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The catastrophic floods in 2008, 2010 and 2020 in western Ukraine: Hydrometeorological processes and the role of upper-level dynamics

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Response to the reviews:

We thank the reviewers for their comments that help us to further improve the manuscript. Based on the reviewers' suggestions, we will implemented the following main changes:

- We better explain the value of considering upper-level PV structures
- We implement several structural changes to improve readability
- We improve several figures as suggested by the reviewers
- To better illustrate the large-scale flow evolution, we include a video supplements available online at:

https://doi.org/10.5446/73098 THE_2020 L.711
https://doi.org/10.5446/73097 THE_2010 L.712
https://doi.org/10.5446/73096 THE_2008 L.713
https://doi.org/10.5446/73095 PV_2020 L.714
https://doi.org/10.5446/73094 PV_2010 L.715
https://doi.org/10.5446/73093 PV_2008 L.716

We added: Synoptic charts focusing on the core period of the floods are presented in Figures 5, 8, 9, and 12, while the Video Supplement illustrates atmospheric processes associated with these events in a broader spatio-temporal context. L. 188-190.

Below we provide a one-to-one response to all points raised by the reviewers. The reviewers' comments are in black and our replies in blue. Line numbers refer to the originally submitted version of our paper.

Reviewer 1

Dear Authors,

the paper is overall well written and presents interesting insights into dynamic drivers of extreme precipitation. Please note, that while I have a general understanding of fluid dynamics and potential vorticity, I am not an expert on detailed potential vorticity dynamics, which is affecting the perspective from which the following comments stem from. I suggest to revise the paper as follows.

Many thanks for your positive overall assessment of our study and for your constructive suggestions!

GENERAL COMMENTS

The overall storyline is clear and well written, and the research questions are clearly stated. The paper is well structured, but I think it could benefit further from some slight restructuring in a few places and from enriching some paragraphs with more detailed information.

While PV structures for predicting floods is mentioned (e.g. line 65 in the introduction and line 640 in the conclusions) it is unclear in what way. Since extreme precipitation (in terms of the case studies) coincides with PV structures, what is the benefit of incorporating them for flood prediction on top of precipitation predictions themselves? Is it related to better medium-range predictability of the large-scale patterns and could it enhance early-warning systems in that way? Further, what about "false-positives" for PV structures, meaning that while PV structures capture the dynamics, there still needs to be enough moisture available for extreme precipitation. Is this included indirectly due to the regional geography, or could only looking at PV structures lead to false-positives for extreme flood prediction? Perhaps you could comment on that and/or elaborate on the specifics on how this can enhance flood prediction more clearly and how moisture sources in combination with PV structures are relevant.

Many thanks for this highly valuable comment. We are happy to discuss more about these aspects in the revised version of the manuscript as follows:

We first mention that these “PV structures”, i.e., filamentary PV streamers and isolated PV cutoffs, are the result of large-scale Rossby wave breaking (RWB). According to climatologies of PV streamers and PV cutoffs (e.g., Wernli and Sprenger 2007; Portmann et al. 2021), Europe, including eastern Europe and Ukraine, is a frequency hotspot of RWB. The resulting upper-level PV structures play an important role in the formation of heavy precipitation events for at least three reasons: (i) PV streamers or cutoffs in baroclinic zones lead to dynamical forcing for ascent to the east of the PV structures, which can lead to the formation of warm conveyor belts (associated with intense precipitation) and/or trigger convection; (ii) these PV structures induce a cyclonic wind field, also in the lower troposphere, which leads to moisture advection to the regions with strong dynamical lifting, because PV streamers and cutoffs typically move slowly, this can lead to sustained fuelling of moist air to the affected region, and (iii) positive upper-level PV anomalies lead to reduced static stability underneath, which can again lead to deep convection. According to de Vries et al. (2024), large RWB contributions to extreme precipitation are evident over Europe during the summer. In the Carpathian region, fractions of daily extreme precipitation occurrences associated with RWB reach 80-100%.

