

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

Ellina Agayar^{1,3}, Moshe Armon^{1,2}, Michael Sprenger¹ and Heini Wernli¹

¹Institute for Atmospheric and Climate Science, ETH Zürich, Zürich, Switzerland

²The Fredy & Nadine Herrmann Institute of Earth Sciences, the Hebrew University of Jerusalem, Jerusalem, Israel

³Odesa I.I. Mechnikov National University, Odesa, Ukraine

Correspondence to: Ellina Agayar (ellina.agayar@env.ethz.ch)

Abstract. Western Ukraine has encountered significant challenges due to three extensive summer rainfall events and major floods in July 2008, July 2010, and June 2020, resulting in numerous fatalities and substantial economic damage. This study investigates the hydrometeorological conditions, as well as the atmospheric processes, that led to these three devastating flood events in the basins of the Tisza, Prut, Siret, and Dniester rivers in western Ukraine. Emphasis is placed on the role of upper-level potential vorticity (PV) structures, analyzed through two complementary approaches: (1) case studies linking the surface weather evolution with upper-level PV dynamics, and (2) a climatological composite analysis on the link between precipitation and upper-level PV, including 22 heavy precipitation events in the period 2000-2022, using reanalysis (ERA5) and satellite-based (IMERG) datasets. The results show that all three floods were driven by multi-day heavy precipitation events, which differed in intensity, spatial extent, and dominant forcing mechanisms. The 2008 event was the most severe, associated with a PV cutoff, intense moisture transport, and extreme precipitation, leading to river levels surpassing historical records. In contrast, the heavy precipitation in July 2010 was driven primarily by direct upper-level dynamic forcing and less moisture transport, which probably caused more localized flooding. The flood in 2020 was notable for its hydrological complexity and evolved more rapidly than the 2008 flood. This event was characterized by remote PV influence, with moisture advection and mesoscale processes playing a more prominent role. In all cases, a persistent atmospheric block hindered the eastward movement of PV structures, maintaining quasi-stationary conditions of prolonged precipitation and moist low-level flow continuously advected against the Carpathian Mountains. Also worth noting, both the 2010 and 2020 events were preceded by several episodes of prolonged precipitation, resulting in saturated soil, gradually increasing river levels and creating favorable conditions for subsequent flooding. The climatological analysis further confirms the strong association between upper-level PV structures and heavy precipitation in the region: 64% of them are associated with a PV streamer, 23% with a PV cutoff, and 13% with combined occurrences of PV streamers and cutoffs. The amplitude and frequency of upper-level PV cutoffs and streamers associated with the heavy precipitation events are largest over eastern Europe, particularly in Romania and Slovenia, pointing out the significance of PV dynamics for heavy precipitation and flood generation in western Ukraine.

1 Introduction

Floods constitute a high-impact natural hazard world-wide and are likely to cause even greater damage in a warmer climate (e.g., Blöschl et al., 2019; Gudmundsson et al., 2021). According to a World Economic Forum report, they pose the highest acute risk of climate-induced deaths and could kill as many as 8.5 million people by 2050 (World Economic Forum, 2024). Rapidly forming and sudden floods, so-called flash floods, often cause severe damage. There is growing evidence that these events are becoming increasingly frequent (Alberston et al., 2017; Blöschl et al., 2017; Didovets et al., 2019). In recent decades, floods and flash floods have severely affected many parts of the world and their meteorological causes were studied thoroughly: for instance, Pakistan, India and China in summer 2010 (Houze et al., 2011; Martius et al., 2012; Thayyen et al., 2013), southern Iran in 2019–2020 (Miri et al., 2023), the Negev desert in southern Israel in 2018 (Rinat et al., 2021), in the contiguous USA (Chu et al., 2025) and Southeast Brazil (Mantovani et al., 2024) and Northern Africa (Armon et al., 2025) in 2023. For Europe, a review of climate change projections of one-day precipitation extremes and floods (Madsen et al., 2014) indicated a general increase in extreme precipitation under a future climate, consistent with the observed trends, although its influence on floods is more complicated (Blöschl et al., 2019; Sharma et al., 2018). Prominent recent examples in Europe are floods in Valencia in 2024 (Morote et al., 2025), in Austria, Germany and the Czech Republic in the same year (Riboldi et al., 2026), in the Emilia-Romagna in June 2023 (Dorrington et al., 2024) and in Palermo in July 2020 (Francipane et al., 2021), as well as the

53 central European floods in August 2002 (Ulbrich et al., 2003) and in June 2013 (Grams et al., 2014). Within this
54 broader European context, eastern Europe has also experienced recurrent large-scale flooding, notably in May 2010
55 (Winschall et al., 2014; Romanescu and Stoleriu, 2017), when the Ukrainian Carpathians were among the most affected
56 regions (ICPDR, 2012). The Carpathians represent one of the most flood-prone mountainous regions in Europe,
57 particularly along the Tisza River basin on the southern slopes and the Dniester River basin on the northeastern slopes.
58 Major floods in these areas have been observed multiple times in the last 50 years (Stefanyshyn, 2022; Snizhko et al.,
59 2023). The last three catastrophic floods and heavy precipitation events in western Ukraine in 2008, 2010, and 2020,
60 affected much of the catchments in the Carpathian region. They caused many fatalities and produced major economic
61 disruptions (State Agency of Water Resources of Ukraine), and are therefore investigated in detail in this study. For
62 instance, in 2008, as reported by the World Health Organization (WHO report, 2008) and the State Agency of Water
63 Resources of Ukraine, the consequences of the flood included the death of 39 people. Approximately 41,000 residential
64 buildings and 34,000 hectares of agricultural land were submerged. The flood also caused significant infrastructure
65 damage, destroying 671 km of highways, 561 pedestrian bridges, 31 km of protective dams and 29 km of coastal
66 fortifications. The total damages from this flood in the Carpathian region amounted to around UAH 2 billion,
67 corresponding at the time to about USD 300 million. This event is considered one of the most severe floods in western
68 Ukraine during the past 60 years. In 2010, as reported by the official assessment (Ukraine Floods: Final Report, 2011),
69 the disaster affected nearly 40,000 people, resulting in five fatalities. A total of 347 settlements were impacted,
70 approximately 15,000 hectares of agricultural land were inundated, and 272 highway and 251 pedestrian bridges were
71 destroyed. The total economic damage from the 2010 flood in western Ukraine was estimated to exceed UAH 900
72 million, i.e., a bit less than half of the damage incurred by the event in 2008. In 2020, according to the Ukrainian Red
73 Cross Society (URCS) and Caritas (Ukraine Floods: Final Report, 2020), a rapid rise of the water levels led to the
74 flooding of 349 settlements and 14,300 houses. The floods also caused damage to over 940 kilometers of roads, more
75 than 140 kilometers of bank protection, and over 300 bridges. More than 55,000 people were affected by the disaster,
76 with 39,000 of those in the hardest-hit Ivano-Frankivsk region, where three fatalities were reported. The estimated
77 damage from the disaster was at least UAH 4 billion, corresponding at the time to about USD 150 million, i.e., about
78 half of the damage cost estimated for the most severe event in 2008.

