egusphere-2024-1054: "**The Connection Between North Atlantic Storm Track Regimes and Eastern Mediterranean Cyclonic Activity**" by Dor Sandler, Hadas Saaroni, Baruch Ziv, Talia Tamarin-Brodsky and Nili Harnik

A point-by-point response to Reviewer 1:

1. **Reviewer 1:** I have read the paper with great interest and I have appreciated the clarity of the methods. I found the results to be novel, they align with recent findings and contribute to the ongoing discussion on the role of large scale circulation in modulating Mediterranean weather and climate extremes in the Mediterranean. I certainly recommend the eventual publication with some revisions, mostly of minor nature.

   If however I have a major concern, this relates to the presentation of the results. Actually, the text is rather dense and probably difficult to follow if someone is not well updated on the subject of this study. For reasons of better articulation, I would recommend smoother introductory phrases in each section of the results (or paragraphs) and a rather clear concluding remark. Some of the minor comments below point towards this direction.

   Response: Many thanks for your thoughtful and detailed review. Your perspective as a reader highlighted the importance of not missing the forest for the trees, especially when dealing with a detail-heavy mechanism consisting of multiple processes. Our revised manuscript aims to be clearer and more intuitively phrased.

2. **Reviewer 1:** There is a thorough presentation of the state of the art on the interactions between different large scale features and Mediterranean cyclones. Several of these interactions are described in detail, but most probably their understanding would be difficult if readers are less familiar with the Mediterranean region and the dynamics of the storm tracks. I would recommend to the authors to introduce a schematic on the main features of the mechanism that lead to Mediterranean cyclogenesis (perhaps somewhere at the end of the paragraph in line 43). One additional idea would be to be a bit more explicit on the objectives and motivations (last paragraph) and thus relocate some of the phrases/parts from the introduction to the main results in order to ease discussion of new findings with respect to previous studies. That would be of help to the reader to better place new results within the state of the art and take their time to process new findings.

Response: As suggested, we added a generalized schematic detailing the Atlantic-Mediterranean cyclogenesis mechanism (lines 43-47). We describe it in three broad steps, so that it might fit multiple processes (see new Fig. 1):

(1) "Perturbation" can describe a WCB-driven ridge or a NAO-induced upper level convergence.

(2) "Propagation" can be related to RWB events as well as quasi-stationary wave packets

(3) "Interaction" is baroclinic growth either via PV streamer or a persistent upper-level trough.

The Results chapter now uses this terminology to give better context to our findings.

The objectives and motivations paragraphs (lines 98-102) were also rephrased to better reflect this.

Lines 43-47: *"While the four components are interconnected [...], they all broadly relate to the same dynamical chain. Figure 1 shows a generalized depiction of this process. First, a low level forcing creates a perturbation of the upper tropospheric flow upstream of the Mediterranean. This perturbation grows and propagates along the polar jet stream. After breaching southward towards the Mediterranean, the meridionally elongated anomaly can interact with Mediterranean cyclones, enhancing their cyclogenesis and development."*

Lines 98-102: *"More specifically, we examine how different regimes of the North Atlantic storm track relate to cyclone inducing flow downstream on synoptic and seasonal time scales. We then inspect whether this connection can be interpreted via the perturbation-propagation-interaction framework (Fig. 1), using explicit analysis of relevant dynamical elements (namely, RWB events, PV streamers and cyclone tracks). Rossby wave packets will not be directly analyzed in this work. While relevant for Eastern Mediterranean precipitation, their connection to the North Atlantic storm track is less apparent."*

3. **Reviewer 1:** Data & Methods. This section is long and its technical nature makes it less attractive to the reader. Please consider inserting subsections. It also seems (except if I missed it) that Fig. 1c is not referenced in the text.

   Response: Subsections are now added to Section 2. Figure 2c (previously 1c) is now referenced in lines 159-160.

4. **Reviewer 1:** Section 3.1/Fig. 3: How are densities and precipitation anomalies defined? Both colorbars seem to describe very small values.

Response: Thank you for catching this. The track density anomalies were accidentally calculated at an hourly resolution. This plot (Fig. 4) now shows track points per month. As for precipitation, units are now changed from ERA5 default ‘m’ to ‘mm’.

5. **Reviewer 1:** Section 3.2: Please reverse the two first phrases. In fact, NAO is mentioned once in the methods and thereafter it is mentioned here introducing a section with a very direct, albeit rather awkward way.

