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Precipitation extremes in Ukraine from 1979 to 2019: Climatology, large-scale flow conditions, and moisture sources

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Final author comments

We thank all three reviewers for their thoughtful and constructive comments that help us to improve the manuscript. Based on the reviewers' suggestions, we implement several changes in the manuscript. The main changes are that:

- We add a new figure to show more insight into the EPEs in summer (in response to suggestion by reviewer #3).
- We further clarify the data availability (in response to comment by reviewer #3).
- We add more discussion about the moisture source composites in comparison to those for upper-level PV (in response to comment by reviewer #2).
- We better motivate the choice of the 100 mm per day threshold to identify EPEs (in response to comment by reviewers #1 and 2).

Below we provide a one-to-one response to all points raised by the reviewers. The reviewers' comments are in red and our replies in black.

Reviewer #3

Overall, I found this manuscript to be clear, concise, and well-written. The study provides a novel climatological investigation of extreme precipitation events (EPEs) in Ukraine, documenting the synoptic-scale conditions in which these events occur and quantifying the moisture sources using a Lagrangian trajectory-based diagnostic. The findings help to address a gap in scientific understanding regarding EPEs in Ukraine.

While the paper is strong overall, I have a number of comments for the authors to consider. Once these comments are satisfactorily addressed, the manuscript may be acceptable for publication.

We express our sincere gratitude to Reviewer #3 for their comprehensive analysis of our work and for providing valuable comments and suggestions for our paper. We are confident that integrating solutions to these specific questions into the revised version of our manuscript will significantly improve its overall quality.

Major comments

In my opinion, the manuscript is lacking in diagnostic analysis of the ingredients and processes resulting in extreme precipitation. Composite analyses and case studies are presented, and the circulation patterns are discussed, but it is still not entirely clear to me how the ingredients for heavy precipitation are established and maintained for these events. Are these events characterized by, for example, particularly anomalous moisture content or strong ascent? Do the key flow features tend to be particularly slow-moving? The study could be strengthened in this regard by inclusion of additional statistical/composite/case study analyses of key ingredients, such as dynamical forcing for ascent (e.g., quasi-geostrophic forcing or frontogenesis), moisture content/moisture flux, and convective instability (e.g., convective available potential energy). Such analyses would help to elucidate how the circulation features shown in Figs. 3 and 4 are linked to the ingredients for heavy precipitation in Ukraine, thereby providing a more complete picture of the synoptic-scale characteristics of the EPEs. Precipitation composites based on the ERA5 could also help to show where in the region the precipitation tends to be focused for the different seasonal groups of EPEs, thereby providing helpful context when interpreting the composite patterns.

We agree with the reviewer that a more in-depth analysis is useful, and we added analyses of composites of total precipitation, TCW and CAPE for a more complete picture of the synoptic-scale characteristics of the EPEs in Ukraine to the Sect. 3.2. The figure below (Fig. R1; similar to Fig. 4) shows anomalies of the total precipitation, TCW and CAPE in physical units at 15 UTC for EPE days in summer. (However, to avoid overloading the paper with additional figures, we added similar figures to the Supplement for the other seasons). The figure shows anomalously high values of TCW and CAPE over the entire Ukraine on summer EPE days.