79 As in other mountainous regions of Europe (e.g., in the Alps, Stucki et al., 2012; Lenggenhager et al., 2018), heavy
80 precipitation in the Carpathian region is often closely linked to the presence of specific upper-level flow features like
81 cutoff low-pressure systems (COLs, Nieto et al., 2008) and surface cyclones (Agayar et al., 2024), atmospheric blocks
82 (Sousa et al., 2017; Lenggenhager and Martius, 2019), and the influence of orography (Kholiavchuk and Cebulska,
83 2019; Torma and Giorgi, 2020). To improve our understanding and the ability to predict floods, it is important to
84 investigate the key large-scale dynamic processes that lead to the heavy precipitation associated with these events.
85 COLs are formed because of Rossby wave breaking (RWB), which may occur when a Rossby wave strongly amplifies
86 and undergoes a nonlinear evolution. One type of Rossby wave breaking, the anticyclonic wave breaking, typically
87 culminates in the formation of narrow high-amplitude troughs, which are often referred to as potential vorticity (PV)
88 streamers (Martius et al., 2006; Moore et al., 2019), and COLs (or PV cutoffs, Portmann et al., 2021). COLs are usually
89 identified as regions on isentropic surfaces where PV values exceed 2 PVU and are isolated from the main stratospheric
90 high-PV reservoir. PV cutoffs are inherently the same phenomenon as COLs (Bell and Bosart, 1993). Since some COLs
91 are relatively long-lived and stationary, they can play an essential role in the formation of multi-day precipitation
92 extremes (Porcu et al., 2003; Givon et al., 2024) and are potential dynamical precursors of unusually long-lasting wet
93 spells (Röthlisberger et al., 2022). These large-scale features typically develop several days before the onset of heavy
94 precipitation and are generally more predictable than local precipitation itself, as suggested for instance by Massacand

95 et al. (1998) and shown in the detailed analysis of the Emilia-Romagna flood in 2023 by Dorrington et al. (2024).
96 Therefore, incorporating PV diagnostics provides valuable dynamical context for identifying synoptic conditions
97 favorable for persistent or extreme rainfall. As a result, monitoring PV structures may improve medium-range
98 predictability and extend the lead time of flood early-warning systems, complementing precipitation forecasts that often
99 remain uncertain at longer lead times.

100 This study explores the atmospheric processes leading to the three most recent catastrophic floods in the basins of the
101 Tisza, Dniester, Prut, and Siret in western Ukraine in the summers of 2008, 2010, and 2020. The reasons for these
102 floods have been investigated in some studies, but they mostly focused on specific regions or individual events. For
103 instance, Kovalets et al. (2015) studied the flood event in the Uzh river basin in July 2008 using a mesoscale
104 meteorological and distributed hydrological model chain. Pirnach et al. (2010) considered microphysical mechanisms
105 leading to the heavy precipitation for the same event. The meteorological causes and socio-economic consequences of
106 the events were studied for the lower part of the Siret and Prut river basins in Romania (Romanescu et al., 2018; Ionita
107 et al., 2021). However, a comprehensive analysis and comparison of the three events, with a focus on the larger-scale
108 dynamical precursors that incorporate relevant climatological aspects, has yet to be conducted. Thus, the goals of this
109 article are: (i) to investigate the hydrological and meteorological characteristics of the catastrophic floods of 2008, 2010
110 and 2020 in western Ukraine; (ii) to study the key large-scale flow features and how the upper-level PV evolved during
111 those floods; (iii) to identify potential differences among these flood events; and (iv) to examine the events in a broader
112 climatological context.

113 After providing a concise overview of the data and methods in Sect. 2, we describe the main aspects of the three heavy
114 precipitation events in Sect. 3. This main part of the study includes a hydrological overview, analysis of precipitation
115 observations, an overview of the large-scale and local-scale flow characteristics. A climatological analysis is presented
116 in Sect. 4. Finally, we discuss and summarize the main outcomes of our study in Sect. 5 and Sect. 6.

117

118 **2 Study area, data and methods**

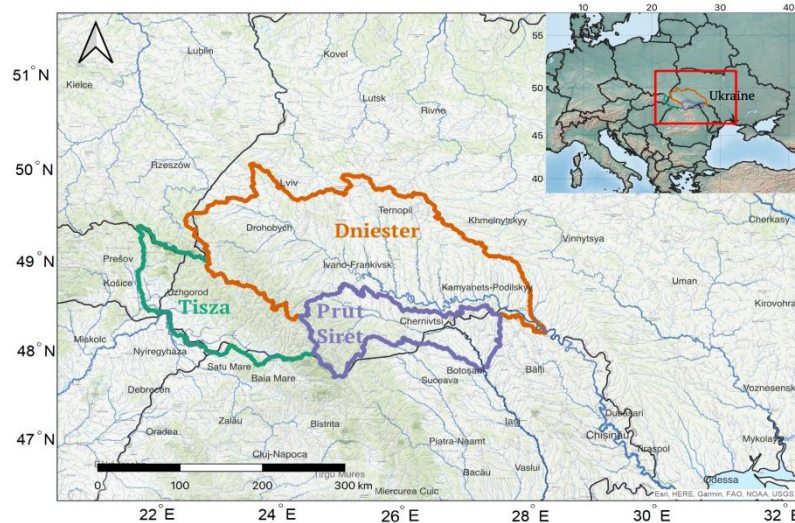
119

120 **2.1 Study area**

121

122 The four main rivers in the Ukrainian Carpathians, Tisza, Prut, Siret, and Dniester are part of the Danube and Dniester
123 catchments (see Table S1). These catchments, along with the topography of the study region, are marked in Fig. 1. **The**
124 **Tisza** basin spans across five countries: Ukraine, Romania, Slovakia, Hungary, and Serbia and is the largest sub-basin
125 within the Danube basin (19.5% of the total area). The Ukrainian segment of the Tisza catchment covers 12,810 km²
126 and is entirely situated within the Transcarpathia region. Climatologically, the eastern part receives the highest
127 precipitation with up to 1500 mm annually. Precipitation gradually decreases towards the lowlands to approximately
128 700 mm. According to hydrological observations, during floods, the water level can rise by 5–6 m (Stefanyshyn, 2022).
129 **The Prut** is a left tributary of the Danube with a length of 299 km within the borders of Ukraine. It originates on the
130 northeastern slopes of the Carpathians at an altitude of 1750 m. In the mountainous part of the basin, annual
131 precipitation reaches up to 1000 mm. **The Siret** is another left tributary of the Danube, meeting the Danube
132 approximately 187 km from its source near Galati, Romania. The upper part of the basin within Ukraine is situated in
133 the eastern Carpathians. Typically, flooding in the Siret catchment occurs in March in association with snow melting.
134 However, during rainfall-induced floods, the maximum water levels tend to exceed those observed during the spring
135 floods. **The highest annual peak discharges occur during the warm season and are characterized by rapid and intensive**
136 **development, what also is typical for Tisza and Prut basins.** For example, according to Moskalenko and Malyska

137 (2021), the time interval between the onset of the precipitation core and the flood peak for catchments with an area of
 138 1000–1200 km² does not exceed 6–10 hours. Finally, the **Dniester** is the largest river in western Ukraine and Moldova.
 139 It originates in the Ukrainian Carpathians (the height of the river source is 760 m), traverses Moldova, and empties into
 140 the Black Sea. Peak discharges of the Dniester are primarily attributed to either the spring thaw or extensive heavy
 141 precipitation in summer and autumn.
 142



143
 144
 145 **Figure 1. Drainage map of the study region, showing the catchments of rivers Dniester, Tisza, Prut and Siret, as**
 146 **well as their major tributary rivers. Source: NaturalEarth (<https://www.naturalearthdata.com/>), and ESRI**
 147 **World Topo map (Sources: Esri, HERE, Garmin, FAO, NOAA, USGS, © OpenStreetMap contributors, and the**
 148 **GIS User Community). To delineate the catchments used in this study, we aggregated catchments from the**
 149 **hydroSHEDS V1 database (Zoom level = 7; Lehner et al., 2008).**
 150

151 Floods occur throughout the entire summer season in the river's upper stretches. During flood events, the water level in
 152 the Dniester rises rapidly, often at a rate of 50–60 cm per hour. In the case of major floods, the water level peaks within
 153 1–2 days (Vyshnevskiy and Kutsiy, 2022).
 154

155 **2.2 Data and methods**

156
 157 For this study, we use multiple datasets. Absolute water level values during floods were obtained from the hydrological
 158 observations for those periods provided by the Department of Hydrological Forecasts of the Ukrainian
 159 Hydrometeorological Center. Data from 66 automatic gauges were used. From these measurements, we defined *flood*
 160 *magnitude* (M , in %) as the ratio between the specific flood depth compared to the maximum historically observed
 161 depth as follows.