   Response: Both reviewers pointed out that NAO isn’t properly incorporated into the first half of the manuscript. We added an introductory paragraph in Section 1 (lines 81-85) and changed the description at the beginning of Section 3.2 (lines 222-232):

   Lines 81-85: *“The positive phase of the North Atlantic Oscillation (NAO) can sometimes trigger the propagation of one such wave packet (Watanabe 2004). A surface high forms in the Western Mediterranean, prompting upper level convergence which excites a wave train along the jet. Watanabe dubbed this process "the NAO downstream extension", and it can be classified under the perturbation step in Fig. 1. NAO phase variability has also been linked to cyclone track density anomalies in the Western Mediterranean (Nissen et al., 2010) and, to a lesser extent, to rainfall in Israel (Black 2012).”*

   Lines 222-232: *“In order to relate the M cluster to other rain inducing patterns in the literature, we focus on its temporal evolution and connection to internal modes. Using the monthly NAO index (taken from NOAA-CPC, see Section 2), we find that all 10 cluster M months have positive NAO values (average index of +1.8 standard deviations). Rainy cluster M months are therefore a subset of the NAO+ phase. […] SLP anomalies organize as a quasi-stationary zonal wave (shading in the left column of fig. 6) that precedes the western Mediterranean high. This pattern corresponds to the "NAO extension" defined by Watanabe (2004).”*

6. **Reviewer 1:** Line 198: what is meant by "to increase the sample size"?

   Response: This line was removed.

7. **Reviewer 1:** Lines 200-201: Could you please provide a descriptive context about the connection of the western blocking high with the NAO positive phase? This will introduce the discussion on Fig. 5 in a smoother way and will articulate better the different parts of the paragraph.

   Response: Please see our answer to comment #5. We now elaborate on the NAO downstream extension mechanism that links the NAO and the high.

8. **Reviewer 1:** Line 208: The pressure low anomaly seems to persist before Lag 0 days (Figs 5b and 5d). Can you please comment on the cyclones occurrence respect to the green hatches. Is it possible that PV streamers and cyclone occurrences are not -always-sequential (in terms of time) to the max of MSLP in the black square in the black box of Fig. 5e. Actually, how would fig. 5 look if lag times are calculated respect to max of precipitation in the eastern Mediterranean?

   Response: This is a good point, which was also brought up by Reviewer 2. The overall number of cyclones increases after lag 0, but there are still cyclones in the Eastern Mediterranean in the previous composite lags. While the RWB-streamer-cyclone sequence is common, we cannot claim it as the only path to cyclogenesis.

   It seems that defining lag 0 around max precipitation fixes this issue. The propagation of the cyclones is better represented, as it is closer in time to lag 0. While the large scale picture is noisier, the overall chain is still present (w.med high → RWB/streamer → e.med cyclones).

9. **Reviewer 1:** Relevant to the previous comment, is it possible that some of the cyclones in CL=5 dataset correspond to stationary lows in the southern side of Turkey/Cyprus? Therefore they might not really correspond to actual mesoscale cyclones?

   Response: We recalculated the main results for CL=3-7. They are mostly unaffected. The track density signature (figure 5) is slightly stronger for a higher confidence level, implying that there is some stationary noise. However it should affect all clusters equally so we chose to keep the analysis as CL=5.

10. **Reviewer 1:** Probably a case study similar to Fig. 7 (or rearrangement of the last section) would be helpful here?

    Response: The reader might find it hard to follow another detail-heavy series of maps. The precipitation-centered composite signal seems clearer now in the revised manuscript.

11. **Reviewer 1:** Line 242: it's January 3rd 1992(?).

    Response: Fixed the date.

12. **Reviewer 1:** Line 274: Probably it is better if you made reference to previous figures.

    Response: Rephrased and added references to relevant figures.

    Lines 306-309: *"The Eastern Mediterranean is generally drier and more stable when the Atlantic storms don't follow the preferable path, i.e., overshooting towards Greenland in the N cluster (Fig. 3a) or undershooting into western Europe in the S cluster (Fig. 3c). This* *is likely due to Mediterranean cyclones forming and reaching their peak more upstream, along the northern coast or near Genoa (shading in Fig. 4a,e).”*

A point-by-point response to Reviewer 2:

1. **Reviewer 2:** The paper puts winter climatological precipitation anomalies in the Middle East in the context of a dynamical chain of mechanisms that control the variability of cyclones in the Eastern Mediterranean. Namely, the large-scale variability of the Atlantic storm track, Rossby wave breaking downstream and the intrusion of PV streamers further downstream into the Mediterranean, eventually promoting cyclogenesis and precipitation in the E. Med. coast. The study confirms the relevance of this chain of events for the E. Mediterranean, a region that was overlooked in previous Mediterranean-wide studies that focused on the most intense cyclones. Further, the authors find an optimum configuration for the Atlantic storm track - extending northeastwards into the North Sea, for positive precipitation anomalies in Israel - a remarkable and clean result. I find the paper generally clear and well written and support its eventual publication in WCD after my concerns are addressed. I further suggest specific points to enhance clarity and help with the interpretation.

