Response to Referee comments (RC1, RC2)

RC1

Summary

This analysis considers the influence of the El Niño - Southern Oscillation (ENSO) on the Middle East region (broadly defined) during the cold season. The analysis focuses on the role of Rossby wave breaking in shifting the jet and on the role of changes in moisture transport in affecting moisture availability and stability. These mechanisms are considered in the context of changes to jet position, barotropic Rossby wave propagation eastward from the eastern tropical Pacific, and baroclinic Rossby wave propagation westward from the western tropical Pacific. The substantial change in ENSO influence over the course of individual months within the cold season is also analyzed. As discussed by the authors, many of these topics have been considered in prior work, although the analysis of Rossby wave breaking appears new and the month-by-month consideration of ENSO influence is more detailed than prior work.

In my opinion, this analysis has the potential to provide an important step forward in our understanding of ENSO influence on the region, especially in terms of the role of Rossby wave breaking, and I enjoyed reading the manuscript. I do think some further analysis is needed to solidify the link with wave breaking, and I think some further discussion is needed to clarify some questions raised in the following. My recommendation is for major revisions to address these aspects, although I expect that addressing these points will be straightforward.

We very much thank the reviewer for the thoughtful and constructive review. Below we respond one by one to the raised questions and comments and indicate the modifications in the manuscript.

Main comments

1. The substantial change in Rossby wave breaking is shown to be co-occurring with changes in precipitation during ENSO phases, and this association certainly suggests an important influence. Unless I missed something, however, the analysis seemed to focus only on the ENSO influence on wave breaking, jet shift, and precipitation, rather than on the direct link between the wave breaking, itself, and the other variables. What would help complete the picture would be to directly examine the connection between the wave breaking, jet shift, and precipitation. For instance, it would be straightforward to define a local wave breaking index and composite precipitation and jet speed based on that index.

We thank the reviewer for this thoughtful comment. The manuscript already includes an analysis from the perspective of precipitation anomalies on wave breaking and jet position characteristics. Figure 4 shows for precipitation and dry-day events, on daily timescales, the co-occurring anomalies in Rossby wave breaking frequencies and the jet position, discussed in the 2nd paragraph of section 4. This analysis provides a reference for interpreting ENSO-based anomalies in wave breaking frequencies and jet position. In other words, by comparing anomalies in the jet position and wave breaking frequencies during ENSO phases (Fig. 5) with those based on precipitation and dry-day events (Fig. 4), we can draw inferences on how ENSO enhances or suppresses precipitation. Regarding the way in which wave breaking influences precipitation and relates to variations in the jet stream, we refer to the existing literature which explored this linkage. Please, see for more information the first three sentences of section 4 from the original version of the manuscript:

"Midlatitude forcing plays a key role in the formation of precipitation across the Middle East during the cool season. Extratropical Rossby waves propagate and break towards lower latitudes, resulting in the formation of upper-level troughs and often cut-off lows (Kahana et al., 2002; Kumar et al., 2015; De Vries et al., 2016, 2018; Tuel et al., 2022; Francis et al., 2025). These upper-level cyclonic circulation patterns can induce cyclogenesis near the surface, intense atmospheric moisture transport from southerly directions, and large-scale ascent, leading to tropospheric conditions conducive to the occurrence of deep moist convection."

Specifically, De Vries et al. (2018) quantified the fraction of annual and extreme precipitation that co-occurs with Rossby wave breaking using various observational datasets. In another study currently in preparation (De Vries et al., 2026b), we further explore the influence of Rossby wave dynamics in conjunction with different phases of the MJO on precipitation variability at daily timescales. To provide some insights into this topic, we add here composites of precipitation (Fig. R1) and the 250-hPa zonal wind anomalies (Fig. R2) for days with anomalously strong and weak Rossby wave breaking, demonstrating the importance of wave breaking on precipitation variability. The coherent patterns of precipitation and upper-tropospheric zonal wind further support the link established in the current study between wave breaking and anomalous precipitation and circulation. Given that (i) this linkage has been addressed in previous work, (ii) will be further detailed in another ongoing study focusing on precipitation variability on daily timescales (De Vries et al., 2026b), see also the figures below, and (iii) the focus of the present manuscript is on the ENSO-Middle Eastern precipitation relation, and that including more information on this aspect would deviate the focus too much, we choose to not add more material on this topic than already provided in Section 4 and Fig. 4.

