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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 #2

The authors present a study of precipitation extremes in recent decades focussed on Ukraine, based on reanalysis data. Combining dynamical parameters with diagnostic fields for precipitation origin, the authors document commonalities in the atmospheric state between extreme precipitation cases, but also show pronounced variability, in particular with regards to the precipitation sources. Similar information has been provided before for neighboring areas, but not in the region studied here. The paper has a logical structure, is overall well-written, and the figures are in general of good quality. I have a few, mostly minor comments with regard to how the analysis could be strengthened further. These remarks concern the methods, presentation of the results, and their relation to published literature. I hope that these comments will be helpful for the authors in their preparation of a revised manuscript.

We thank Reviewer #2 for the helpful comments and are glad to see the main messages of this manuscript are acknowledged and appreciated by the reviewer.

Minor comments

1. The selection of the extreme precipitation events could be better justified. For example, to which percentile does the 100 mm day^{-1} threshold correspond to in different regions of Ukraine? With a constant threshold value, it seems that some events could be more extreme in

some regions than in others. How sensitive are the results to this choice of threshold? This item is also connected to a better presentation of the climatological precipitation pattern in the study region (see below).

We agree that we should better motivate the choice of our threshold, and also, that alternative approaches of identifying extreme events (e.g., with a percentile threshold) could also be meaningful. We added the following: "Our threshold of 100 mm day^{-1}, exceeded on average once a year in the stations of the study area, is chosen from expert knowledge, as it is often used to define extreme precipitation events in different countries. For instance, Martin-Vide et al. (2008) used this threshold to determine EPEs in the western Mediterranean, and Tramblay et al. (2013) in southern France. Boissier and Vinet (2009) identified the value of 100 mm day^{-1} as a critical threshold that could trigger fatalities. Also in Ukraine, this threshold is used to identify an event as extreme.

In order to relate this threshold to a percentile we consider eight stations across different regions of Ukraine: two stations in the west: Chernovci and Yaremche; two in the central part: Nejin and Olevsk; two in the eastern part: Izum and Mariupol; and two stations in the south: Odessa and Ai-Petry. For all stations in mountainous areas, as well as in flat regions, the threshold of 100 mm day^{-1} corresponds to the 99.9th percentile or higher. These percentiles highlight that the selected threshold of $\geq$ 100 mm day^{-1} indeed selects extreme, i.e., very rare events." These events are so rare that we cannot robustly assess regional differences of percentiles (recall that in total we have only 75 events at all stations).

2. Figure 1 does not provide a lot of information. It could be more informative to instead show for example the seasonal precipitation total in a 4-panel figure, and place the events with their maximum precipitation as text labels on top of the background.

We appreciate the reviewer's comment; indeed, it would be interesting to show the seasonal precipitation total. However, on one hand, the seasonal and annual distribution of precipitation in Ukraine is well presented in the book "Climate of Ukraine" and other atlases (https://uhmi.org.ua/conf/climate_changes/presentation_pdf/plenary_session/Lipinskiy_et_al.pdf, see page 15). Climatological precipitation is largest in the west of Ukraine (annual total >1000 mm), and generally lower along the coast of the Black Sea (annual total <500 mm), except for again high values in the south of Crimea. On the other hand, Fig. 1 clearly shows the geographical features of the territory. If EPE data was superimposed on climatological precipitation maps, this visibility might be compromised. We therefore decided to leave Fig. 1 as is, but we will include a brief description of the precipitation climatology in Ukraine in the revised paper.

3. I find the results do nicely align with several other studies that have been done regarding the moisture sources of extreme precipitation in the Mediterranean and Central Europe, maybe also other regions, that are cited in the introduction. However, I found the discussion a bit brief, and more specific comparison could be done to the existing literature after presentation of the results. For example, the authors find, in agreement with above mentioned previous studies, that there is more structure/regularity in the upper-level circulation than in the moisture sources fields. Why is that so, and what does that imply? At least it could be stated as an overarching finding, and the question be raised, even if the authors do not want to speculate about possible reasons.

We thank Reviewer #2 for this suggestion, and we added the following discussion to Sect. 3.3 (Seasonal mean moisture sources): ”It is noteworthy, that there is less structure in the fields of moisture sources compared to the upper-level circulation. This may be due to the fact that the upper-level circulation is often governed by coherent flow features. For example, the presence of a strong jet stream or a well-defined upper-level trough. This implies their somewhat more consistent structure compared to the more variable moisture sources. Since by far most of the global water vapor is located in the lower troposphere, moisture source fields are influenced by factors like sea surface temperatures, local evaporation, soil moisture availability, moisture transport, and low-level winds. For example, Winschall et al., (2014) investigated the importance of intensified local and remote evaporation for Mediterranean precipitation extremes. Krug et al. (2022) determined that the evaporation anomalies are related to wind-speed anomalies indicating mainly dynamically driven evaporation. Grams et al. (2014) emphasized the significant role of soil moisture preconditioning. For instance, intense precipitation events can moisten the previously dry soil and might subsequently serve as moisture sources for subsequent extreme precipitation events (Bohlinger et al., 2017). This complex interaction between various preconditioning factors and the eventually emerging moisture source patterns should be investigated in more detail in future research.”

4. I did not find Table 1 so useful, at least not in this location in the paper. Maybe this table should rather be introduced along with the seasonal results? There is also a lot to read in this table, which seems almost like a duplication of the writing in the results section. Maybe the table could be simplified, or some kind of coding of different "event types" could be devised, such that the table provides more comparable information at a glance?

We appreciate the reviewer’s comment. Indeed, it is probable that this table would be better placed along with the seasonal results, because it summarizes all these findings. However, we have chosen not to shorten the content in the current version, because we think this table provides a clear and relatively complete overview of seasonal differences, taking into account quantitative changes in the presented parameters. But we (a) introduced some abbreviations for geographical definitions to shorten the text, (b) changed the term "positive PV anomaly" to PV+, and (c) added text in the caption to explain the table better. We hope that the revised version is clearer for the readers and the changes sufficient for the reviewer.

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