   Response: We appreciate your insights and comments for our manuscript. Your review brought to our attention that some concepts and mechanisms were not as clearly explained as we had hoped, and it highlighted various minor errors that went unnoticed. The revised version addresses these issues and is now more consistent.

2. **Reviewer 2:** The NAO index is first mentioned in the methods section, without being introduced earlier in the introduction. Actually, lines 257-260 can better fit in the introduction as motivation, in my view.

   Response: This issue was also brought up by reviewer 1. The NAO and its relevance to our question are now introduced in section 1. We also relate it more explicitly to our results in section 3. Please see our answer above to reviewer 1 comment #5:

   > Both reviewers pointed out that NAO isn’t properly incorporated into the first half of the manuscript. We added an introductory paragraph in Section 1 (lines 81-85) and changed the description at the beginning of Section 3.2 (lines 222-232):
   >
   > Lines 81-85: *“The positive phase of the North Atlantic Oscillation (NAO) can sometimes trigger the propagation of one such wave packet (Watanabe 2004). A surface high forms in the Western Mediterranean, prompting upper level convergence which excites a wave train along the jet. Watanabe dubbed this process "the NAO downstream extension", and it can be*

classified under the perturbation step in Fig. 1. NAO phase variability has also been linked to cyclone track density anomalies in the Western Mediterranean (Nissen et al., 2010) and, to a lesser extent, to rainfall in Israel (Black 2012).”

Lines 222-232: *“In order to relate the M cluster to other rain inducing patterns in the literature, we focus on its temporal evolution and connection to internal modes. Using the monthly NAO index (taken from NOAA-CPC, see Section 2), we find that all 10 cluster M months have positive NAO values (average index of +1.8 standard deviations). Rainy cluster M months are therefore a subset of the NAO+ phase. [...] SLP anomalies organize as a quasi-stationary zonal wave (shading in the left column of fig. 6) that precedes the western Mediterranean high. This pattern corresponds to the "NAO extension" defined by Watanabe (2004).”*

3. **Reviewer 2:** The number of cyclones considered (1058) seems too low for CL=5, it should be >3000, please clarify.

   Response: We only analyze DJF cyclones (1058 out of the 3808 annual total). This clarification was added to the text:

   Lines 123-124: *“1058 tracks were identified in the Mediterranean area [...] for DJF months during the study period.”*

4. **Reviewer 2:** Line 141: on which isentropic level are RWB identified?

   Response: The RWB algorithm uses 200 hPa isobaric PV. Added to the text: Lines 160-161 *“This is done for PV contours between 1.5–7.5 PVU on a 200 hPa isobaric level”.*

5. **Reviewer 2:** Line 145: The choice of considering only anticyclonic wave breaking needs a justification. Givon et al (2024) show the relevance of cyclonic breaking events for Mediterranean cyclones and precipitation. (Givon, Y., Hess, O., Flaounas, E., Catto, J. L., Sprenger, M., & Raveh-Rubin, S. (2024). Process-based classification of Mediterranean cyclones using potential vorticity. Weather and Climate Dynamics, 5(1), 133-162).

   Response: This is a good point. We considered including cyclonic RWBs, but it seemed to weaken the resulting composite signal. This is supported by results from another study: Tamarin-Brodsky & Harnik (2024) found that anticyclonic RWBs specifically are connected to an increase in Mediterranean cyclogenesis (see their figure 4a,c). As for the Givon et al. (2024) classification, there are two relevant clusters for this issue: the CWB cluster is mostly an autumn pattern, and the combined AWB+CWB cluster is captured by our algorithm as it is mostly anticyclonic. We now discuss this point in Section 2.

Lines 166-170: *"Cyclonic wave breaking events can lead to cyclogenesis, albeit not as robustly as in the anticyclonic case. When comparing cyclonic and anticyclonic RWBs, Tamarin-Brodsky & Harnik (2024) found a considerably larger number of Mediterranean cyclones to the southeast of the latter. Also, the influence of cyclonic RWBs is limited mainly to autumn months, according to a PV based classification of Mediterranean cyclones (Givon et al., 2024)."*

6. **Reviewer 2:** Line 176-177: need to support this with reference(s).