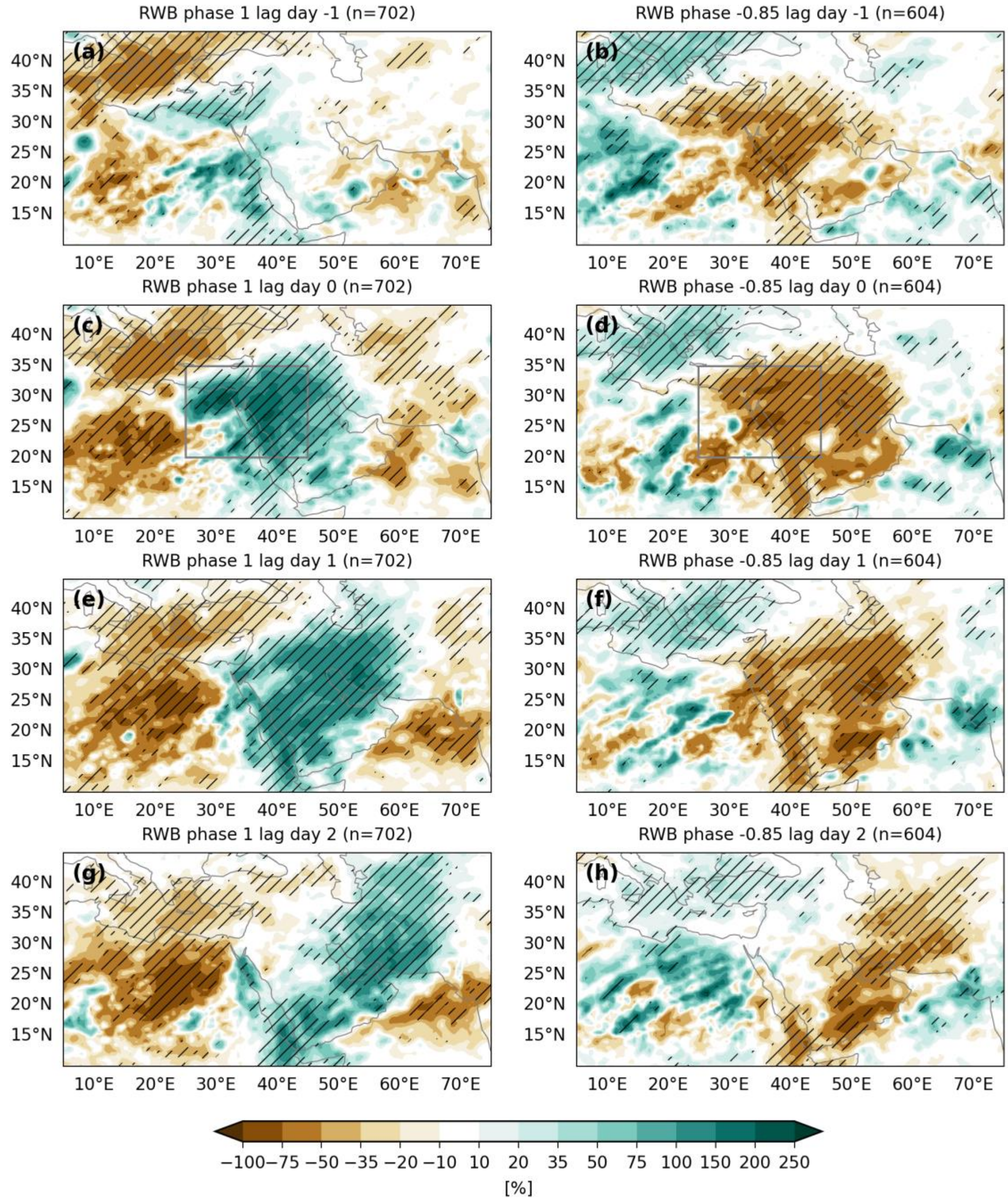

Fig. R1. Relative precipitation anomalies from daily MSWEP data based on (left) increased and (right) decreased Rossby wave breaking frequencies, defined by running mean anomalies in stratospheric PV structures aggregated over 300-350 K isentropic surfaces with in a region of 25-45E, 20-35N (denoted in grey in panel c,d), exceeding 1 standard deviation and falling below -0.85 standard deviation from climatology. The columns show the lag of (a,b) day -1, (c,d) day 0, (e,f) day +1, (g,h) day +2 with respect to the onset of anomalous RWB events. Hatching denotes regions where the anomalies are considered significant at the $p < 0.05$ level.

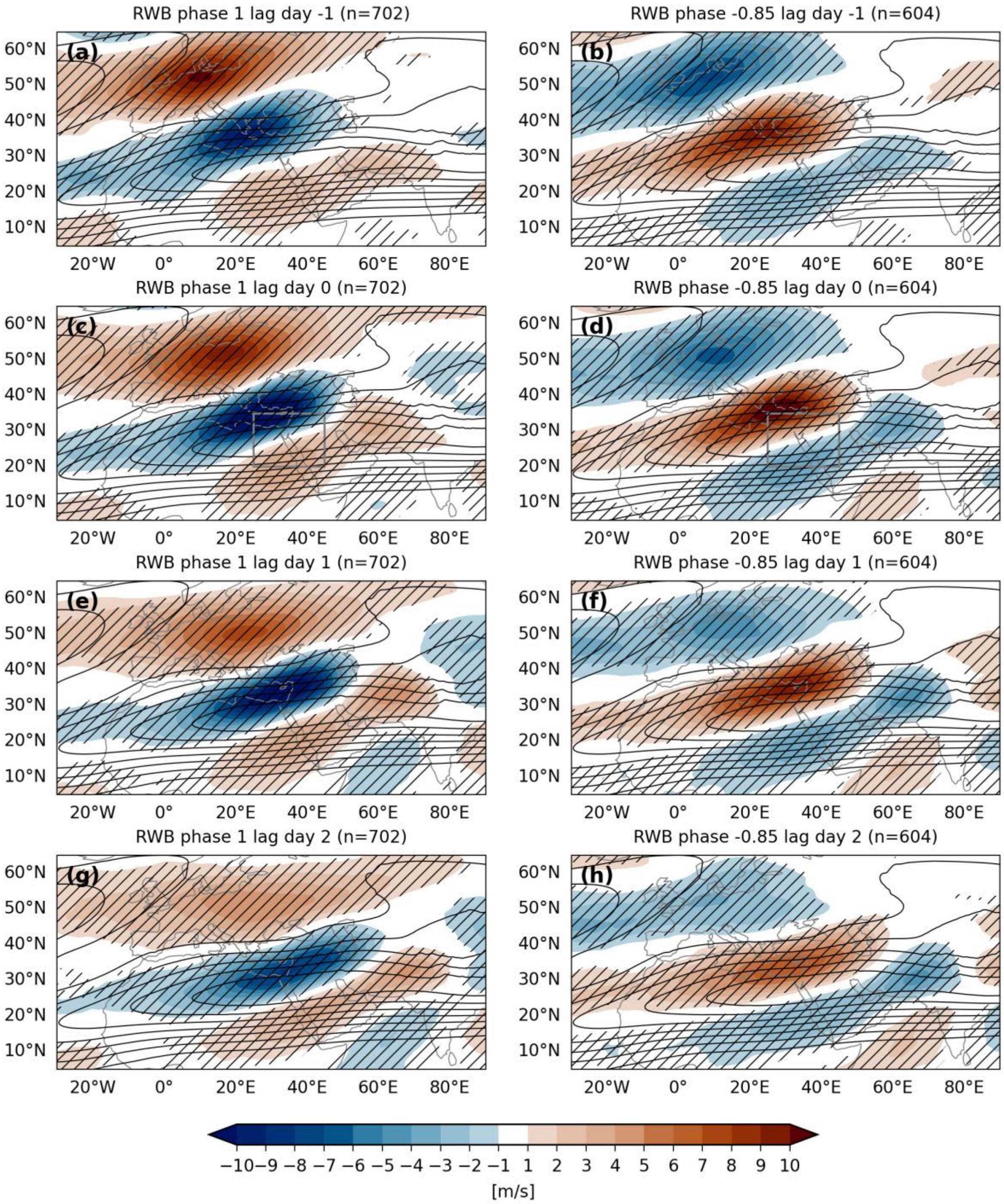

Fig. R2. As Fig. R1, but then for the 250-hPa zonal wind anomalies with black contours showing the climatological mean 250-hPa zonal wind.

2. It was somewhat unclear to me as to how the influence of the baroclinic Rossby wave on the regional precipitation was being interpreted. One hypothesis that has been put forward is that the interaction between the wave and the mean flow results in isentropic downgliding over the region (e.g., Barlow et al. 2007, Hoell et al. 2012). How does that mechanism fit (or not fit) into the authors' interpretation of the mechanisms at play? Or, put another way, the schematic shown as Fig. 9 in Barlow et al. (2016) highlights regional changes to vertical motion, moisture flux, and storm tracks, in the context of influence from both baroclinic and barotropic Rossby waves. Is the key new idea here that the storm track changes can be linked to the Rossby wave breaking, or do the authors have something different in mind?

We thank the reviewer for drawing our attention to these two points. To the first point, on the isentropic downgliding over the region (during La Nina, and vice versa, large-scale ascent during El Niño), we agree with this perspective and believe it to be consistent with our analysis. We complement the discussion in section 6 and add the following sentences:

"The circulation response over the Middle East to Indo-Pacific tropical convection anomalies is consistent with the monsoon-desert mechanism of Rodwell and Hoskins (1996, 2001). According to this mechanism, reduced (enhanced) tropical convection sets up west-to-east upsloping (down sloping) isentropic surfaces facilitating isentropic upward-moving (down-gliding) air masses, resulting in large-scale ascent (subsidence), favoring (suppressing) precipitation formation (Barlow et al., 2005, 2007). This mechanism is evident from widespread mid-tropospheric ascent (descent) over the broader Middle East region in Fig. 9a (Fig. 9c)."