Some studies indicated that indeed, upper-level PV structures have improved medium-range predictability compared to the heavy precipitation itself and therefore considering forecasts of upper-level PV can serve as an important early alert system – however, the reviewer is right in mentioning the false alarm issue. Not all PV structures necessarily lead to intense precipitation and flooding, but – because of the dynamical reasons mentioned above – many of them do. As a result, as dynamical drivers occur on a wide range of spatial scales and are an essential component in operational forecasts of extreme rainfall and associated flooding, monitoring PV structures may improve medium-range predictability and extend the lead time of flood early-warning systems, complementing precipitation forecasts that often remain uncertain at longer lead times. A recent study on the predictability of extreme precipitation and its precursors by Dorrington et al. (2024), which investigated ECMWF forecasts of the flood event in central Italy in May 2023, concluded “… that a precursor perspective [focusing on upper-level flow structures] was able to identify the growing possibility of the … extreme event 8 d beforehand – 4 d earlier than the direct precipitation forecast.”.

In the revised manuscript, we added more discussion: «These large-scale features typically develop several days before the onset of heavy precipitation and are generally more predictable than local precipitation itself, as suggested for instance by Massacand et al. (1998) and shown in the detailed analysis of the Emilia-Romagna flood in 2023 by Dorrington et al. (2024). Therefore, incorporating PV diagnostics provides valuable dynamical context for identifying synoptic conditions favorable for persistent or extreme rainfall. As a result, monitoring PV structures may improve medium-range predictability and extend the lead time of flood early-warning systems, complementing precipitation forecasts that often remain uncertain at longer lead times.» L.93-99.

As mentioned by the reviewer, a second important requirement is the availability of moisture, which is typically fulfilled due to long-range transport of moisture associated with these PV structures. Moreover, the moisture flux appears to be the major factor distinguishing precipitation severity (e.g., Froidevaux and Martius, 2016). Therefore, relying solely on PV diagnostics could potentially lead to false-positive indications of flood-favourable conditions. We didn't conduct moisture source diagnostics specifically for those flood cases, other than analysing low-level equivalent potential temperature fields. However, according to our previous investigation (Agayar et al., 2024), extreme rainfall events in western Ukraine typically occur when the PV structure directly interacts with local moisture fields enhanced by regional orography, leading to strong localized convection. Such events may also occur when PV streamers or cutoffs interact with strong moisture transport from the Black Sea. Another key aspect of forecasting severe floods is the duration of the precipitation period, which largely depends on the large-scale flow configuration, its orientation relative to the mountain slopes and potentially the presence of atmospheric blocking.

We added in the revised manuscript: «Since the horizontal moisture transport is a major factor distinguishing precipitation severity (e.g., Froidevaux and Martius, 2016), extreme rainfall events in western Ukraine typically occur when the PV structure directly interacts with enhanced local moisture and regional orography, leading to strong localized convection.» L.627-629.

For the climatological analysis, the separation between PV streamers and cutoffs is quantified, but the composites are only provided for both together. I wonder if the climatological analysis could benefit from a separate look into either PV state, and in particular their influence for the most extreme precipitation.

Thank you for this suggestion. It seems tempting to look at PV streamers and cutoff separately, but their distinction is often not so clear. The same flow situation typically occurs as a PV streamer on one isentropic level and as a PV cutoff at a slightly lower level (reflecting the fact that the stratospheric PV structures get narrower / smaller when going deeper into the troposphere). Therefore, considering the two forms of PV structures together appears to be the most meaningful way for the climatological part of our study. However, since we also looked at the two structures separately, we show the respective figures here in response to your comment.