   Response: Added two references to this statement.

   Line 201: *"It thus captures the known east-west gradient in cyclonic activity (Ziv et al., 2006; Feldstein & Dayan, 2008) […]"*

7. **Reviewer 2:** Reference to weather regimes (lines 178-182): The resemblance to known weather regimes is not as immediate as the authors state. For example, the N cluster is not a clear Atlantic Ridge but seems rather a combination of Atlantic Ridge and Greenland Blocking. The S cluster may be somewhat similar to a Scandinavian Trough (e.g., Fig. 1 in Hochman et al. 2021). (Hochman, A., Messori, G., Quinting, J. F., Pinto, J. G., & Grams, C. M. (2021). Do Atlantic-European weather regimes physically exist?. Geophysical Research Letters, 48(20), e2021GL095574).

   Response: This paragraph is now rephrased to better reflect the ambiguity of the weather regimes. The relation to NAO+ is the most robust and is therefore mentioned first.

   Lines 203-208: *"The large-scale flow over the North Atlantic displays some elements of known regional weather regimes (fig. 5). Composite anomalies of 500 hPa geopotential height show a zonally oriented signal for the M cluster, corresponding to the positive phase of the NAO (this connection is further explored in subsection 3.3). The jet stream (thick black curve in fig. 5) is shifted poleward and more extended to the east (fig. 5b). An upper tropospheric trough can be seen over the Eastern Mediterranean, enhancing cyclonic activity. Meanwhile, the high over the northwest Atlantic in cluster N is reminiscent of blocking regimes (an Atlantic Ridge or a Greenland Blocking).The S cluster does not have a clear weather regime analog, but both dry clusters feature a statistically significant anticyclonic flow in the upper levels over the Eastern Mediterranean."*

8. **Reviewer 2:** Interpretation of EKE. I find the interpretation of EKE anomalies when projected on short time scales rather unintuitive. For better readability, I hope the readers can elaborate further on these by referring to the specific figure panels. For example, Line 186: Could you interpret the relation of the positive EKE anomalies to the overall high geopotential anomalies? Also, what is the

meaning of the positive EKE in the southeastern Mediterranean in this dry regime? In Fig. 7a: it is unclear how is EKE related to the meandering jet/ tropopause shape. Please also elaborate where the statement in lines 248-249 can be seen in the figures.

Response: As we understand this, monthly EKE maps can imply increased presence of storms over cyclogenetic regions. For example, Lehmann & Coumou (2015) showed significant negative correlation between wintertime monthly EKE and monthly 500 hPa GPH over the Mediterranean. In figure 5b,c (previously figure 4b,c), we see that positive EKE anomalies occur north of ridges, where we would expect a stronger jet to drive storms. The negative EKE anomaly in fig. 5a is located on the southern flank of a ridge, perhaps related to a weaker mean flow.

As for the positive Mediterranean EKE anomaly in the N cluster, this is indeed unclear. This might hint at higher frequency waves on the subtropical jet, or perhaps more energetic Mediterranean cyclones. The latter hypothesis would align with the positive rain anomalies over southern Turkey in cluster N (fig. 4b).

The discussion of daily EKE maps (previously fig. 7 and lines 248-249) was removed in favor of a clearer depiction of eddies (see fig. 8). Instead of daily EKE (which is indeed unintuitive), we now represent Atlantic storms as SLP lows with a low-level meridional heat flux (vT850). The approximate paths of the eddies were also added to the figure to show their interaction with the blocking. The paragraph was rewritten to better reflect the results in the figure.

Lines 278-282: *"The first several days include two major elements of an M cluster flow: a high pressure center (solid blue contours) over the eastern Atlantic, and Atlantic lows propagating northeast (low SLP and high meridional heat flux, denoted by dashed blue and solid red contours, respectively). The eastern blocking high persists throughout the period for over two weeks, while directing eddies poleward, most of them reaching Scandinavia (thick arrows in Fig. 8). On the northern edge of the high, RWB events form (yellow markers) and then develop downstream into PV streamers over the Eastern Mediterranean."*

9. **Reviewer 2:** RWB diagnostic (Figs 1c, 4c, 7, Lines 192-195): The illustration in Fig. 1c indicates that the zonal extent of the identified RWB feature is the same as the PV streamer just to its south, as it essentially identified the tropospheric streamer. Having this in mind, it was unclear how ~30 degrees of longitude separate RWB from the PV streamers in Fig. 4, 5, 7 and the accompanying text. Also, in Fig. 7a: RWB is identified in the Bay of Biscay, but a RWB is not apparent in the plotted PV field. Please clarify this discrepancy and possibly add illustrative examples for the

detection of RWB from the Mediterranean when the method is described.