To further demonstrate how ENSO modulates mid-tropospheric vertical motion, we add 500-hPa anomalies to Fig. 9 (please see the revised figure in the manuscript). Please note that the revised Figure 9 also uses a different colorbar.

To the second point, our study has a strong synthesizing focus and brings together three mechanisms which were so far mostly discussed in isolation in previous work. What is particularly new in this perspective is that it links the previously noted regional shift in the latitudinal position of the jet to the global zonally symmetric shift of the jet. The baroclinic and barotropic Rossby wave response has been demonstrated in previous work. In contrast, the zonally symmetric latitudinal shift of the jet has been suggested (e.g., Barlow et al., 2016, section 4c) but remained rather elusive and is now clearly shown in our study, including its relationship with anomalous Rossby wave breaking occurrences. That said, we realize that some elements in our Figure 14 (Fig. 13 in the revised manuscript) resemble Fig. 9 from Barlow et al (2016). We rectify this by acknowledging this explicitly in the caption of the figure and adding this sentence:

"This depiction is inspired by Fig. 9 from Barlow et al. (2016), showing mechanisms (2) and (3) for La Niña conditions."

On a similar note, we have added references to the text in Section 6 to better acknowledge previously identified and discussed mechanisms (please, see the revised manuscript with tracked changes).

3. It seems to me that it is still not clear which mechanisms are the most important. Regionally, there are changes to vertical velocity, moisture availability, stability, and storm tracks, and they are being influenced by at least two external influences: the remotely generated baroclinic and barotropic Rossby waves. This is further complicated by the fact that changes due to any one factor will also influence the others (e.g., externally-forced subsidence reduces precipitation and storm strength, which then causes less moisture to be pulled in, and so influences moisture transport). I think this complexity might be good to discuss in the summary section.

We agree that the mechanisms, their interactions, and respective contributions are very complex and hard to disentangle. Addressing these aspects is well beyond the scope of our study and would, for example, require model experiments. Moreover, it is likely that the relative contributions of the three mechanisms vary across ENSO phases and seasons, given the varying precipitation response to different ENSO phases and months. We add the following text to the second-to-last paragraph of the conclusions, recognizing the complexity of the respective contributions from these mechanisms, and pointing to model experiments which may help solve this question:

"While our analysis brings together various mechanisms through which tropical Pacific SST forcing modulates precipitation variability over the Middle East, future research may further quantify the relative importance of these mechanisms, for example, based on numerical model experiments. Based on our findings, we anticipate that the relative importance of these mechanisms may vary across ENSO phases and seasons."

Other comments

1. Previous work has suggested that the type or "flavor" of ENSO event is important (e.g., central vs. eastern, temperature or temperature gradient in the western Pacific, link to Indian Ocean SSTs, etc.). How does that relate to the current work?

We are aware of previous work exploring how different ENSO flavors and SST patterns may bring about different Middle Eastern precipitation responses from the canonical ENSO phases. We consider these aspects to be beyond the goal of our study but recognize that not accounting for these aspects is a potential limitation of our study, which should be kept in mind when interpreting the results. To acknowledge this, we add this point to the list of limitations of our study in the concluding paragraph of the conclusions:

"Third, our analysis does not account for the influence of different ENSO flavors, such as variations in west-central Pacific SST gradients or the eastward extent of Pacific SST anomalies into the eastern Indian Ocean (Hoell et al., 2013a, 2014b, 2017, 2018), which may modify the Middle Eastern precipitation response. Fourth, …"

2. The region considered here is broader than most definitions of the "Middle East," and extends into areas variously referred to as Southwest or Central Asia in prior work. While I'm not aware of general agreement on terminology, it's probably worth commenting on this in the introduction, to reduce the chance of confusion.

We agree that terminology for the study region is arbitrary. Several definitions exist for the Middle East, including the countries from Egypt to Iran (from west to east) and Oman-Yemen to Turkey (from south to north) to covering a wider region from northwest Africa into Central Asia. Indeed, our study region extends into Southwest Asia. While this term may be politically more correct (the term “Middle East” has some origin from colonial times), we still opt for using Middle East as this may be the most commonly used and well-known term corresponding to our defined region of interest, which is entirely based on objective hydroclimatic conditions. We comment on the terminology to give some clarity, and add the following sentences to the 2nd paragraph of section 2.2 where the definition of the study region is defined:

“Note that our region of interest extends somewhat beyond the area typically defined as the Middle East and covers a substantial portion of Southwest Asia. Nevertheless, following common practice, we use the term Middle East throughout this study when referring to the region of interest.”

3. The Gill-Matsuno response, on its own, does not appear sufficient to produce a baroclinic Rossby wave that extends into the region; rather, it appears necessary to also include the effect of the mean zonal wind. Aspects of this are explored in a simple model in Barlow (2012), in a linear baroclinic model in Barlow et al. (2002), and in a GCM in Barlow et al. (2007).

We complement the text on this aspect by adding a phrase to the relevant sentence in section 6:

“The Gill-Matsuno response explains that anomalous tropical heating (cooling) leads to a Rossby wave response, interacting with the mean flow, in the form of an upper-tropospheric anticyclonic (cyclonic) circulation anomaly to the northwest and southwest, accompanied by a lower-tropospheric cyclonic (anticyclonic) circulation anomaly …”.

We also wish to refer to the added text, as discussed under the response to major comment 2 above, which also provides further details on this mechanism.

4. The notable change in ENSO influence over the course of the cold season for Iran is considered in Nuroozi et al. (2025), in the context of moisture transport, which may be of interest to the authors.

We thank the reviewer for pointing to this study. We added this reference along with those of other studies, acknowledging previous work addressing the intraseasonal variability of the ENSO influence on Middle Eastern precipitation (the last sentence of the 3rd paragraph of the introduction).

Regards,

Mathew Barlow

References

Barlow, M., H. Cullen, and B. Lyon, 2002: Drought in Central and Southwest Asia: La Niña, the Warm Pool, and Indian Ocean Precipitation. *J. Climate*, **15**, 697–700, https://doi.org/10.1175/1520-0442(2002)015<0697:DICASA>2.0.CO;2.

Barlow, M., Hoell, A. and Colby, F., 2007: Examining the wintertime response to tropical convection over the Indian Ocean by modifying convective heating in a full atmospheric model. *Geophysical research letters*, *34*(19).

Barlow, M., 2012: Africa and West Asia. In: Intraseasonal Variability in the Atmosphere-Ocean Climate System. Springer Praxis Books. Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-642-13914-7_13

Barlow, M., B. Zaitchik, S. Paz, E. Black, J. Evans, and A. Hoell, 2016: A Review of Drought in the Middle East and Southwest Asia. *J. Climate*, **29**, 8547–8574, https://doi.org/10.1175/JCLI-D-13-00692.1.

