles of subsections 4.3 and 4.4, these subsections discuss also the tropospheric-deep PV tower not only the upper-level structure.
The section will be rewritten to "Evolution of the upper-level structure and associated PV-tower in the IFS analyses".

L302: I have a hard time to identify the low PV values aloft. Please clarify or change color bar..
Figure 8 will be updated to Fig 6 here, which includes contours for PV=0 in blue, so it is now clearer where the blue areas (showing negative PV) are.

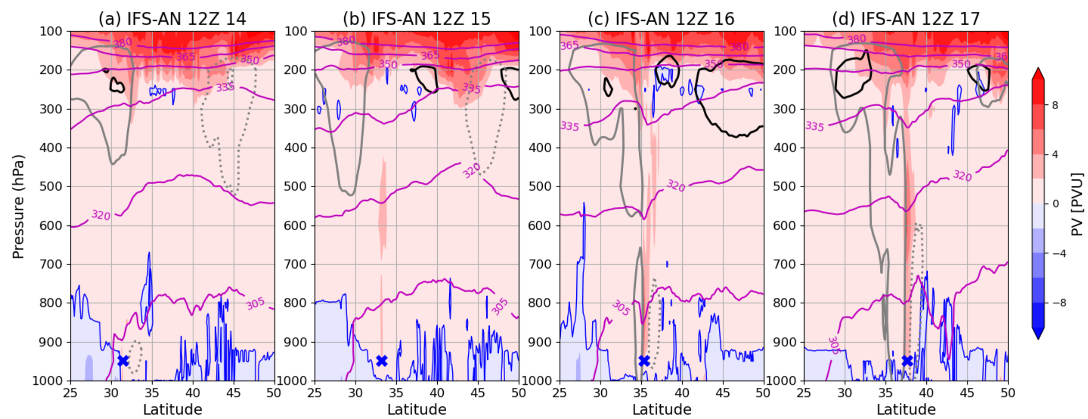

Figure 6: As manuscript's Fig 8 but including blue contours for $PV = 0\ PUV$

L405: suggest adding: "size of the" dots.
It will be included in the future version of the manuscript.

Anonymous Referee #2

1 General comments

1. The tittle does not totally represent the content of the study and the conclusions: It focus more on the mechanisms that favor the development of Ianos rather than on the interaction between a warm sea or warmer sea and the convective factors that provoke Ianos cyclogenesis. It deals with this issue, but it is not the main part of the study, in my opinion. Indeed, in the abstract we do not see any focus on this.
See reply to second point in the major comments section of Reviewer #1. We propose to change the title to:
The impact of preceding convection in the development of Medicane Ianos and the role of sea surface temperature

2. The study argues about the importance of baroclinic forcing in the development of Ianos, i.e. from a midlatitude meteorology point of view, but given it is a tropical transition phenomenon, it lacks addressing its development for a tropical meteorology point of view, i.e., the dynamics of convection

and its organization. Therefore, I would explicitly mention this concern about the partial view of this phenomenon in this study when discussing the results and conclusions.
We will include an analysis of the cyclone phase space (CPS) during Ianos and other changes detailed in the reply to the general comment of reviewer #1.

2 Specific points

1. I would try to reduce the length of the article, especially Section 4.2, 4.3, 4.4 (which are not the main body of the line of arguments; or also merging 4.3 and 4.4 after summarising) and Conclusions and just focus on the main important aspects for understanding the main message about the mechanisms involved in Ianos' cyclogenesis and the role of the SST (although this is not mainly addressed).
We will try to make the text more concise in these sections when revising the paper. However, given that, in response to the reviewers' comments we plan to include a new section on cyclone phase space diagnosis, the overall length of the article is not likely to reduce.

2. Section 1 (Introduction):

   (a) L35-40: I would argue that upper-level baroclinic forcing is essential for the development of precursors to medicanes, not for the intensification of medicanes, at least for those robust (tropical) ones.
   The intensification of medicanes is not well understood and could be case dependent. The paragraph containing this line and the following paragraph will be rewritten to make a clearer point about their uncertainties.

3. Sections 4.1 and 4.2:

   (a) L197: What is the argument to say that it becomes a medicane at this time?
   This line will be rewritten in line with the results from the new section on the new cyclone phase space diagnostic. See Figure 1 here for the CPS anlaysis. It will incorporated in the rewritten text.

   (b) Figure 2: As the different initialization times are indicated by a different symbol, I would put just the same color for the CTL, -2K and +2K groups. In this way, the interpretation becomes clearer without too much noise.
   We would prefer the current colour system as it highlights how the simulations with similar SST forcing change across initialisation times more clearly. Moreover, if we kept the same legend for all figures showing timeseries, which reduces space and simplifies the reading, timeseries in Figure 6 would be even harder to differentiate.