162
$$M = \frac{H_{max} - H_{minh}}{H_{maxh} - H_{minh}} \times 100\%,$$

163 where H_{max} is the maximum height of the specific flood, the historic minimum level is H_{minh} and the historic maximum
 164 height is H_{maxh} .

165
 166 Values $M > 100\%$ denote events that exceed the previously recorded maximum height of the river. Given that full
 167 historical records, continuous discharge measurement, and flood return periods could not be obtained, we used flood
 168 magnitude as a measure for the severity of the event. It is important to note the reported flood magnitude addresses river

169 depth rather than discharge. Given a linear increase in river depth, we can expect a linear increase in river cross-section
170 and a power law increase in water flow velocity (e.g., Chow, 1959).

171 To evaluate the amount of rainfall, we used daily precipitation observations from 21 meteorological stations. Because of
172 the convective nature of some of the highest precipitation events in this area, we supplemented the station data with
173 satellite-based precipitation fields from the Final Run IMERG V07 dataset (Huffman et al., 2023), which estimates
174 global surface precipitation rates at a high spatial resolution of 0.1° every 30 minutes. [The IMERG dataset was selected
175 for precipitation analysis owing to its higher spatial resolution and more accurate representation of precipitation
176 intensity compared to ERA5. For reference, precipitation distributions from ERA5 for the three flood events are
177 presented in the Supplementary Material \(Fig. S.1\).](#)

178 The synoptic evolution during the core period of the floods is investigated with daily sequences of isentropic PV charts
179 and maps of mean sea level pressure, equivalent potential temperature at 850 hPa, and geopotential height at 500 hPa.
180 For this, we used the global atmospheric reanalysis dataset of the European Centre for Medium-Range Weather
181 Forecasts ERA5 (Hersbach et al., 2020). All fields were interpolated to a regular grid with a spatial resolution of 0.5°
182 longitude \times 0.5° latitude and available with a temporal resolution of 1 hour. To investigate the dynamical processes in
183 terms of PV, stratospheric PV streamers and PV cutoffs were identified every hour on different isentropes following the
184 methodology of Wernli and Sprenger (2007), but we will focus on PV at 330 K, a usually convenient isentrope to study
185 mid-latitude flow dynamics in summer (Hoskins et al., 1985). [PV is calculated in the standard way, as the scalar product
186 of the vorticity vector and the gradient of potential temperature, divided by density \(Holton and Hakim, 2013\). Both
187 IMERG and ERA5 cover the period 2000–2022, which allows for a coherent investigation of the link between PV
188 structures and heavy precipitation observed by satellite. Synoptic charts focusing on the core period of the floods are
189 presented in Figures 5, 8, 9, and 12, while the Video Supplement illustrates atmospheric processes associated with these
190 events in a broader spatio-temporal context.](#)

191

192 **3 Case studies of extreme floods**

193

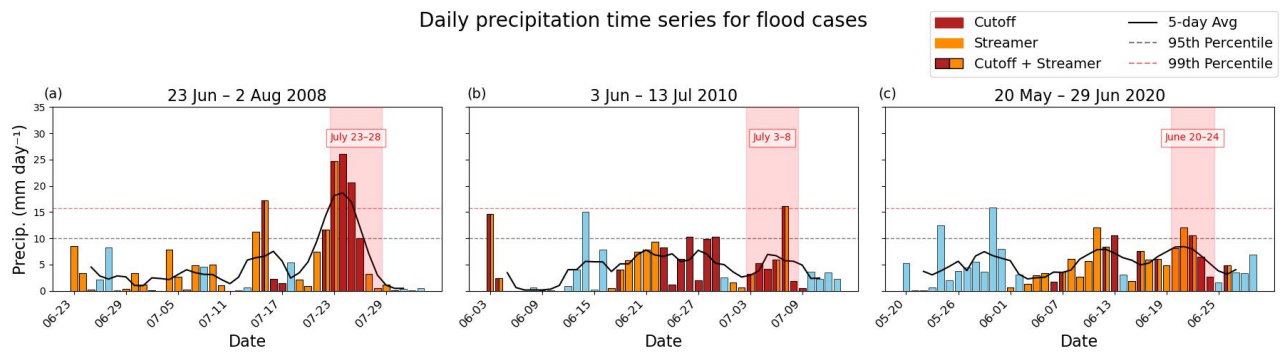
194 **3.1 Selection of cases**

195

196 To obtain a first impression of the temporal evolution of precipitation and the associated upper-level PV dynamics
197 during the three events, Fig. 2 shows time series of precipitation and the occurrence of PV streamers and cutoffs,
198 covering the period from 30 days before the onset of each event to five days after its end. The area with PV in
199 southeastern Europe is defined as the region between 15° – 35° E and 40° – 55° N (see Fig. 13, brown box). The
200 frequency of PV structures during extreme precipitation days is quantified using binary (0/1) masks, where a value of 1
201 is assigned to grid points located within a PV streamer or cutoff, and 0 otherwise. The cases differ in terms of the time
202 evolution of precipitation and share similarities in terms of upper-level PV structures. [The method to determine the link
203 between precipitation and the PV structures is described in more detail in Section 4.](#)

204

205



206
 207
 208 **Figure 2. Time series of daily precipitation from IMERG, averaged in the rectangular box (15°–35°E and 40°–**
 209 **55°N), for the three case studies (the main flood events are marked by pink shading). The bars are color-coded to**
 210 **distinguish between precipitation events related to PV cutoffs (red), PV streamers (orange), a combination of the**
 211 **two (red and orange), and those not related to PV structures (blue). The black line shows a five day rolling**
 212 **average, and the grey and pink dashed lines denote the 95th and 99th percentiles of climatological summer**
 213 **precipitation, respectively.**
 214

215 The first event (Fig. 2a), on 23–28 July 2008, is the most intense, with three consecutive days far exceeding the 99th
 216 precipitation percentile at the onset of the flood event. The month before the event had several wet episodes, but
 217 accumulated precipitation during the pre-event phase was clearly smaller than for the other two events. The main event
 218 was initiated by the formation of a PV streamer that transformed into a PV cutoff, which persisted during the extreme
 219 precipitation period. The second event (Fig. 2b), on 3–8 July 2010, also features one day with extreme precipitation
 220 beyond the 99th percentile, but during the event onset, averaged precipitation was modest and clearly below the 95th
 221 percentile. However, this event was linked to an extended, about two-week period of heavy precipitation with persistent
 222 PV structures before the flood, which acted as a preconditioning phase of the hydrological extreme. Both during this
 223 preconditioning phase and the main flood event, precipitation was related with upper-level PV features. The third event
 224 (Fig. 2c), on 20–24 June 2020, had an even longer, about four-week long preconditioning phase, again at most times
 225 associated with an upper-level PV structure, and eventually, like the 2nd case, comparatively modest precipitation (two
 226 days above the 95th percentile) during the flood event itself. This extended preconditioning period contributed to soil
 227 saturation and the accumulation of conditions favorable to flooding. The following sections provide a more in-depth
 228 description of the three events, based on observations of river discharge and precipitation, and a more detailed analysis
 229 of the large-scale flow evolution.