Hoell, A., M. Barlow, and R. Saini, 2012: The Leading Pattern of Intraseasonal and Interannual Indian Ocean Precipitation Variability and Its Relationship with Asian Circulation during the Boreal Cold Season. *J. Climate*, **25**, 7509–7526, https://doi.org/10.1175/JCLI-D-11-00572.1.

Nuroozi, H., Shirvani, A., & Barlow, M., 2025: The relationship between moisture in the low level of the troposphere and seasonal precipitation over Iran. Meteorological Applications, 32(2), e70033. https://doi.org/10.1002/met.70033

References

Barlow, M., Wheeler, M., Lyon, B., and Cullen, H.: Modulation of daily precipitation over southwest Asia by the Madden-Julian Oscillation, Mon. Weath, Rev., 3579-3594, https://doi.org/10.1175/MWR3026.1, 2005.

Barlow, M., Hoell, A., and Colby, F.: Examining the wintertime response to tropical convection over the Indian Ocean by modifying convective heating in a full atmospheric model, Geophys. Res. Lett, 34, L19702, https://doi.org/10.1029/2007GL030043, 2007.

de Vries, A. J., Feldstein, S. B., Riemer, M., Tyrlis, E., Sprenger, M., Baumgart, M., Fnais, M., and Lelieveld, J.: Dynamics of tropical-extratropical interactions and extreme precipitation events in Saudi Arabia in autumn, winter and spring, Q. J. Roy. Meteor. Soc., 142, 1862–1880, https://doi.org/10.1002/qj.2781, 2016.

de Vries, A. J., Ouwersloot, H. G., Feldstein, S. B., Riemer, M., El Kenawy, A. M., McCabe, M. F., and Lelieveld, J.: Identification of tropical-extratropical interactions and extreme precipitation events in the Middle East based on potential vorticity and moisture transport, J. Geophys. Res.-Atmos., 123, 861–881, https://doi.org/10.1002/2017JD027587, 2018.

de Vries, A. J., Feldstein, S. B., Fragkoulidis, G., P. Yadav, Y., and Domeisen D.: The influence of the Madden-Julian Oscillation and extratropical Rossby wave dynamics on (multi)day precipitation variability in the arid Middle East during the wet season. *In preparation for WCD.*

Francis, D., Fonseca, R., Nelli, N., Cherif, C., Yarragunta, Y., Zittis, G., and de Vries, A. J.: From cause to consequence: examining the historic April 2024 rainstorm in the United Arab Emirates through the lens of climate change, npj Clim.Atmos. Sci., 8, 183, https://www.nature.com/articles/s41612-025-01073-1, 2025.

Hoell, A., Funk, C.: The ENSO-related West Pacific Sea surface temperature gradient, J. Climate, 9545-9562, https://doi.org/10.1175/JCLI-D-12-00344.1, 2013a.

Hoell, A., Funk, C., and Barlow, M.: La Niña diversity and northwest Indian Ocean Rim teleconnections. Clim. Dynam., 43, 2707–2724, https://doi.org/10.1007/s00382-014-2083-y, 2014b.
Hoell, A., Barlow, M., Cannon, F., and Xu, T.: Oceanic origins of historical southwest Asia precipitation during the boreal cold season, J. Climate, 30, 2885–2903, https://doi.org/10.1175/JCLID-16-0519.1, 2017.

Hoell, A., Barlow, M., Xu, T., and Zhang, T.: Cold Season Southwest Asia Precipitation Sensitivity to El Niño–Southern Oscillation Events, J. Climate, 31, 4463–4482, https://doi.org/10.1175/JCLI-D-17-0456.1, 2018.

Kahana, R., Ziv, B., Enzel, Y., and Dayan, U.: Synoptic climatology of major floods in the Negev Desert, Israel, Int J. Climatol., 22, 867–882, https://doi.org/10.1002/joc.766, 2002.

Kumar, K. N., Ouarda, T. B. M. J., Sandeep, S., and Ajayamohan, R. S.: Wintertime precipitation variability over the Arabian Peninsula and its relationship with ENSO in the CAM4 simulations, Clim. Dyn., 47, 2443-2454, https://link.springer.com/article/10.1007/s00382-016-2973-2, 2016.

Rodwell, M. J. and Hoskins, B. J.: Monsoon and the dynamics of deserts. Quarterly Journal of the Royal Meteorological Society, 122, 1385–1404. https://doi.org/10.1002/qj.49712253408, 1996.

Rodwell, M. J. and Hoskins, B. J.: Subtropical anticyclones and summer monsoons, 14, 3192-3211, https://doi.org/10.1175/1520-0442(2001)014%3C3192:SAASM%3E2.0.CO;2, 2001.

Tuel, A., Choi, Y.-W., AlRukaibi, D., Eltahir, E. A. B.: Extreme storms in Southwest Asia (Northern Arabian Peninsula) under current and future climate, Clim. Dyn., 58, 1509-1524, https://link.springer.com/article/10.1007/s00382-021-05975-7, 2022.

RC2

General Remarks:
The article presents a careful and comprehensive analysis of the effects of ENSO on Middle Eastern precipitation, as well as the underlying mechanisms within. The region of interest and atmospheric diagnostics are chosen and presented with clear reasoning, and objective, straightforward criteria. After a spatial and temporal analysis of the precipitation signal during ENSO years, the authors investigate various dynamical and thermodynamical mechanisms that might explain the ENSO-precipitation relationship.

While ENSO's influence over the Middle East region has been a topic of academic discussion over several decades (as detailed by the authors), this article provides an important perspective by demonstrating and tying together three leading mechanisms, and exploring their overall relevance for a signal covering a large and varied domain. Global patterns are analyzed explicitly and given clear theoretical context, all of which provides an insightful and robust explanation for the ENSO-Middle East link.

Aside from several clarifying questions and minor comments, I will present one conceptual issue that should be better addressed before publication. Dynamically speaking, the analysis describes very clean, nearly symmetrical drivers for positive and negative precipitation anomalies: equatorward/poleward jet positions, antiphase difference in barotropic Rossby waves, cyclonic/anticyclonic Gill-Matsuno like response.

We thank the reviewer very much for the positive feedback and for recognizing and acknowledging the merit of the study. Below, we respond to the comments and indicate the implemented revisions in the manuscript.

However, while the authors do describe the precipitation response is "asymmetric", one could argue that the El Nino phase has hardly a consistent effect, except for a specific 20-year period (~1980-2000). Evidence for this is especially notable in Fig. 2: relative to La Nina-driven drying, positive rain anomalies are considerably weaker and occupy a smaller part of the domain. Additionally, several counter-examples are found in the second half of the time series (4-5 negative/near-zero anomalies for 8 El Nino years). Finally, the Nino3.4-precipitation regression is very similar when comparing neutral and positive ENSO values. How do the authors explain this apparent difference? Does the El Nino rain response manifest as localized-yet-extreme anomalies? Is it a handful of outlier rainy years that dominate the composite response? Is it a more autumn-centered phenomenon that is smoothed out when analyzing the entire cold season? If I'm following the article's logic correctly, I can say that it shows a robust mechanism for La Nina-driven drying, while highlighting how the inverse El Nino conditions are not sufficient for consistently generating positive rain anomalies. For further discussion of this point, see below.