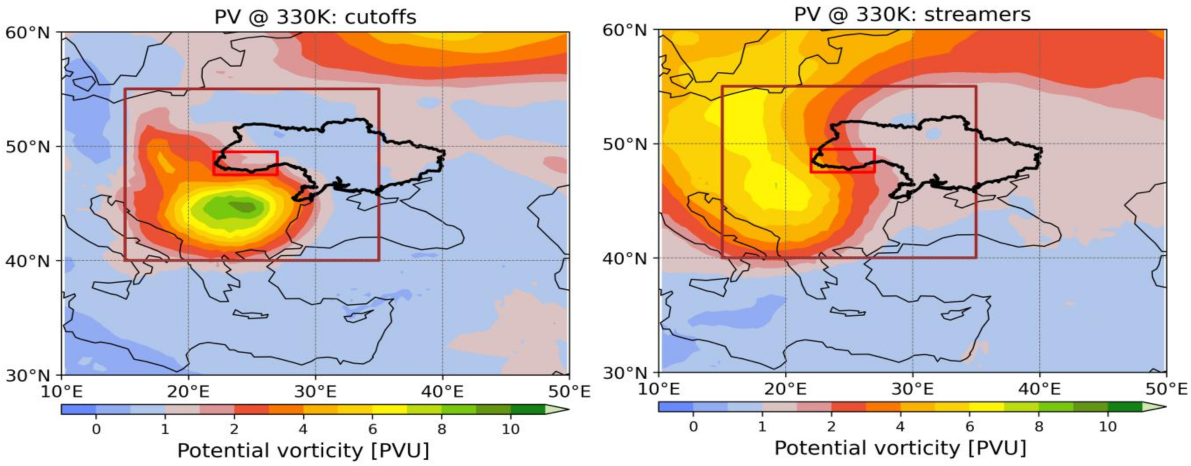

Figure 1. Composites of PV cutoffs and streamers on 330 K related to 22 heavy precipitation events in western Ukraine (red box) in summer; (a) shows the mean PV field of cutoffs and (b) the mean PV field of streamers (amplitude, in PVU). The brown box is used for the selection of PV features.

SPECIFIC COMMENTS

- Regarding the restructuring, the hydrological overviews for the case studies in sections 3.2.1, 3.3.1, 3.4.1 contain last paragraphs about various impacts. I think moving these into the introduction and talk about impacts there improves the flow of the text, due to the hydrology (and following precipitation) not being interrupted by impacts.

Thanks. We added this text to the introduction. L. 61-78.

- In section 2.1, the catchments are described and therein for Dniester, peak discharge characteristics are explained. Perhaps consider also adding similar information for the other catchments to highlight typical peak discharge characteristics.

Yes, we agree with the reviewer that including peak discharge characteristics for the Carpathian catchments would contribute to a more comprehensive understanding of regional hydrological features.

We added: “The highest annual peak discharges occur during the warm season and are characterized by rapid development. For example, according to Moskalenko and Malytska (2021), the time interval between the onset of the precipitation core and the flood peak for catchments with an area of about 1000 km² does not exceed 6–10 hours.” L. 135-138.

- The period covered is 2000–2022, but ERA5 at least is available for longer. While it may be out of scope for this study, an outlook could mention extending this analysis to investigate potential changes/trends/intensification of PV dynamics.

Please note that this is primarily a study about three high-impact flood events and not a study about climatological trends. Also, one of objectives of this study was to combine ERA5 data with IMERG precipitation estimates, which provide high-resolution (0.1°) half-hourly global surface precipitation data. However, IMERG is only available from 2000 onward. To ensure temporal consistency between precipitation and dynamical datasets, we therefore restricted our analysis to the overlapping period 2000–2022. But we agree with the reviewer that such an analysis would be interesting, and we will mention this in the outlook.

We added: “Both IMERG and ERA5 cover the period 2000–2022, which allows for a coherent investigation of the link between PV structures and heavy precipitation observed by satellite.” L. 186-188.

- lines 233-234: it is mentioned that first "the most significant precipitation" and then the "highest precipitation intensity" followed the day after. What is meant with most significant if it's not the highest?

Thank you for pointing that out, we realize that this sentence might be misleading. We mean that during the five-day flood period, a few distinct precipitation peaks were observed, varying in intensity and local impact, with the second peak being the most significant.