230

231 3.2 The Case of 23–28 July 2008

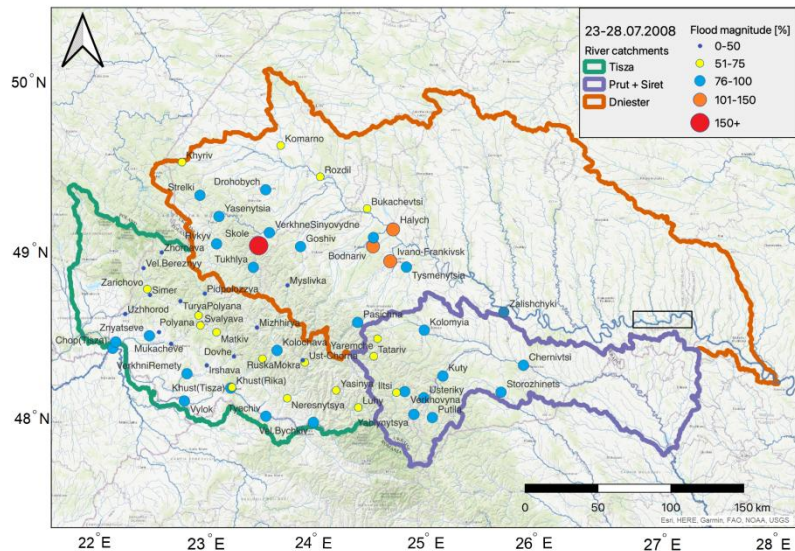
232

233 3.2.1 Hydrological overview

234

235 According to the State Agency of Water Resources of Ukraine, in late July 2008, an extreme rain flood occurred in
 236 western Ukraine (most severely in the Carpathian region), which, in terms of hydrological characteristics, was close to
 237 the historical high flood that occurred in this area in June 1969. Settlements in the valleys of the Dniester and Prut
 238 suffered from significant damage where flood magnitudes reached particularly high values. The flood could have been
 239 even more extensive, had it not been for the Dniester reservoir (marked as a black rectangle in Fig. 3) reducing the
 240 water inflow into the lower part of the Dniester catchment. The inflow into the reservoir was the largest in its history,
 241 with a maximum value of 5,680 m³ s⁻¹ (and an output discharge from the reservoir of 3400 m³ s⁻¹) on 27 July. Figure 3
 242 shows that in the Dniester basin the calculated flood magnitude exceeded 50% at many Carpathian hydrological stations,

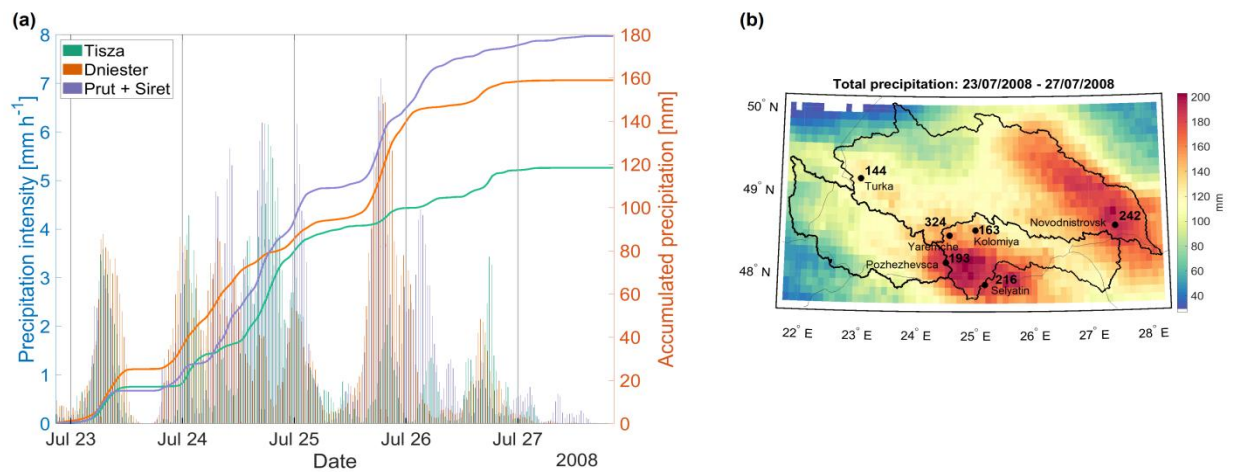
243 and, at certain gauges near Ivano-Frankivsk it exceeded 100%, reaching a maximum of 339% further west at Skole. In
 244 the Prut and Siret basins, all stations experienced floods with magnitudes between 67% and 100%, with the highest
 245 value noted at Yablynytsya in the southwest of the catchment. In the Tisza basin, 32 out of 34 hydrological stations
 246 indicated floods, with magnitudes between 35% and 100%, with the highest value observed at Velykyi Bychkiv.
 247



248
 249 **Figure 3. Map of the flood-affected areas in three catchments in western Ukraine in July 2008. Orange and red**
 250 **dots mark flood magnitudes $M > 100\%$; light blue, yellow and dark blue dots $< 100\%$ at the gauging stations.**
 251 **The black rectangle marks the location of the Dniester reservoir.**
 252
 253

254 **3.2.2 Observed precipitation**

255
 256 In the last ten days of July 2008, heavy rainfall impacted the northwestern part of Ukraine. According to IMERG data,
 257 between 23–28 July, accumulated precipitation amounted to approximately 180 mm in the Prut and Siret catchments,
 258 160 mm in the Dniester catchment, and around 120 mm in the Tisza River area (Fig. 4a). Maximum rainfall intensity
 259 recorded during this period reached 4–7 mm·h⁻¹ averaged over the Prut and Dniester River basins. The area impacted
 260 by precipitation exceeding 100 mm encompassed all three catchments (Fig. 4b). The first rainfall peak occurred on 23
 261 July, with maximum precipitation recorded in the upper reaches of the Dniester, Prut, and Siret catchments, triggering a
 262 sharp rise in water levels in the rivers. **The second precipitation maximum, recorded on 24–25 July, produced the**
 263 **highest rainfall intensity and affected all river basins. The third and final peak, occurring on 26 July, was largely**
 264 **restricted to the Tisza and Dniester basins.** This four-day precipitation sequence led to maximum inflow into the lower
 265 reaches of the Dniester on 27 July (see Sect. 3.2.1). An analysis of the spatial correspondence between IMERG data
 266 and surface observations showed satisfactory results. However, higher precipitation totals were recorded at individual
 267 stations compared to the spatially averaged estimates from IMERG. For instance, Yaremche in the Prut catchment
 268 recorded 324 mm of rain between 23–27 July, nearly double the normal July precipitation (Fig. S3a). **This indicates that**
 269 **IMERG struggles to capture high-intensity, short-duration events in complex terrain.**



270

271
272
273
274
275
276

Figure 4. Precipitation intensity and accumulation during the 2008 flood in western Ukraine (from IMERG). (a) Half hourly (left axis, bars) and accumulated (right axis, lines) precipitation averaged over each catchment, the black ticks along the x-axis indicate 00 UTC of the respective day; (b) spatial distribution of five day accumulated precipitation in the study area. Numbers are accumulated precipitation values based on observations from meteorological stations (black dots indicate station locations).

277
278
279

In Novodnistrovsk in the Dniester catchment, precipitation reached 242 mm between 23 and 26 July, which is 2.5 times the monthly climatological average. Several other stations recorded precipitation amounts that surpassed historical maximum records.