We agree that the El Niño wetting effect is weaker than the La Niña drying effect. However, the results do show a clear and substantial wetting during El Nino, so our results do not support the suggestion of "hardly a consistent effect". Specifically, in response to the arguments and questions above: (1) while the significant negative anomalies under La Niña dominate a large part of the domain, significant positive anomalies do also emerge under El Niño conditions (see hatching in Fig. 2a), with values larger than 10% over a large part of the domain, regionally larger than 20% above climatology, and locally (over the southern Arabian Peninsula) larger than 50% (Fig. 2a); (2) while the El Niño wetting may appear to dominate in the early two decades and to reduce during the last two decades, please, note that the two last decades were drier in general. In other words, when considering the El Nino anomalies during the last two decades with respect to the precipitation climatology of the last two decades, these anomalies will become larger, that is, less negative or more positive. Please, see also our more detailed response to this point to the first major comment below. (3) the regression was done only for two domains, that is, Nino3.4 positive and negative values. For more clarity, we have now updated the figure and computed the slope, p-value, and correlation for a range of Nino3.4 index values for El Niño, neutral, and La Niña phases, showing a slope of 25.5 and 9.1 mm, a p-value of 0.11 and 0.41, and a correlation of 0.44 and 0.24 for Nino3.4 index values below -0.5 and above 0.5, respectively (see Fig. 2 in the revised version of the manuscript, also added below as Fig R3). Please also note that the slope (change in precipitation per degree SST anomaly in the central Pacific) is not the same as looking at actual precipitation anomalies during different ENSO phases. (4) Our analysis does not show any indication that the El Niño response is linked to localized extreme anomalies given that our study focuses on precipitation amounts and not extremes (although this could indeed be the case given that the El Niño effect is strongest in autumn and late spring when extreme precipitation tends to have a more localized and convective character than in winter). (5) we have no reason to believe that the El Niño wetting effect results from a few outliers. In that case, the precipitation anomalies in Figures 2 and 3 would not be significant. Moreover, Hoell et al. (2018) showed, based on a large ensemble climate model simulation, that 50% of El Niño events were linked to wet Middle East (Southwestern Asia) conditions, but 20-30% of El Niño events with dry conditions. In other words, these model experiments suggest that most, but not all El Niño events lead to wet conditions. Our results are consistent with these model-based findings. (6) indeed, the El Niño wetting effect clearly dominates in autumn, but is also apparent – though mostly non-significant – in spring (Figs. 3 and A1).

To acknowledge more clearly that decadal variability can modify the relationship between ENSO and Middle Eastern precipitation, we conclude the summarizing paragraph of section 3 by adding the sentence:

"Note that the influence of ENSO on Middle Eastern precipitation variability is susceptible to decadal variability, and thus does not ensure a similar relationship before and after our period of consideration nor a stationary relationship during our period of consideration (1979-2020)."

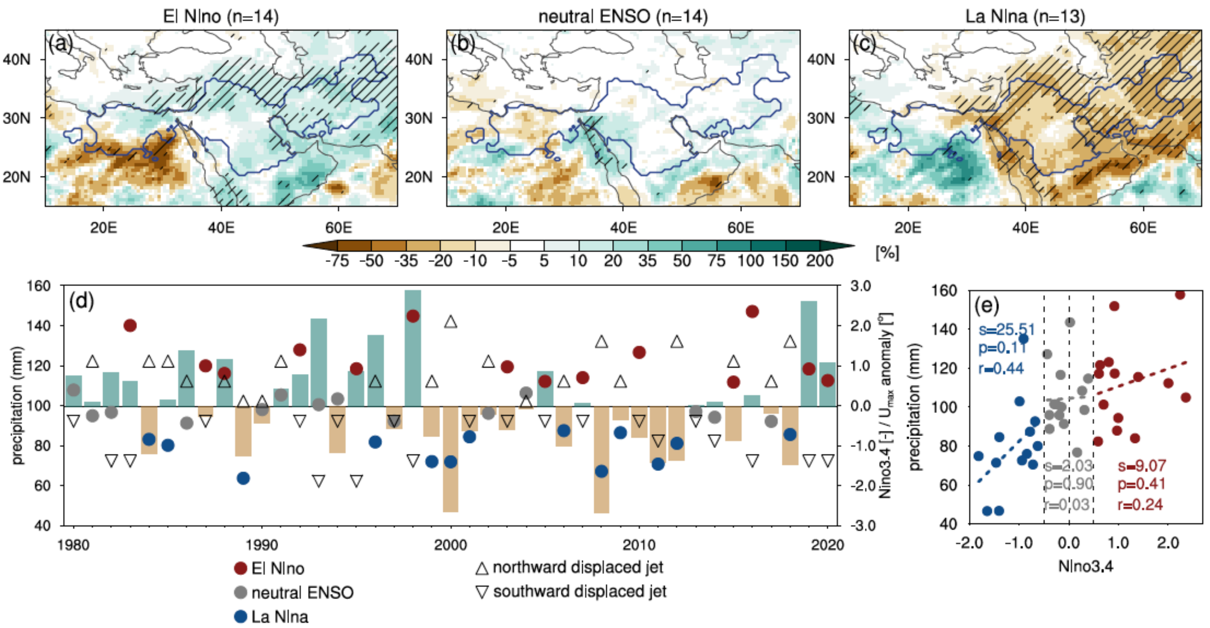

Fig. R3. As Fig.2 from the original manuscript, but now with regression analysis in panel (e) for Nino3.4 index values corresponding to all the ENSO phases.

Major Comments:

1. Fig 2(d-e): based on both subplots, it seems that the dry La Nina is consistent and robust. As you mention, there are only two instances where Nino3.4 is significantly negative and precipitation anomaly is non-negative. When comparing this signal to El Nino years, you write that "the relationship between cool-season precipitation and ENSO exhibits substantial asymmetry" and cite decadal effects and SST driven counter-examples.

However, I would argue that from 2000 onward, the El Nino-positive rain anomaly signal seems close to random. Of the 8 El Nino years, 3 have negative anomalies, 2 have weak positive anomalies and only 3 have notable positive precipitation anomalies. The time dependence of this connection was previously studied for a local test case in Price et al (1998): they use a longer time series from 1930 to investigate ENSO related rain anomalies in Israel, and note that no significant correlation can be found up until the 1980s.