Response: Thank you for pointing out this apparent discrepancy. It is mostly an issue of graphics and scale. Our algorithm finds that the mean zonal extent of a RWB is 33°. The streamer is essentially the RWB's equatorward-advected tongue with a scale of ~10° (the D parameter is set to 800km). Under these conditions the longitudinal distance between the two is reasonable, as the initial breaking skews and elongates before reaching the Mediterranean.

Figure 1 doesn't show gridlines so the scale is misleading. Figure 1b is 50° long and 1c is 20° long. We now mention this in section 2.

Lines 163-164: *"Under these parameters, the typical zonal extent of a RWB is ~30° (note that the scale for fig. 2c is roughly 3 times larger than fig. 2b)."*

The second issue was in the choice of PV level and color scale. We changed figure 8 (previously 7) to show 200 hPa isobaric PV and adjusted the color scale accordingly. The Biscay breaking in fig. 8a is clearer now.

10. Reviewer 2: Fig. 3 caption: add units to the shaded variables and clarify the color of the hatches.

Response: Corrected the caption.

*"**Figure 4.** [...] (a,c,e) Monthly cyclones track density (shading, number of tracks per month) and PV streamer density anomaly (hatches). For streamers, only statistically significant anomalies are shown (95% confidence on a 500 sample bootstrap test). Positive anomalies are shown in red and negative ones in blue. (b,d,f) Monthly precipitation anomalies (shading, mm). Areas with over 95% statistical significance are highlighted in pink hatches."*

11. Reviewer 2: Fig. 5 caption: add units to the shaded variables and clarify how the anomalies are defined.

Response: Added units and a description of the anomalies (now Fig. 6).

12. Reviewer 2: Fig. 6: add a colorbar for panels a,c.

Response: Colorbar is added.

13. Reviewer 2: Composites in subsection 3.2: The choice of centralizing the composites on the high-SLP anomaly needs further motivation. Why not on the cyclones in the E. Med. or the resulting precipitation?

Response: This point was also brought up by reviewer 1. See their comment 8 and our answer below:

Reviewer 1: Line 208: The pressure low anomaly seems to persist before Lag 0 days (Figs 5b and 5d). Can you please comment on the cyclones occurrence respect to the green hatches. Is it possible that PV streamers and cyclone occurrences are not -always- sequential (in terms of time) to the max of MSLP in the black square in the black box of Fig. 5e. Actually, how would fig. 5 look if lag times are calculated respect to max of precipitation in the eastern Mediterranean?

Response: This is a good point, which was also brought up by Reviewer 2. The overall number of cyclones increases after lag 0, but there are still cyclones in the Eastern Mediterranean in the previous composite lags. While the RWB-streamer-cyclone sequence is common, we cannot claim it as the only path to cyclogenesis.

It seems that defining lag 0 around max precipitation fixes this issue. The propagation of the cyclones is better defined, as it is closer in time to lag 0. While the large scale picture is noisier, the overall chain is still present (w.med high → RWB/streamer → e.med cyclones).

14. **Reviewer 2:** Reference to Rossby wave packets: This concept is mentioned a few times throughout the text (e.g., line 213, 247, 282), but it is not directly shown and discussed in the text and figures. This notion should be then stated with caution, or elaborated further in the results.

Response: Added a clarification to the introduction section. While RWP-like structures appear in our results, they are not the focus of the mechanism discussed.

Lines 99-102: *“We then inspect whether this connection can be interpreted via the perturbation-propagation-interaction framework (Fig. 1), using explicit analysis of relevant dynamical elements (namely, RWB events, PV streamers and cyclone tracks). Rossby wave packets will not be directly analyzed in this work. While relevant for Eastern Mediterranean precipitation, their connection to the North Atlantic storm track is less apparent.”*

Technical corrections:

- 1 caption: snapshop => snapshot; “5 and 3” => add “pvu” fixed
- Line 63: a hundred => two hundred fixed
- Line 87: replace dot by a comma line was rephrased
- Line 102: add “Yearly” before “accumulated” the line states “accumulated annual rainfall”
- Line 115: delete “(described above)” deleted
- Line 140: An => A fixed
- Line 155: should “mm” be “%”? yes! fixed
- Line 207: purple => red fixed

- Line 228: refer to Table 1 after “cyclones”. done
- Line 256: the part of the sentence after “i.e.,” is unclear and seems incomplete. Separated the sentence into two parts.