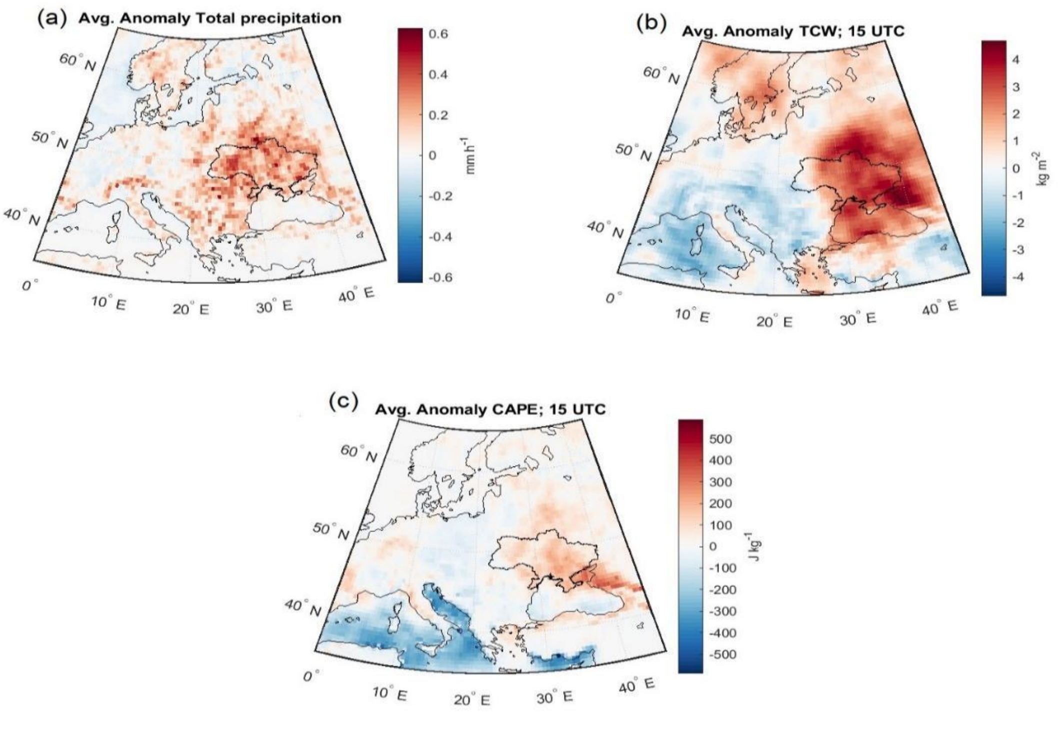

Fig. R1 Anomalies of total precipitation, TCW and CAPE at 15 UTC on EPE days in summer.

How was the 100 mm day^{-1} threshold selected, and how extreme is it for the various stations? I recommend quantifying where this threshold fits in the climatological distribution at each station. Would it be possible to identify EPEs as daily precipitation totals exceeding an upper percentile (e.g., 95th percentile) of the climatological distribution for each station instead of a fixed threshold?

See our response to minor comment 1 of reviewer #2. Note that with our choice of the threshold we identify less than 100 EPEs at about 200 stations over 40 years. Therefore, the corresponding percentile is much larger than the 95th percentile mentioned by the reviewer, indicating that this study focuses on extreme, i.e., very rare events.

There is redundancy in showing maps of both 500-hPa geopotential height and near-tropopause PV. Both fields depict qualitatively similar structures and patterns of the upper-level flow. Is it necessary to show both fields?

We agree that there is some redundancy between these fields, but as discussed in many studies about the usefulness of upper-level PV charts (e.g., Hoskins et al., 1985), the PV charts show more structural details that can be useful to understand the dynamics. So far, studies showing PV charts have not been conducted for the Ukrainian domain. On the other hand, the choice of the classical 500-hPa charts is motivated by the fact that it has been widely use in synoptic analyses. Thus, to show the similarities and differences of the two fields, we think that both fields are quite useful for our paper.

Minor comments

Line 82: Do all of the stations have the same record length? Are they all available for 1979–2019?

Thanks for this question, it's really worth covering this point in more detail.

For this study, 215 meteorological stations and posts (including aviation weather stations, gauging stations, etc.) with daily data from 1979 to 2019 are used. From this dataset, 183 stations were selected for our study due to having a complete set of data. The remaining 32 stations did not have the same record length for various reasons. Nevertheless, these stations were still tested for the presence of extreme precipitation events (EPE) ≥ 100 mm day^{-1}, and no such extreme events were recorded. Due to the absence of data in the Ukrainian meteorological network for certain regions of Crimea from February 2015 to December 2019, additional data were obtained using open-access observations for this region (SYNOP observational data). Unfortunately, data for four stations in the Donetsk and Lugansk regions for the period of 2015-2019 are not openly available. In this region, a 36-year dataset was employed to identify days with extreme precipitation (≥ 100 mm day^{-1}). We will add this more detailed explanation of the utilized dataset in the revised manuscript.

Line 88: It would be more accurate to state that the reanalysis data were interpolated to a 0.5° grid; the actual ERA5 model resolution is finer than 0.5°.

Yes, thanks.

Line 167: Is "intense" warranted here? What is the quantitative basis for this adjective in this context?

We agree with this suggestion. We now simply write “above a baroclinic zone”.

Comment on Figs. 3 and 4: I recommend the following changes to make these plots easier to read and interpret: (1) make the contours and arrows thicker, (2) make the outline of Ukraine thicker and perhaps plot it in a different color to make it more visible, (3) increase the font size for the lat/lon and color bar labels.

We thank the reviewer for pointing our attention to this matter. We have revised all figures and hope that the resolution is now improved.

Line 225: Is the PV anomaly pattern in the summer composite perhaps a reflection of the occurrence of PV cut-offs?

Yes, indeed, high-PV cutoffs over Eastern Europe repeatedly formed, locally changing the static stability, and thus providing the ideal mesoscale environment for the formation of EPEs and triggering cyclogenesis over Ukraine. Also note, that the Black Sea region is characterized by a local maximum in the frequency of PV cutoffs in all seasons (see Fig. 3 in Portmann et al., 2021). We add a brief discussion of this to the text.