280
281
282
283

Thus, in late July 2008, northwestern Ukraine experienced intense precipitation, with accumulated totals exceeding 100 mm across the Prut, Siret, Dniester, and Tisza catchments, triggering rapid river level rises, leading to peak inflow in the lower Dniester. *At three gauge stations, specifically Yaremche, Novodnistrovsk, and Pozhezhevsca reported totals exceeded historical records.*

284

285 3.2.3 Synoptic and PV analysis

286

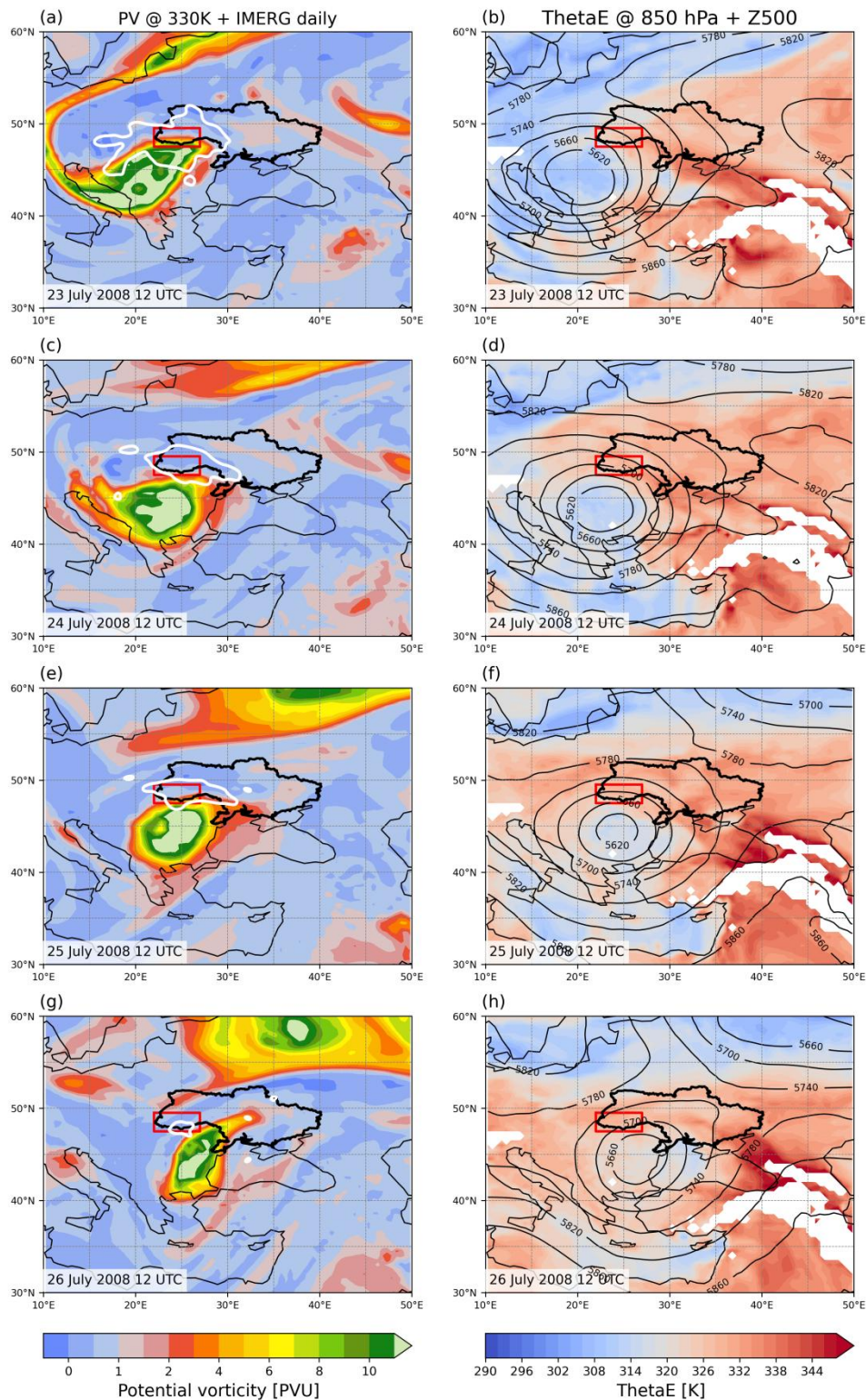
287
288
289
290
291
292
293
294
295

At 1200 UTC on 23 July 2008 (Fig. 5a,b), a quasi-stationary surface trough stretched from the Black Sea towards western Ukraine and the Balkans, and a broad upper-level trough extended from Scandinavia over southeastern Europe, where a closed circulation center had formed over the Balkans on the previous day (not shown). The driver of this process was Rossby wave breaking over central Europe leading to the formation of a PV streamer with high PV values (8-10 PVU) over the Balkans, which advected comparatively cool air over eastern Europe, including the flood regions in western Ukraine (red rectangle). The northern flank of the streamer on the 330 K isentrope was located along 50° N, affecting western and southwestern Ukraine (Fig. 5a). During the next hours, parts of the PV streamer separated from the main stratospheric high PV-reservoir, resulting in a PV cutoff at 330 K (see also Fig. 2a), and a COL over southeastern Europe by 1800 UTC on 23 July (not shown).

296
297
298
299
300

During the subsequent 24 hours, the PV cutoff remained stationary over southeastern Europe, reaching maximum intensity (8–11 PVU) over Serbia, Romania, and Bulgaria at all isentropic levels, pointing to its deep vertical extent (PV on 330 K is shown in Fig. 5c). This cutoff was completely surrounded by tropospheric air with near-zero PV values, and an area of heavy precipitation was located northeast of it. The strong southeasterly flow established between the PV cutoff and the downstream ridge advected warm and humid air into western Ukraine (Fig. 5d).

301



302

303

304

305

306

307

308

309

310

311

312

Figure 5. Flood event on 23–27 July 2008 (see dates in bottom left of panels), based on ERA5. (a,c,e,g) show PV on 330 K (colour shading) and precipitation (white contours for 15 mm day⁻¹; (b,d,f,h) show 850 hPa equivalent potential temperature (colour shading every 2 K) and 500 hPa geopotential height (black contours, every 40 m). The red rectangle highlights the region affected by the flood.

The horizontal low-tropospheric flow was directed perpendicular to the eastern Carpathians and persisted for a few days, causing forced orographic ascent along the eastern slope, which in turn, amplified precipitation. These weather conditions resulted in peak rainfall across all catchments on 24 July (Fig. 4a) and well-defined frontal cloud systems can be seen in the IR satellite image (Fig. S4a). On 25 July, the Scandinavian and southeastern blocking persisted, as well as

313 the PV cutoff over western Ukraine (Fig. 5e,f), which appeared as a broad, quasi-circular cloud system (Fig. S4b). The
314 isolation of a cold air pool over Bulgaria beneath the cutoff facilitated the advection of relatively cold air into the lower
315 troposphere. This, combined with the ascent of warm air along the northeastern flank of the cutoff (Fig. 5f), enhanced
316 low-level convergence and triggered intense precipitation from 1800 UTC on 25 July. Similar large-scale conditions
317 prevail one day later, on 26 July (Fig. 5g,h). The cyclonic system over Romania begins to weaken, and at the same time,
318 the PV cutoff shifts southeastward toward the Black Sea but continues to influence the flood-affected regions.
319 Precipitation is still generated, particularly along the western and northwestern flanks of the system. On 27 July, the PV
320 cutoff deformed into an elongated PV filament and shifted to the east along the north coast of the Black Sea associated
321 with the decay of the COL over southeastern Europe (not shown). Despite this, a minor area of precipitation over the
322 flood-affected region persisted throughout the day.

323 Thus, Rossby wave breaking and the formation of an intense PV streamer were key in the development of a quasi-
324 stationary PV cutoff (or COL) over eastern Europe. The eastward and northward movement of the COL was
325 significantly hindered by a blocking system over the eastern European plain and Scandinavia. This COL persisted for
326 approximately four days, continuously generating sustained precipitation predominantly along its northern flank,
327 directly over the impacted areas. In addition, the orientation of the low-level horizontal flow was primarily
328 perpendicular to the Carpathian Mountains, promoting orographic lifting on the windward slopes, and thus enhancing
329 cloud formation and rainfall rates. In turn, the persistent precipitation and associated latent heat release in the mid-
330 troposphere, might have contributed to upper-level ridge amplification and likely reinforced the blocking pattern (Pfahl
331 et al., 2015).