We agree that several studies have noted that the linkage between ENSO and Middle Eastern precipitation is not stationary, but subject to decadal variability. To shed light onto the El Niño signal before and after 2000, we have reproduced Figure 2, but then for the period of 1979 to 1998 and 2020 to 2020 where precipitation anomalies are computed relative to climatology for these two respective periods (Figs. R4 and R5). We note that (1) El Niño signals for the period of 1979 to 1999 and 2020 to 2020 demonstrate mostly positive precipitation anomalies within the region of interest of similar magnitude (Fig. R4a, R5a). Please, note that reduced significance signal for both periods may result from reduced sample size. (2) from the 8 El Niño seasons during the last two decades, 3 have weakly negative and 5 have weak to substantial positive anomalies (Fig. R5d). To clarity our point here, please, note that the mean precipitation for the period of 2000-2020 is about 90 mm per year (compared to 100 mm per year for the entire period of 1979-2020), as indicated by the horizontal black line, and thus, the green bars become larger and the brownish bars smaller compared to Fig. 2d. (3) while the slope and correlation between the Nino3.4 index and precipitation anomalies is rather similar for both El Niño and La Niña phases for the period of 1979-1999 (Fig. R4e), they are rather different for the period of 2000-2020, with an increased slope and correlation for La Niña and a near-zero slope and correlation for El Niño (Fig. R5e). While this indeed consistent with the reviewer's suggestion that the relevance of El Niño wetting since the 2000s is reduced (Fig. R5e), we emphasize that precipitation anomalies themselves are positive under El Niño conditions throughout most of the study region (Fig. R5a). We feel that further discussing these aspects based on the two-decade periods is beyond the scope of the current study and that these specific numbers are also subject to limited sample size.

For completeness, we now include Price et al. (1998) when referring to multidecadal variability in the ENSO- Middle Eastern precipitation relationship, that is, in the 3rd paragraph of the introduction and in the last paragraph of the conclusions.

We also add the following text to the second-to-last paragraph of section 3 to acknowledge the varying relationship of Middle Eastern precipitation to El Niño and La Niña conditions during the first two and the last two decades of the study period.

"Note that these numbers are sensitive to the period under consideration. When repeating these computations for the two first and the two last decades of the study period, the slope and correlation are similar for El Niño and La Niña conditions during 1979-1999 but rather different between both ENSO phases during 2000-2020 with a strengthened slope and correlation for La Niña conditions and a near-zero slope and correlation for El Niño conditions (not shown)."

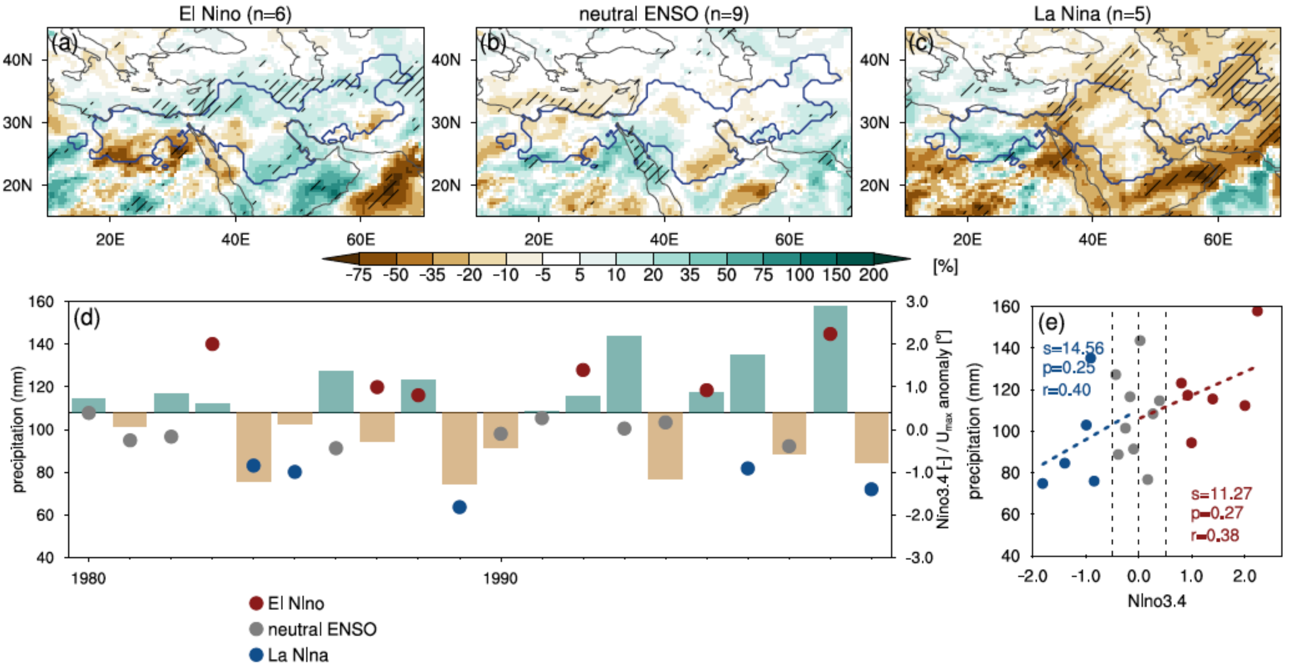

Fig. R4. As Fig. 2 from the original manuscript, but now for the period of 1979 to 1999 only, based on the precipitation climatology of 1979-19999.

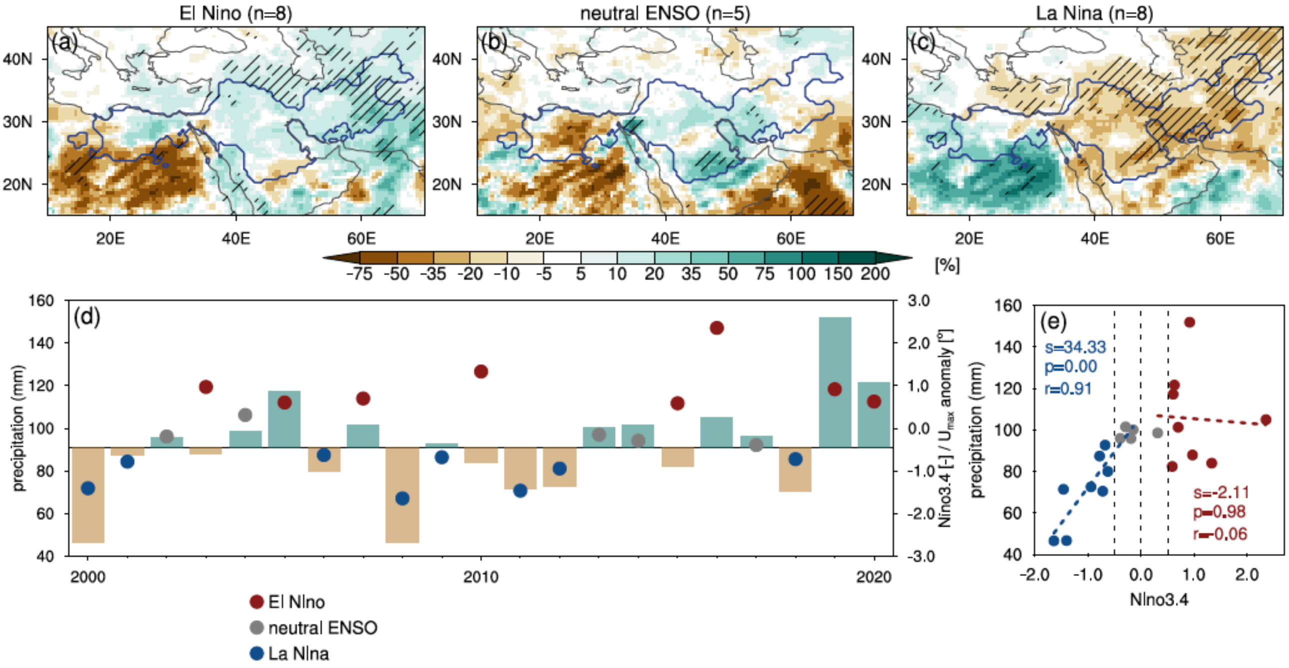

Fig. R5. As Fig. 2 from the original manuscript, but now for the period of 2000 to 2020 only, based on the precipitation climatology of 2000-2020.