   (c) L215-225: It would be nice to make this analysis more complete by adding the CPS or at least the VTU values for each run, to provide a clearer idea of its tropical (or not) structure.
   A new section on the cyclone phase space diagnostic will be added. See also the reply to general comment of reviewer #1

   (d) L233: Could you provide more evidence for the dry-eyes mechanism of triggering these thunderstorms.
   The SEVIRI water vapour image omitted from the manuscript is shown in Fig. 7 here. There is a clear dry filament extending from a low-pressure system situated out in the southern North Atlantic, North of Madeira, crossing Northwesterly through the Northeast section of the Iberian Peninsula, passing south of the Balearic islands, bending above North Africa and ending on the Sidra Gulf where convection is taking place South of Sicily. This image is publicly accessible (after registration) from the referenced CEDA data centre.
   Further work could be done to attribute the event to the dry-eye mechanism, e.g. check whether the filament is collocated with a stratospheric PV filament. However, this attribution exercise is described with a speculative tone in our manuscript ("one possible mechanism ..."). We chose to avoid showing Fig. 7 and undertaking the attribution work to reduce the length of the paper. Detailing this process is beyond the scope of the paper..

4. Section 4.3:

   (a) L304-305: Why the authors compare this development with those of extratropical cyclones and not with those of tropical transition? I would argue that this is a typical development for tropical transition cyclones and the result of Ianos acquiring a more robust tropical structure.

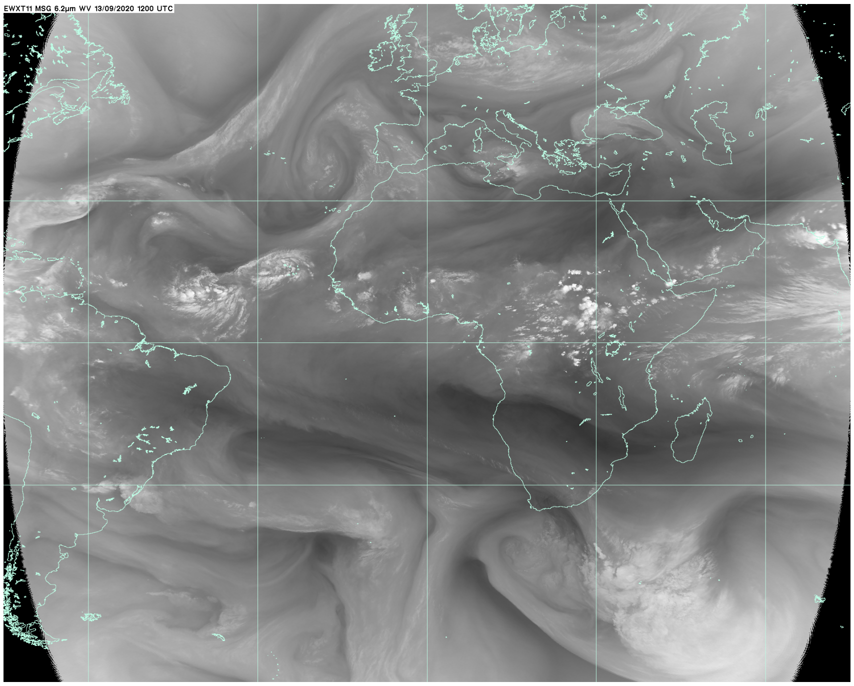

Figure 7: SEVIRI water vapour image at $12Z\,13$, see manuscript for further details.

Panel (c) in Fig. 8 shows the $12Z\,16$ validation time, when Ianos has not yet developed an axi-symmetric warm core (Figure 1 here). Panel (d) shows Ianos where it has already developed the axi-symmetric warm core. We will include a comparison with the results of Galarneau et al. (2015), where the PV tower of surface lows near PV streamers is compared between cases undergoing TT with those which do not.

(b) L307: Talking about tropical-like transition here is not suitable as this is not a rubust definition in the literature. The best way to deal with this type of development is talking about the tropical transition process, to be more in line with the community that study cyclone transitions.
The term "tropical-like transition" will be replaced by medicane or axi-symmetric warm core where applicable. We will detail the process of tropical-like transition for medicanes in the introduction in the revised paper.