332

333 **3.3 The Case of 3–8 July 2010**

334

335 The flooding in western Ukraine in July 2010 is one of numerous extreme weather events that unfolded during that year
336 globally, [including episodes of intense rainfall and flooding, as already noted in the Introduction](#), and the Russian heat
337 wave and wildfires in July and August (Matsueda, 2011; Dole et al., 2011; Lau and Kim, 2012). While these extreme
338 events are commonly addressed individually, it is plausible that some of them are interconnected. The focus here is on
339 the connection between the Ukrainian flood event and the Russian heatwave. In the summer of 2010, the blocking
340 anticyclone in Eurasia, associated with the Russian heatwave, persisted for about 50 days (Schneidereit et al., 2012).
341 According to Trenberth (2012), a series of blocking anticyclones, manifesting as negative upper-level PV anomalies,
342 prevented storms and frontal systems from reaching western Russia. The blocks persisted throughout July, and the
343 blocking frequency reached values of twice the climatological frequency (Matsueda, 2011).

344

345 **3.3.1 Hydrological overview**

346

347 According to ICPDR (2012), this event was the final and most severe in a series of significant floods that affected
348 western Ukraine and neighboring countries, including Poland, the Czech Republic, Slovakia, Hungary, Austria, and
349 Serbia, between 10 May and 10 July 2010. In Ukraine, most severely impacted were the Uzhhorod, Chernivtsi, and
350 Ivano-Frankivsk regions, which experienced precipitation totals in a few days equivalent to 2–4 months of
351 climatological rainfall, resulting in a dramatic rise in river water levels. In the Dniester River basin, flood magnitudes
352 reached 50–100% at several stations and even 150% at Skole and Bodnariv (Fig. 6).

353

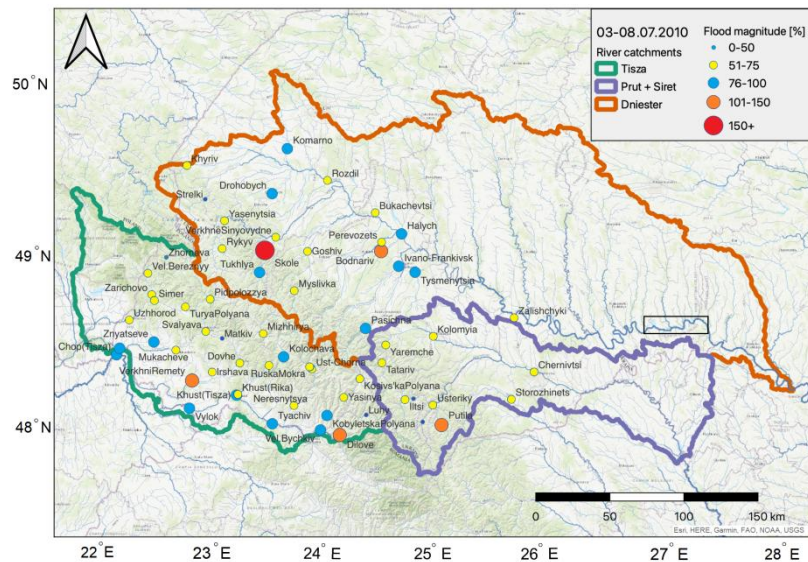


Figure 6. As Fig. 3, but for the event on 3–8 July 2010.

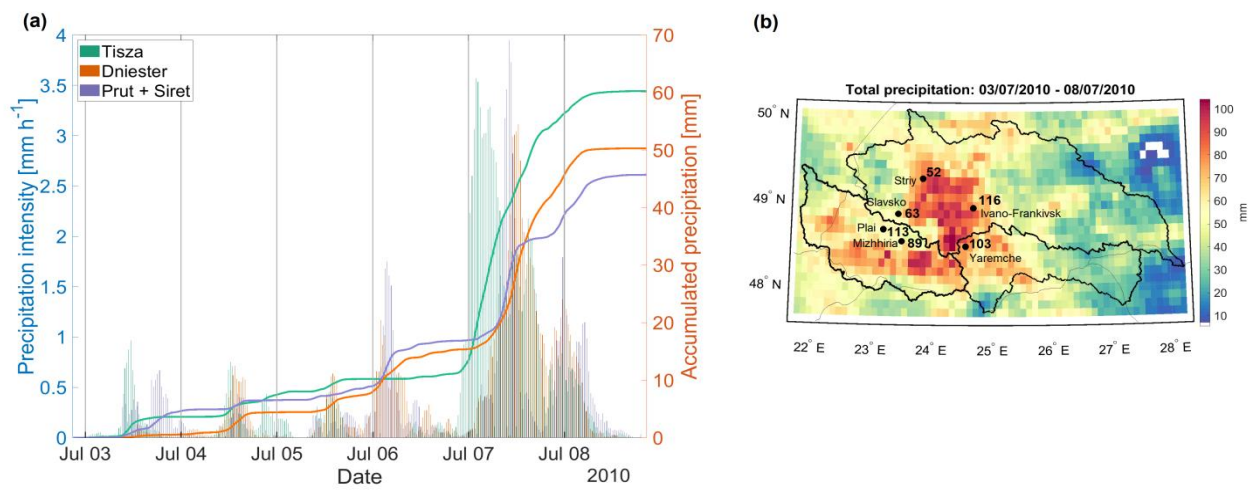
In the Prut and Siret river basins, flood magnitudes reached 50–70% at nine stations, and 100% at Putyla. This flood affected the entire Tisza River basin, with flood magnitudes exceeding 50% at all monitoring sites and values of about 100% at Dilove and Khust. A series of rainfall-induced flood waves were recorded at the Dniester reservoir, with a maximum inflow of $3,800 \text{ m}^3 \text{ s}^{-1}$ on 10 July (State Agency of Water Resources of Ukraine).

3.3.2 Observed precipitation

In May–July 2010, in the pre-flood period, precipitation occurred in several multi-day episodes, ultimately contributing to catastrophic flooding across central and eastern Europe (Romanescu and Stoleriu, 2017). In western Ukraine, the heavy rainfall events began in mid-May 2010, followed by a few additional waves of prolonged, high-intensity rainfall on 3–4 June, 13–16 June and 18–30 June (Fig. 2b). Although these events fall outside the primary scope of this study, they warrant mention because they are significant as precondition processes that prepared the hydrological system for the catastrophic flooding observed at the beginning of July 2010 in western Ukraine.

In the latter half of May, the synoptic situation was characterized by a low-pressure system, related to PV cutoff, over central Europe and Italy, which then moved eastwards and reached southeast Europe (Bissolli et al., 2011). There it remained stationary and transported subtropical warm and moist air northwards from North Africa and the eastern Mediterranean towards the Carpathian Mountains. This induced orographically enhanced heavy precipitation in eastern Europe, including Western Ukraine. In Ukraine, the flood covered part of the Lviv and Ivano-Frankivsk regions, and most of the Zakarpattia region. High flood levels were recorded at the lower Tisza and Latorytsa. On 20 May Latorytsa at Chop reached 701 cm (the historical maximum being 750 cm) (ICPDR, 2012). A similar synoptic pattern occurred in late June, when another low-pressure system, also associated with a PV cutoff (Fig. 2b), induced intense rainfall over the same region. From 16 to 30 June, the Prut River Basin in Ukraine experienced 232 mm of precipitation, which is equivalent to six months' average rainfall, leading to a series of floods in the upper Prut basin (ICPDR, 2012). The final rainfall episode took place between 3–8 July, triggering extensive flooding in the Tisza, Dniester, Prut, and Siret River catchments, particularly affecting the Ivano-Frankivsk region. IMERG precipitation data indicated maximum accumulated rainfall over this period of approximately 60 mm in the Tisza catchment, 51 mm in the Dniester, and 46