Line 235: How much variability is there among the events in the composites with respect to the PV anomaly pattern? It might be worthwhile to also plot the composite standard deviation as a measure of the case-to-case variability.

We have plots for the standard deviation of PV for each season (Fig. R2). The standard deviation exhibits a seasonal variation, reaching its peak (approximately 1,7 SD) during winter and reaching a minimum of 0,7 SD in summer, in the main PV anomaly regions. We note, however, that these fields should be regarded with caution in all seasons except summer, because of the low number of events.

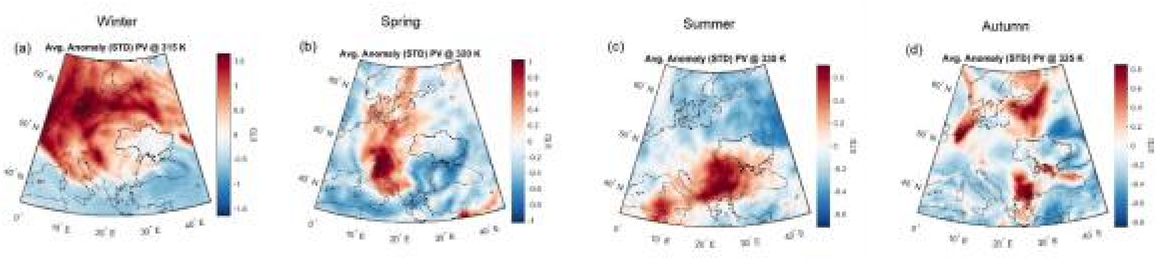

Fig. R2 Variability of PV anomalies during EPEs for the different seasons (in standard deviation units).

Line 238: It is not clear to me what the authors mean by "northward", “southward”, “eastward”, and "westward" here. Do these descriptions refer to the direction of the PV anomaly gradient vector?

Here we mean that in different seasons, the location of PV anomalies in relation to the region of Ukraine varies. In winter, the PV anomaly is situated north (northeast) of Ukraine, in spring it shifts to the west, in summer it moves to the south, and in autumn, it is positioned to the east.

Lines 239–240: I encourage the authors to include a discussion of the possible implications of the composite PV anomaly patterns for forcing of vertical motion over Ukraine. In my opinion, a more direct link needs to be established between the composite flow patterns and the processes that caused the extreme precipitation.

Yes, indeed, we have added the following: ”In each season, EPEs appear to be preconditioned largely by a moist southwestern flow at the eastern flank of the upper-level PV anomalies, which leads to dynamic lifting via positive vorticity advection, causing reduced tropospheric stability. Their localization corresponds to the seasonal location of PV anomalies.” (L.247-251).

Lines 405–406: When making statements for which direct evidence is not shown, I recommend including "(not shown).”

Added. Thanks!

Lines 463–465: “The exception were winter EPEs…” This conclusion seems inconsistent with the 500-hPa Z and PV anomaly composites for the winter EPEs, which appear to depict strong troughs immediately upstream of Ukraine.

Yes, this conclusion was made for two individual cases (28 December 1999 and 21 December 1993), where a relatively clear zonal upper tropospheric flow over Ukraine could be identified. In the case of 28 December 1999, a shallow short-wave disturbance in the westerly flow was observed. When comparing the composites of Z and PV anomalies with individual cases, we cannot expect to see an identical pattern of the distribution of meteorological parameters. This is because these composites represent maps for all winter cases, and they may not always perfectly coincide with specific synoptic events.

Typographical corrections

Line 229: I suggest removing "but not least" here.

Yes, agree.

Line 238: Change “consistently” to “consistent”

Changed. Thanks!

Line 285: Change “more important” to “greater”

Changed. Thanks!

Line 309: Remove “very”

Removed. Thanks!

References:

1. Tramblay, Y., Neppel, L., Carreau, J., and Najib, K., Non-stationary frequency analysis of heavy rainfall events in southern France: Hydrological Sciences Journal. 58 (2). 280–294. https://doi.org/10.1080/02626667.2012.754988, 2013.

2. Martin-Vide, J., Sanchez-Lorenzo, A., Lopez-Bustins, J. A., Cordobilla, M. J., Garcia-Manuel, A., and Raso, J. M.: Torrential rainfall in northeast of the Iberian Peninsula: synoptic patterns and WeMO influence, Adv. Sci. Res., 2, 99–105, https://doi.org/10.5194/asr-2-99-2008, 2008.

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