To avoid ambiguity, the sentence now reads: «The second precipitation maximum, recorded on 24–25 July, produced the highest rainfall intensity and affected all river basins. The third and final peak, occurring on 26 July, was largely restricted to the Tisza and Dniester basins.» L. 262-264.

- Fig. 4b: It looks like there is a significant difference between the station data for Yaremche and the gridded data. Perhaps this can be commented on, including possible conclusions about uncertainty in either dataset. Same in Fig. 7b and the station Plai and in Fig. 11b for Yaremche.

A possible reason for discrepancies between the station data for Yaremche in 2008 and 2020, and for Plai in 2010, is the difference between pixel data and point measurements. Rain gauge stations measure precipitation at a single point location, while the IMERG dataset with a spatiotemporal resolution of (0.1° × 0.1°, 30 min) represents an average value over a grid cell. If rainfall is spatially variable (e.g., convective storms), a station may record heavy rain while the grid average is lower. Satellite products may also underestimate precipitation in complex orographic regions, e.g., the Carpathian Mountains. However, there is a valid question why this issue mainly affects these two stations.
First, we note that we use the IMERG version “Final Run IMERG V07”, which is bias adjusted with the monthly total precipitation of some gauge stations. The Plai rain gauge is a high-mountain station situated at 1343 m a.s.l. During the five-day precipitation period in July 2010, 99.6 mm was recorded on 7 July, while daily totals on the remaining days ranged between 0 and 13 mm. This pattern indicates a short-lived but very intense convective event concentrated on a single day. It is well known, that IMERG may struggle to accurately capture high-intensity, short-duration convective precipitation, particularly in high mountainous terrain (>1500 m) (Navarro et al., 2020; Lledó et al., 2024). In turn, the station Yaremche. located at 531 m a.s.l. in a narrow mountain valley with complex orography, recorded extremely high precipitation intensities over five consecutive days (in July 2008) and during three days in June 2020. Under such conditions, satellite products may underestimate peak intensities, especially when precipitation is strongly influenced by orographic lifting and localized enhancement.
At the same time, it should be acknowledged that precipitation estimation in complex mountainous regions remains challenging for both satellite-based products and gauge measurements, because ground truth in such areas should be taken with caution.

We added: “This indicates that IMERG struggles to capture high-intensity, short-duration events in complex terrain.” L. 268-269.

- In section 3.3, the very first paragraph discusses not just the particular case study, but also other extreme weather events globally. These fit better into the introduction rather than the specific section for the case study.

We appreciate the reviewer's comment. Indeed, it would be possible to shift the first paragraph of Section 3 to the Introduction. However, we intended to highlight the potential connection between this flood event and other extreme weather events occurring worldwide during the same period. Therefore, we propose to replace the list of flood events with the phrase «including episodes of intense rainfall and flooding, as already noted in the Introduction» (L.336) while keeping the paragraph in its current location.

TECHNICAL COMMENTS

- line 61: "mountainous"

Yes, you are right. We changed it. L.79

- Fig. 1, 3, 6, 10: labels/units on the map (°N, °E, ..)

This has been corrected, thanks.

- Fig. 3, 6, 10: I find the flood magnitude symbols hard to read, specifically the differences between 51 and 76 as well as between 101 and 150.

We have changed as suggested, thanks.

- Fig. 4a, 7a,: The overlapping colours between catchments/lineplots and the y-axis are confusing at first. Perhaps consider different colours for the two y-axes.

We thank the reviewer for the valuable suggestion. In our view, the primary source of confusion appears to be the overlap between the bar graphs, rather than the shared colour scheme used for both line and bar representations. While changing the colours is a possible solution, doing so would introduce six distinct colours for each plot, which may increase visual clutter and reduce clarity. An alternative approach would be to present the precipitation data for each catchment in separate subplots. However, this would entail adding two additional panels per figure, potentially increasing the visual load and making the figures more demanding for readers.

- Fig. 5, 8, 9, 12: The precipitation values in the left-hand column plots are very hard to read

We have revised the precipitation contours. Because we want to emphasize the spatial localization of precipitation rather than the detailed intensity distribution, we now show only a single precipitation isoline (15 mm) and have increased its thickness for better visibility.