(c) In this section and the rest of the sections, I miss discussions about the upper-level dynamics that considers the jet streak behaviour. It is true that the PV field is related to the jet dynamics, but it would be interesting to also consider the analysis/explanations from the jet's QG forcing perspective in the analysis of this section and the following ones. There is not a clear relationship between the position of the surface low and upper-level jets at the time of Ianos cyclogenesis (Fig. 8.b). Ianos sits at the southern tip of the southerly flow while it intensifies one day later (Fig 8.c) as well as near the left jet exit region of the southwesterly jet streak. Hence, Ianos is in an optimal location for intensification relative to the southwesterly jet streak but the interpretation considering both nearby jets is not straightforward.

5. Sections 4.5 and 4.6:

(a) MetUM means full solution?
MetUM means that the θ, PV and pressure fields shown are from the spectrally filtered simulation output (as detailed in caption of Fig 12). These fields are shown mostly for indicative purposes associated to relevant dynamical processes. It will be clarified in the caption

(b) L403: Is not the y-axis showing the dates? (Figure 14).
The description of Figure 14 in text and caption will been changed, see reply to "(Fig. 14)" minor comment from reviewer #1

(c) L467 By watching Figure 16 (a-b), one could argue that the forcing at lower levels is stronger in (a) and, therefore, conclusions derived from Figure 15 are subject to the level of choice (700 hPa). If we choose 800 hPa or 850 hPa, for instance, conclusions could be different. Indeed,

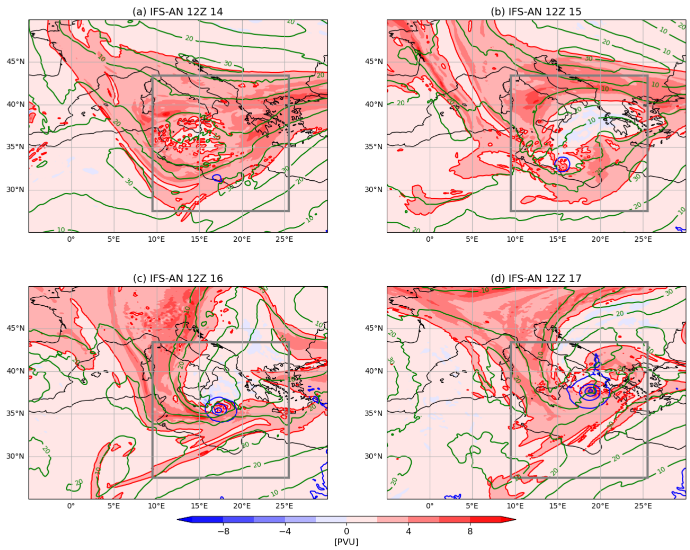

Figure 8: Same as Figure 7 in the manuscript but showing wind speed contours instead of wind vectors, every 10 m/s.

the signal seems to decrease a lot at the 700 hPa level. Please, elaborate more on this. Why not choose 800 hPa (it would still avoid boundary layer effects)? This argument of similar low-level forcing appears to be quite weak.
It is the level chosen by Deveson et al. (2002). See reply to the first major comment of reviewer #1. The text and figures in the section on quasi-geostrophic analysis will be edited in the revised version.

6. Section 6 (conclusions):

   (a) L538-544: I see the idea of the authors here, but I don't fully see the relationship between Ianos' development and this mechanism in extratropical transitions and downstream cascade of events. The link is about the upper-level PV modification by a diabatic source, but just up to this point.
   Although we are considering a medicane rather than a tropical cyclone here, the extratropical transition of a TC is relevant as it is an example of diabatic processes preconditioning environmental baroclinicity and cyclone reinforcement. Thus we think it is relevant to highlight this evolution for those readers interested in how diabatic processes and baroclinicity interact with each other. The sentences will be rewritten to make this point clearer

   (b) L541-544: An analysis focusing on the tropical transition perspective would make the article more complete. The paragraph will be replaced by one which details the TT pathway from meridional thought precursors from Bentley et al. (2017), with further references to TT metrics and processes.

   (c) 545-552 I think this part is not very well connected with Ianos' mechanisms and it could derive some confusion.
   These lines will be removed and replaced by a paragraph liking our results to the TT literature detailed in the reply above.

   (d) L562: I would not mention this hypothetical situation as (as you discuss later) the model is uncoupled and a robust analysis about model performance in this case has not been undergone. This scenario could be quite fictitious.
   We think this paragraph provides enough context to understand how "fictitious" our simulations with +2K SST could be. Its purpose is mainly to motivate future work to understand the role of SST under a changing climate and its possible impact on medicane development, as well as to advocate for the use of regional coupled models at convective scales for climate

studies. The end of the last sentence of the paragraph will be rewritten to refocus its point into a modelling perspective, where our results are more relevant.

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