384 mm in the Prut and Siret catchments (Fig. 7a). On 3–4 July, precipitation intensity remained relatively low, with
 385 averaged values around 0.5–1 mm·h⁻¹ across all three river basins.
 386

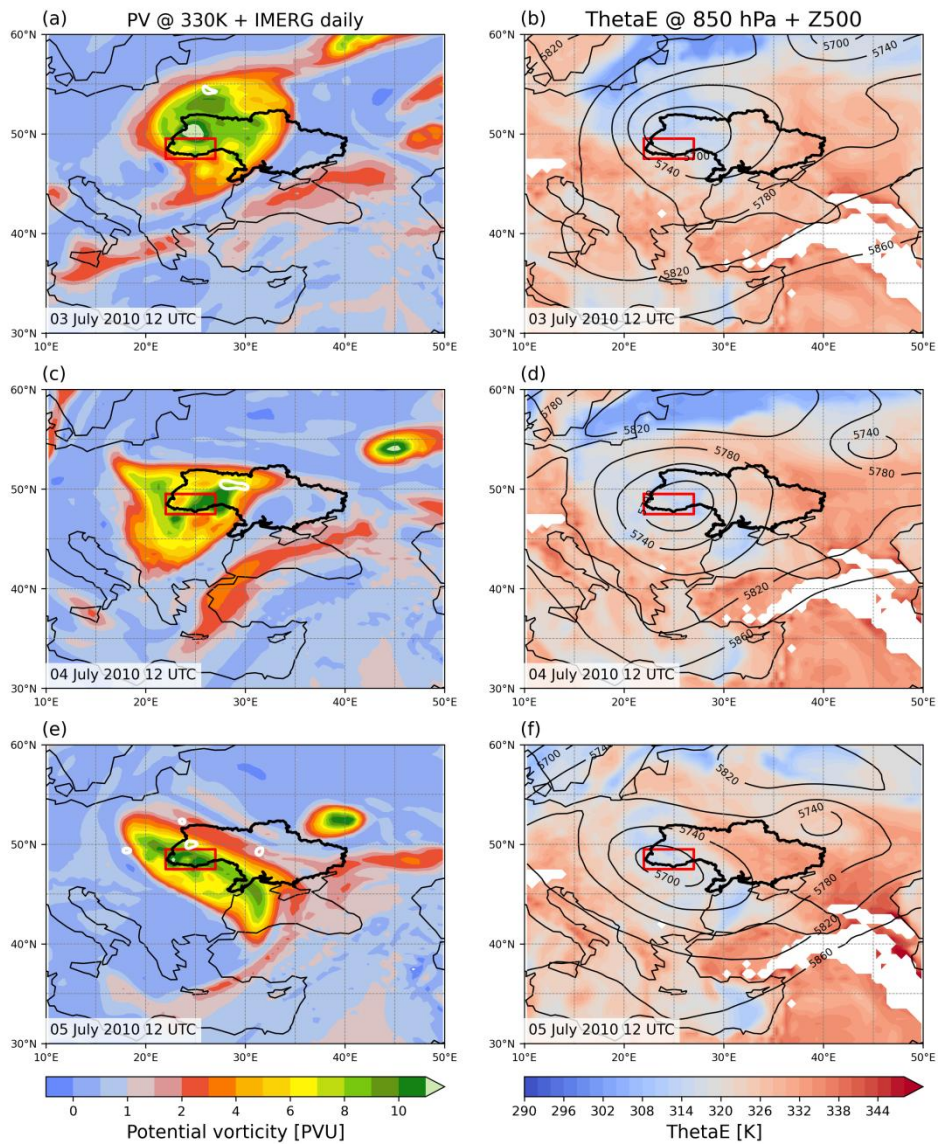


387
 388
 389 **Figure 7. As Fig. 4, but for the flood event on 3–8 July 2010.**

390
 391 During 7 July, peak precipitation intensity rose significantly in all three catchments, reaching 4 mm·h⁻¹ in the Dniester
 392 and Prut regions. The spatial pattern of rainfall during this event is complex. It features elongated precipitation bands
 393 across western Ukraine, impacting not only the Tisza and Prut catchments and upper reaches of the Dniester basin but
 394 also extending further north (Fig. 7b). According to station observations, the 24-hour accumulated precipitation
 395 registered at Ivano-Frankivsk exceeded the July climatological precipitation by a factor of 1.2 (Fig. S3b).
 396 In summary, precipitation accumulation during the 2010 flood occurred in several distinct periods, leading to increased
 397 soil moisture and a gradual increase in river water levels, as noted by Berghuijs et al. (2019). This served as a primary
 398 catalyst for large-scale flooding across much of Europe. The final precipitation episode, which occurred between 3-8
 399 July, showed relatively moderate precipitation intensity peaking on 7 July.

400
 401 **3.3.3 Synoptic and PV analysis**

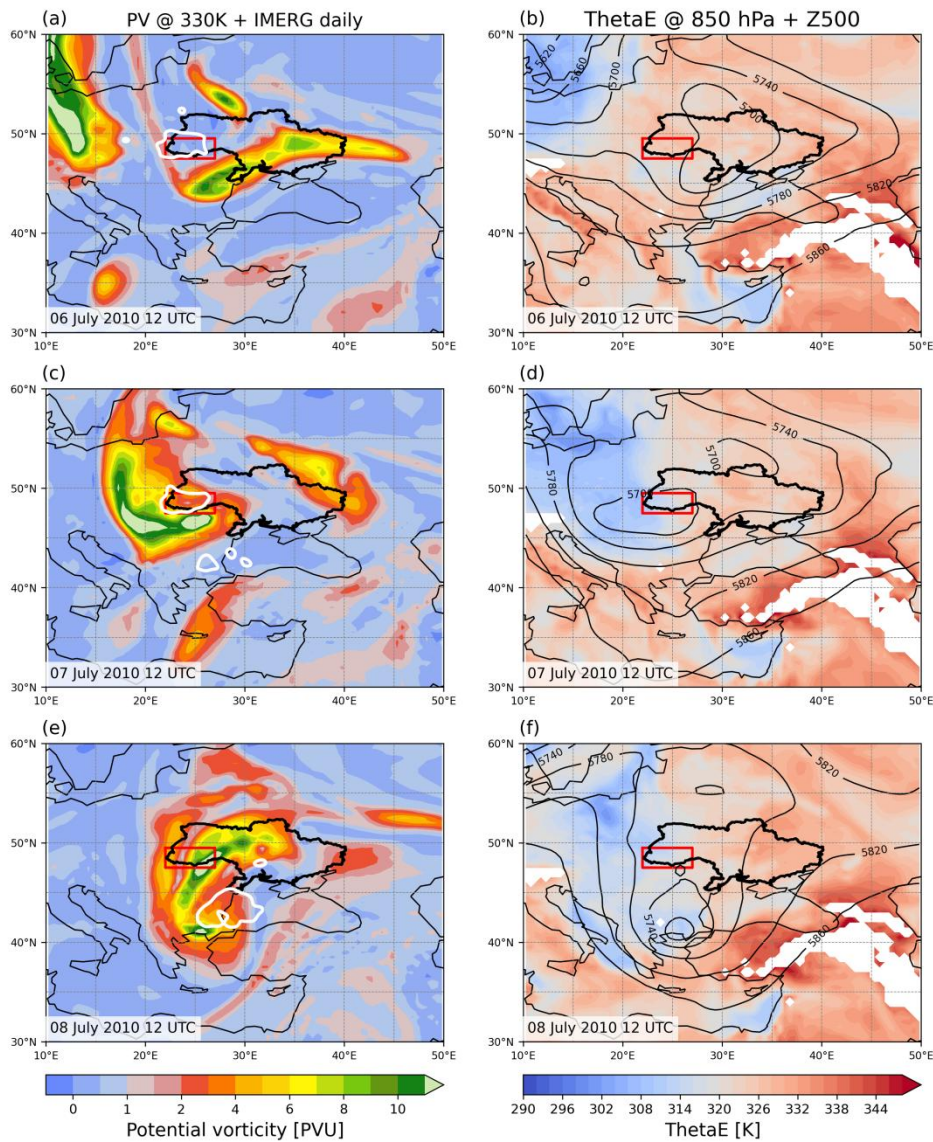
402
 403 On 3 July 2010, a surface anticyclone was located over the Scandinavian Peninsula and Baltic region (Fig. 8a), aligned
 404 with the presence of an upper-level ridge above Scandinavia (not shown). Meanwhile, an upper-level trough, stretching
 405 from northeastern Russia (Fig. 8b), advected cold air into western Ukraine. This trough is associated with a strong COL
 406 with high PV values (6–11 PVU), which formed due to an anticyclonic Rossby wave breaking downstream of the
 407 Scandinavian block (not shown) directly above the flood area (red rectangle in Fig. 8).