- line 252: How many stations did report new records? Perhaps consider just adding the numerical value.

We agree with the reviewer and added: «At three gauge stations, specifically Yaremche, Novodnistrovsk, and Pozhezhevsca totals exceeding historical records were recorded.» L. 282-283.

- line 307: "it is plausible" (missing "is")

Yes, you are right. We changed it. L. 338.

- line 417, 418, 683: Rossby Wave Breaking is abbreviated as RWB, please just add the explanation the first time it's mentioned (or vice versa add "(RWB)" the first time Rossby wave breaking is mentioned)

Thanks, we followed this advice. L.85.

- line 510: 99th percentile from all days, or wet-days only?

This represents the 99th percentile of all daily precipitation in summer.

We added: "First, heavy precipitation events were identified as days when the accumulated precipitation in the domain, indicated again by the red box in Fig. 13, exceeded the 99th percentile of all daily precipitation in summer. L. 531.

- line 560, 609: looks like there are two spaces before "(Fig. 14b,e)" and between "the high-pressure"

Correct, thanks!

- line 678: please properly link the IMERG doi as url

Added. Thanks! L.703.

- line 684: "Index of /staff..." looks like a mistake, please add a correct link/url/doi

Thank you. A video supplements available online. L.707-716.

Reviewer 2

The study investigates the link between the upper-level dynamics and heavy precipitation or river floods for 3 case studies and complements the findings by a composite study. The paper is well structured and well written and contributes to the importance of upper-level structures for heavy precipitation and floods in eastern Europe.

Many thanks for your positive overall assessment of our study and for your constructive suggestions!

The study is well suited for EGUsphere. I recommend minor revisions before publication.

GENERAL COMMENTS

I think it is worth to mention how PV is calculated in favour for readers with more hydrological background. Best placed in Section 2.2.

We add in Section 2.2 that "PV is calculated in the standard way, as the scalar product of the vorticity vector and the gradient of potential temperature, divided by density (Holton and Hakim, 2013)." L. 185-186.

I was wondering if you compared observed precipitation from satellites and stations with ERA5. I was wondering if ERA5 precipitation was lower or just whether the resolution was not sufficient for the study. If precipitation is well described, maybe the investigation period could be extended to 1950 in future work with maybe a look into trends due to climate change.

We did not include a comparison between ERA5 and IMERG precipitation datasets in this study, primarily due to the limited spatial resolution of ERA5, which is not sufficient for our study region. Nevertheless, previous studies have performed such comparisons across various regions (Navarro et al., 2020; Lledó et al., 2024). These analyses indicate that, while ERA5 reproduces the overall spatial distribution of precipitation in reasonable agreement with IMERG, it tends to underestimate precipitation amounts, particularly in regions characterized by complex orography (see also Riboldi et al., 2025). However, we concur with the reviewer that it could be interesting to compare ERA5 and IMERG datasets for our specific flood cases. In response to this comment, we have added precipitation maps based on ERA5 to the Supplementary Material (Fig. S1). A comparison with IMERG shows that, although ERA5 reproduces the overall spatial distribution of precipitation reasonably well, it underestimates small-scale spatial variability as well as total precipitation intensity.

We added to Sec. 2.2: "The IMERG dataset was selected for precipitation analysis owing to its higher spatial resolution and more accurate representation of precipitation intensity compared to ERA5. For reference, precipitation distributions from ERA5 for the three flood events are presented in the Supplementary Material (Fig. S1)". L. 174-177.