2. Another aspect to consider in the El Nino-positive rain relationship is that the absolute amounts are small. Figure 3 shows that the rain enhancing effect is strongest in OCT and MAY. These are months where mean total amounts reach ~3-5 mm per month. So if that amount is doubled during El Nino years, what are we to learn from this? Is there a possibility, for example, that this could be one additional rain producing system that bumped the overall average?

No, the information in Figure 3 shows that the one-and-a-half to two-times larger precipitation amounts in October, November, and May during El Niño conditions compared to neutral ENSO conditions are *not* resulting from only one or a few events. Please refer to the distribution expressed by the boxes and whiskers, indicating that the 25th, 50th (median), and 75th percentiles of precipitation during El Nino events are substantially and consistently larger than those of neutral ENSO conditions. In other words, the distribution of spatially aggregated precipitation amounts for the different ENSO phases, including El Niño, supports a robust influence of ENSO on Middle Eastern precipitation. We add the following sentence clarifying this in the manuscript:

"Note that the precipitation increase under El Niño conditions is not only apparent from the mean, but also from the precipitation distribution in general, showing substantial increases for the 25th, 50th, and 75th percentiles (Fig. 3a)."

We agree that the absolute rainfall amounts in October and May are small, but the same signals are observed in November (Fig. 3a) and in the cool-season average anomalies (Fig. 2a), showing that the El Niño – positive precipitation anomaly is substantial and robust.

3. A separate but related issue is spatial heterogeneity. The effect seems to be concentrated over a specific area within your chosen domain: the "fertile crescent" (Jordan, Syria, Iraq), parts of Iran, and Central Asian countries like Turkmenistan or Afghanistan. Meanwhile, the Arabian peninsula and North Africa show no statistically significant signal, while occupying roughly 50% of the domain. Do you have intuition as to why? Also, is there a possibility that including these large no-signal areas in the analysis weakens your overall result?

We agree that the signal has some spatial heterogeneity, which is the case for both El Niño and La Niña phases. We emphasize that most of the precipitation signal over the Arabian Peninsula during both ENSO phases is consistent with the general signal found in the domain (precipitation increase for El Niño and decrease for La Niña), even if the signal is not significant everywhere (Fig. 2a-c). Please, note that significant positive precipitation anomalies do emerge over the northeastern, southeastern, and southwestern portions of the Arabian Peninsula for El Niño (Fig.2a). Regarding northeastern Africa, we argue that this region does not affect the analysis much since absolute rainfall amounts here are extremely low (upper Egypt is one of the driest regions on Earth; Fig. 1c), and thus have a very small effect on the spatially aggregated values only. We keep this area as a part of our study region, consistent with the objective hydroclimatic criteria to define the target region (please see section 2.2).

Minor Comments, Typos:

1. Pg. 5, line 155: Should be 10-45N instead of 10-45E.

Thank you for spotting this error, it is corrected.

2. Pg. 6, line 171: Please note the sample size in this section as well. How many rainy and dry events were included in each subset?

We added the number of daily precipitation events (n=377) and dry-day events (n=394) in the text.

3. Pg. 7, eq. 2: Consider changing the subscript notation for the layers. The "max" notation alludes to maximum pressure and/or h, which is confusing for the reader.

We agree with the comment and change p_{max} to p_{top}.

4. Pg. 8 line 233-234: How do you explain the Red Sea precipitation anomaly during neutral ENSO? This is interesting as it seems larger (albeit more local) than most positive/negative phase precipitation anomalies.

We do not have a clear explanation for the positive precipitation anomalies over the northern part of the Red Sea region during neutral ENSO. We also note that the anomalies – exceeding 35% from climatology – are in the same range as the positive anomalies during El Niño (reaching even over 50% in the southern Arabian Peninsula) and during La Nina (falling below -35% from climatology over the northern Red Sea and southern Arabian Peninsula).

5. Fig. 2: (1) The text mentions anomalies between -35% to +20%, however the colorbar spans from -70% to 200%. Or is it showing mm? Please clarify. (2) The caption mentions a 1000 -sample Monte Carlo test, while the methods section says 10000 samples (line 179).

Regarding the first point, the figure indeed shows relative anomalies (in %), not absolute anomalies. We chose this rather large range of values to facilitate a direct comparison to the anomalies on a monthly basis (Figure A1). To the second point, thank you for spotting this. The initial analysis was based on 1,000 samples, but the final analysis, shown in the study, was based on 10,000 samples. We correct the error in the caption. Please note that the analysis based on daily precipitation and dry-day events, shown in Fig. 4, is based on 1,000 sample sizes, now clearly indicated in the caption of that figure.

6. Pg. 11, line 349-351: "The similarity between the ENSO-based composites and those based on precipitation and dry-day events suggests that El Nino and La Nina events induce wet and dry conditions, respectively, through latitudinal shifts in the jet stream accompanied by anomalies in Rossby wave breaking frequencies." You can check this directly. How many of your 377 precipitation events fall within the 14 El Nino years? (and same for the 394 dry events and 13 La Nina years)

Of course, we could evaluate how many of the precipitation and dry-day events fall within El Niño or La Niña seasons / conditions, but that would most likely show very similar result to that already shown in Figs 2 and 3. The point of this paragraph (and Figure 4) is to provide a process-based understanding of how tropical Pacific SST forcing (ENSO) brings about precipitation anomalies over the Middle East. For that purpose, we construct composites of the atmospheric circulation based on precipitation and dry-day events on daily timescales, showing circulation patterns leading to wet and dry conditions. This framework helps to provide a reference for interpreting signals in the circulation during El Niño and La Niña phases.

7. In Section 4 you present a compelling argument for the role of the subtropical jet position and wave breaking. Does the eddy driven midlatitude jet play any part in this interaction? The purple/green contours over Western Europe in figs 5a,c might support this. Also, note the interesting zonal wave structure arising in fig 4a between 30-60N. Previous works (Raveh-Rubin & Flaounas 2017; Sandler et al., 2024) show that equatorward polar jet undulations affect precipitation specifically in the Eastern Mediterranean. Another possible direction could be merged jet regimes (Harnik et al., 2014; Suresan et al., 2025) which can lead to extreme precipitation anomalies worldwide.