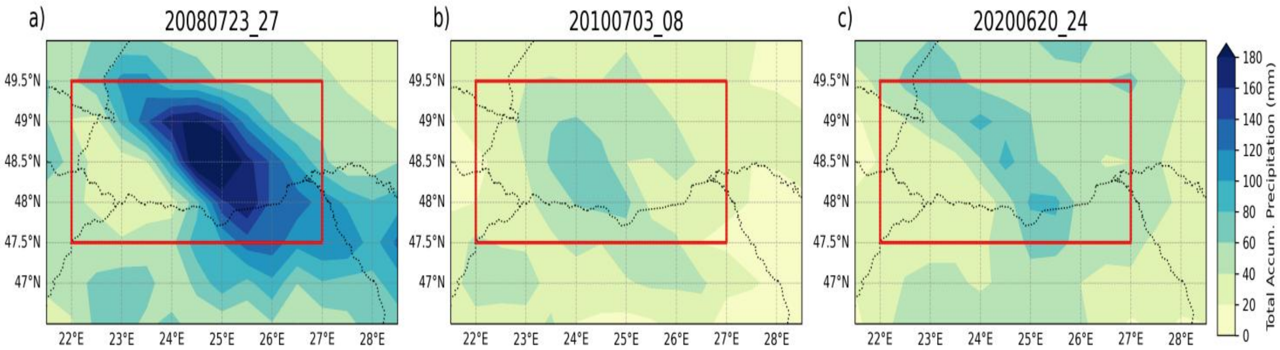

Figure S1. Accumulated precipitation from ERA5 for the three flood events in western Ukraine, from ERA5 (a) 23-27 July 2008, (b) 3-8 July 2010 and (c)20-24 June 2020.

For me it was hard to imagine how the large-scale dynamics especially over Scandinavia or Russia looked like just by seeing the southern remains in the Figures depicting the evolution of PV and ThetaE. I would be very happy to see figures with larger spatial extent in the supplement.

Video supplements are available online. L.707-716.

Maybe the video supplement would accomplish this, however, the link did not work, and it is not mentioned in the manuscript. I think that would also help to better grasp the mentioned importance of up- and downstream blocking.

Thanks for comments. Video supplements are available online.L.707-716.

SPECIFIC COMMENTS

L164: How is it defined if the precipitation is related to a streamer or cutoff? How many grid points are needed to relate to one of these (20% like below)? How does it look like if there are both? Or is it more or less a timing issue? One day first streamer than cutoff = both? Please clarify.

The determination of the link between precipitation and PV structure is described in more detail in Section 4. Yes, we identified PV streamers and PV cutoffs associated with these flood events, which covered at least 20% of the extended domain shown by the brown box in Fig. 13. A day is defined as "both" when at least one cutoff event and one streamer event, each exceeding a cover threshold of 20%, occur on the same calendar day.

We added to Sec. 3.1: "The method to determine the link between precipitation and the PV structures is described in more detail in Section 4." L. 202-203.
And we added to Sec. 4: "A day is defined as "both" when at least one cutoff event and one streamer event, each exceeding a cover threshold of 20%, occur on the same calendar day." L. 547-548.

L201ff: I am confused … isn't the reservoir downstream of the flooded regions? How could the reservoir help to reduce the flood magnitude?

The 2008 flood primarily affected western Ukraine, which is the focus of this study. However, other regions of Ukraine, Moldova, and Romania were also affected, though less severely, as the Dniester Reservoir reduced the flood magnitude downstream.
To clarify this point, we added "the Dniester" to the text: "The flood could have been even more extensive, had it not been for the Dniester reservoir (marked as a black rectangle in Fig. 3) reducing the water inflow into the lower part of the Dniester catchment." L. 240.

L310-312: what does that hypothetically mean for the flood in Ukraine? Transition to next section? Or is it the other way around since blocks after flooding events? Impact of precipitation onto the Russian block by latent heat release? How does this correlate to Trenberth 2012 mentioned in L310.

Thank you for this insightful comment. According to Trenberth (2012), several interacting large-scale processes contributed to the occurrence of multiple high-impact climate extremes during summer 2010, including those affecting the Black Sea region.
The high sea surface temperatures during June-August 2010 were associated with enhanced atmospheric moisture content and anomalously strong diabatic heating over the northern Indian Ocean and the tropical Atlantic. These heating anomalies modified the large-scale atmospheric circulation by forcing quasi-stationary Rossby waves and altering monsoons. Trenberth (2012, Fig. 13) suggested that the resulting Rossby wave train extended into Europe, producing anomalous cyclonic conditions over the Mediterranean region, while persistent anticyclonic conditions developed farther downstream over western Russia. This set the stage for the "blocking" anticyclone and associated Russian heatwave. As shown by Lenggenhager et al. (2018), blocks through their persistence and longevity, might particularly affect the occurrence frequency of such multi-day heavy precipitation events as the blocks can slow down the propagation speed of individual cyclonic systems. Generally, the chance of heavy precipitation increases in areas southeast to southwest of the blocks and in some cases also northwest of the block. In addition, latent heat release associated with intense precipitation can further contribute to the maintenance of the blocking anticyclone itself.

Therefore, in the case of the 2010 Ukrainian flood, it was this combination of factors that created favourable conditions for prolonged and extreme precipitation accumulation.

L377: how do you see the surface anticyclone over the Scandinavian Peninsula in Fig 8a? Maybe it is indicated by the low PV values in the north of the figure.? Think about adding a figure with larger extent to the supplement to make this clear. See third general comment.

Thanks! Video supplements are available online. L.707-716.

L542: which is of course not surprising. comparing a case study with a composite you will almost always find stronger values than in the climatology maybe you compare the strength of the anomalies from your case studies with the anomalies of the other 19 events.

Thank you for your valuable comment. While it falls beyond the scope of the present study, this is indeed an interesting point. We include now a figure with all PV anomalies associated with extreme precipitation events in the Supplement (Fig. S7). They indicate a clear relationship between PV structures and extreme precipitation events in western Ukraine for all events. Additionally, the intensity of these anomalies is comparable to that of the flood-producing cases presented in the manuscript (6–10 PVU). However, PV values comparable to the most intense precipitation case of July 2008 occurred only once, in August 2005, when PV exceeded 11 PVU.