Indeed, the eddy-driven jet can be expected to play an important role. Specifically, we discuss these signals as equatorward and eastward propagating Rossby waves, which play a key role in precipitation formation over the Middle East on (multi)day timescales. This aspect is further detailed in another manuscript on precipitation variability on (multi)day timescales, currently in preparation (De Vries et al., 2026b). On monthly timescales, the signatures of the eddy-driven jet (or rather, undulations in the jet, manifesting as Rossby waves) emerge primarily as cyclonic and anticyclonic barotropic Rossby wave patterns, which have been discussed in detail in the manuscript, corresponding to mechanism number (2) in section 6 and Figure 14 (Figure 13 of the revised manuscript).

8. Pg. 12, line 377: "show a significant increase under El Niño conditions during October ($p < 0.05$), November ($p < 0.1$), and May ($p < 0.05$); Fig. 8a". Is the reference to the figure a typo? Or should it be in parantheses?

The reference to Fig. 8a is correct. We remove the semicolon and add brackets for more clarity:

"show a significant increase under El Niño conditions during October ($p < 0.05$), November ($p < 0.1$), and May ($p < 0.05$) (Fig. 8a)."

9. Figure 9: I suggest changing the color scale. Throughout the text you use red-brown to blue for El Nino/La Nina and dry/wet anomalies. This can create confusion for understanding Imax.

We agree with the comment and replace the colorbar by one with orange-purple colors, which has not been used for other variables in the study, avoiding confusion.

10. Pg. 16, lines 496-498: "Similarly, El Niño conditions coincided with several devastating floods during autumn in 1987, 1994, 1997, 2009, 2015, and 2018..." It makes sense to mention droughts as region-spanning phenomena, but it might be worth specifying where these El Nino-enhanced floods occured within the Middle East. Does it fit your spatial composites in Fig. 2?

Thank you for this comment. The locations and timing of these floods match mostly with the El Nino precipitation signals found in Fig. A1. Specifically, the autumn floods of 1987, 1994, and 1997 occurred in the Levant and Fertile Crescent, where precipitation is significantly increased under El Niño conditions (Fig. A1a,d). Likewise, the spring floods in the United Arab Emirates in April 2024 correspond with the strong and significant precipitation increase over this region in spring (Fig. A1s). However, the autumn flooding of November 2009, 2015, and 2018 in the Jeddah region and of May 1982 in the Levant do not align with the precipitation response under El Nino in these regions and seasons. Therefore, we correct the text as follows:

"Similarly, El Niño conditions coincided with several devastating floods in the Levant in autumn of 1987, 1994, and 1997 and in the United Arab Emirates in spring 2024 (Krichak et al., 2012; De Vries et al., 2013; Kadhum et al., 2022; Francis et al., 2025; Hussein et al., 2025), corresponding to regions and seasons with increased precipitation under El Niño conditions (Fig. A1)."

References

Dasari, H. P., Desamsetti, S., Langodan, S., Attada, R., Ashok, K., and Hoteit, I.: Long-term changes in the Arabian Peninsula rainfall and their relationship with the ENSO signals in the tropical Indo-Pacific, Clim. Dyn., 59, 1715-1731, https://link.springer.com/article/10.1007/s00382-021-06062-7, 2021.

de Vries, A. J., Tyrlis, E., Edry, D., Krichak, S. O., Steil, B., and Lelieveld, J.: Extreme precipitation events in the Middle East: Dynamics of the Active Red Sea Trough, J. Geophys. Res.-Atmos., 118, 7087–7108, https://doi.org/10.1002/jgrd.50569, 2013.

de Vries, A. J., Feldstein, S. B., Fragkoulidis, G., P. Yadav, Y., and Domeisen D.: The influence of the Madden-Julian Oscillation and extratropical Rossby wave dynamics on (multi)day precipitation variability in the arid Middle East during the wet season. *In preparation for WCD.*

Francis, D., Fonseca, R., Nelli, N., Cherif, C., Yarragunta, Y., Zittis, G., and de Vries, A. J.: From cause to consequence: examining the historic April 2024 rainstorm in the United Arab Emirates through the lens of climate change, npj Clim.Atmos. Sci., 8, 183, https://www.nature.com/articles/s41612-025-01073-1, 2025.

Hoell, A., Funk, C.: The ENSO-related West Pacific Sea surface temperature gradient, J. Climate, 9545-9562, https://doi.org/10.1175/JCLI-D-12-00344.1, 2013a.

Hoell, A., Funk, C., and Barlow, M.: La Niña diversity and northwest Indian Ocean Rim teleconnections. Clim. Dynam., 43, 2707–2724, https://doi.org/10.1007/s00382-014-2083-y, 2014b.

Hoell, A., Barlow, M., Cannon, F., and Xu, T.: Oceanic origins of historical southwest Asia precipitation during the boreal cold season, J. Climate, 30, 2885–2903, https://doi.org/10.1175/JCLID-16-0519.1, 2017.

Hoell, A., Barlow, M., Xu, T., and Zhang, T.: Cold Season Southwest Asia Precipitation Sensitivity to El Niño–Southern Oscillation Events, J. Climate, 31, 4463–4482, https://doi.org/10.1175/JCLI-D-17-0456.1, 2018.

Hussein, K., Alhosani, N., Al-Areeq, A. M., Aghbari, A. A., Elkamali, M., Alsumaiti, T. Sharif, H. O., Almurshidi, A. M. G., and Abdalati, W.: Unprecedented rainfall in the United Arab Emirates: hydrologic and flood impact analysis of the April 2024 event, 121,9363-9385, https://link.springer.com/article/10.1007/s11069-025-07156-9, 2025.

Kadhum, J. H., Al-Zuhairi, M. F., Hashim, A. A.: Synoptic and dynamic analysis of few extreme rainfall events in Iraq, 8, 4939-4952, https://link.springer.com/article/10.1007/s40808-022-01419-1, 2022.

Kahana, R., Ziv, B., Enzel, Y., and Dayan, U.: Synoptic climatology of major floods in the Negev Desert, Israel, Int J. Climatol., 22, 867–882, https://doi.org/10.1002/joc.766, 2002.

Kang, I.-S., Rashid, I. U., Kucharski, F., Almazroui, M., Alkhalaf, A. K.: Multidecadal changes in the relationship between ENSO and wet-season precipitation in the Arabian Peninsula, J. Climate, 28, 4743-4752, https://doi.org/10.1175/JCLI-D-14-00388.1, 2015.

Krichak, S. O., Breitgand, J. S., and Feldstein, S. B.: A conceptual model for the identification of the Active Red Sea Trough Synoptic events over the southeastern Mediterranean, J. Appl. Meteor. Climatol., 51, 962–971. https://doi.org/10.1175/JAMC-D-11-0223.1, 2012.

Price, C., Stone, L., Huppert, A., Rajagopalan, B., and Alpert, P.: A possible link between El Nino and precipitation in Israel, Geophys. Res. Lett., 25, 3963–3966, https://doi.org/10.1029/1998GL900098, 1998.