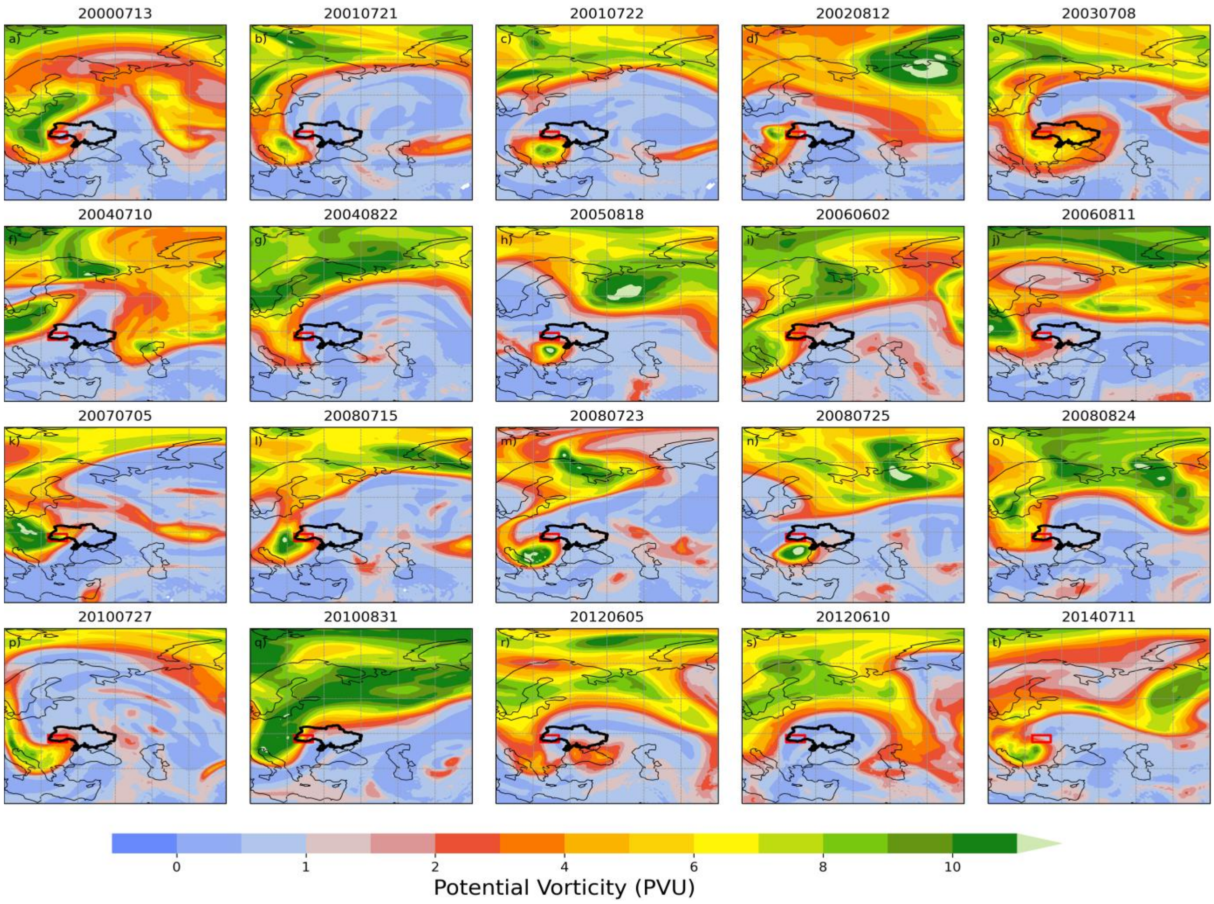

Figure S7. PV daily mean on 330 K on the peak precipitation day for 20 extreme precipitation events from 2000 to 2022 in western Ukraine.

We added: "For all heavy precipitation events (Fig. S7), including the three flood cases, the associated PV features have a more intense amplitude than the PV climatological composite related to HPE (Fig. 13a)." L. 564-565.

TECHNICAL COMMENTS

L137: description of Hmin is missing

Thank you for your comment. The parameter Hmin is not included in our formulation. The metric is defined as:

$$M = \frac{H_{max} - H_{minh}}{H_{maxh} - H_{minh}} \times 100\%,$$

Thus, the equation involves three parameters only: H_{max} is the maximum height of the specific flood, the historic minimum level is H_{minh} and the historic maximum height is H_{maxh}.

L139: how is historical defined: everything before the specific event or a certain period of time?

In this context, the historical period is defined as the full observation record available at a given hydrological station. For rivers in Ukraine, these time series are generally substantial, often extending beyond 100 years.

Fig. 4: mm/h or mm/30 min since data has a 30min resolution according to caption

You are correct that IMERG data have a native temporal resolution of 30 minutes. However, the fields were processed and values are shown in standardized units, such as mm/h or mm/day, which are commonly used for analysis.

L307: missing is in it is plausible

Yes, you are right. We changed it. L.338.

L345: related to [a] PV-cutoff? remove -? rest of study PV cutoff is written without -

Yes, thanks.

L403: due to [the] interaction.. add the?

We have changed as suggested, thanks. L.430.

L404: air masses?

This has been corrected, thanks. L.431.

L507: PV structures were instead of are

Yes, thanks. L.528.

L509: Over how many days/hours is the precipitation accumulated? accumulated daily precipitation?

Yes, this is daily accumulated precipitation, as shown in Fig. S2 of the Supplementary Material.

L515: forcing for? I would suggest forcing of

We thank the reviewer for this comment. The phrase "forcing for ascent" represents the standard meteorological terminology for processes that promote vertical motion, particularly within the framework of synoptic-scale dynamics and quasi-geostrophic (QG) theory (e.g. Holton and Hakim, 2013).

L679: Link does not work

We added the correct links. L.711-716.

L684: I could not access the video since no link was present in the pdf. I assume the video would have helped the access the whole upper-level situation including the blocks and so on.

Video supplements are available online. L.707-715.

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