408

409 **Figure 8. As Fig. 5, but for 3–5 July 2010.**

410
 411 The presence of the COL can also be inferred from the satellite image at 1200 UTC (Fig. S5a), showing a broken frontal
 412 cloud band with clusters of deep convective clouds over the flood region, and cloud-free zones near the center of the
 413 COL, indicating dry upper-level stratospheric air. On 4 July (Fig. 8c,d) the PV cutoff maintained a quasi-stationary
 414 position over western Ukraine, showing only a slight decrease in intensity. Despite this weakening, the system remained
 415 dynamically active, continuously generating cyclonic circulation and moisture convergence in the lower troposphere by
 416 advecting warm and moist air toward a baroclinic zone. A low-level cold-air core associated with the COL was
 417 identified only over western Ukraine, likely indicating the onset of an occlusion process, leading to an increase in
 418 precipitation intensity after 1200 UTC. On 5 July, the PV structure evolved into a stretched, northwest–southeast–
 419 oriented structure, while still anchored quasi-stationarily over southwestern Ukraine, maintaining intense PV values of
 420 9–11 PVU on 330 K (Fig. 8e). One day later, the PV cutoff, now in the form of a long, narrow PV filament stretching
 421 along 50°N, moved south of the flood area and precipitation rates began to decline after 1200 UTC. Importantly, during
 422 the same period, a next high-PV trough extending from Scandinavia to the Black Sea intensified meridionally, giving
 423 rise to a new, elongated PV streamer west of the main precipitation zone (Fig. 9a,c), approximately 24 hours prior to the
 424 precipitation peak.



425

426 **Figure 9. As Fig. 5, but for 6–8 July 2010.**

427 On July 7, the geopotential height field at 500 hPa shows two distinct low-pressure cores (Fig. 9d). One core was
 428 located over Romania and southwestern Ukraine, associated with the newly developing PV streamer, while the other
 429 formed towards the northeast of Ukraine, linked to the remnant PV cutoff from the previous period (Fig. 9c). The new
 430 PV streamer also induced strong cold-air advection, intensifying low-level baroclinicity due to the interaction with
 431 potentially unstable moist and warm air masses transported from the southeast. This process, combined with forced
 432 orographic ascent along the Carpathian Mountains, contributed to the development of strong convective activity over
 433 the target region. This is supported by IR satellite image, which reveals a well-defined, cyclonically curved cloud spiral
 434 (Fig. S5b), with enhanced cloud tops on the poleward side, indicative of strong convection. This system produced the
 435 most intense precipitation recorded during the entire six-day period in the flood regions.

436 On 8 July, the trough over Ukraine narrowed (Fig. 9f) and the PV cutoff shifted southward (Fig. 9e). However, it
 437 remained dynamically relevant and continued to exert a strong influence on the flood-affected region. In particular, the
 438 pronounced PV gradient and the associated strong northerly winds (not shown) along the western flank of the cutoff
 439 persisted over the Carpathian Mountains, supporting precipitation during the first part of 8 July. However, as the cutoff

440 core moved further south toward the Marmara Sea (not shown), its influence over the Carpathian region diminished,
 441 leading to a gradual weakening and ending of precipitation.
 442 Thus, at the beginning of July 2010, two episodes of Rossby wave breaking occurred, which, in turn, led to
 443 meridionally oriented stratospheric PV streamers, that consequently evolved into PV cutoffs. During the first three days,
 444 a PV cutoff over the flood region formed due to anticyclonic RWB downstream of the Scandinavian blocking
 445 anticyclone. The second PV cutoff evolved from cyclonic RWB, which occurred over the next few days in parallel to
 446 the intensification of the western Russian atmospheric block. These quasi-persistent blocking features north of Ukraine
 447 helped the PV structures to remain stationary over western Ukraine for six days, thus enabling the continuous transport
 448 of moisture-laden air into the region. This air was forced to ascend through both baroclinicity and the Carpathian
 449 orography.

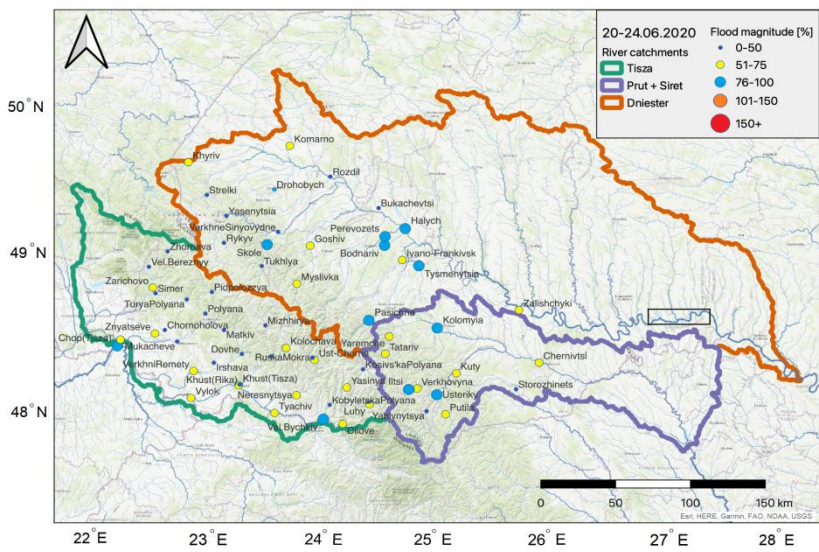
450
 451 **3.4 The Case of 20–24 June 2020**

452
 453 **3.4.1 Hydrological overview**

454
 455 The flood in June 2020 was notable for its hydrological complexity and its more rapidly evolution than the 2008 flood.
 456 The flood began in mid-June due to intense precipitation in the region and the highlands of the Carpathians during late
 457 May and the first half of June. The flood magnitude across the Tisza River basin varied between 50–75%, except in
 458 some southwestern and southern stations, where it reached 100% (Fig.10).

459 The flood magnitude in the tributaries of the Prut, Siret, and Dniester catchments ranged from 50% to 100%, reflecting
 460 significant hydrological variability across the region. Notably, at the Iltsi station in the Prut and Siret River catchment,
 461 peak discharge reached $276 \text{ m}^3 \text{ s}^{-1}$. According to data from the Boris Sreznevsky Central Geophysical Observatory
 462 (Ukraine), this value is approximately 1.5 times higher than the historical maximum of $192 \text{ m}^3 \text{ s}^{-1}$, which was recorded
 463 twice in 1969 and 1996. At the stations Myslivka (in the Dniester basin) and Ruska Mokra (in the Tisza basin), the
 464 maximum flood levels were comparable to those observed during the July 2008 floods. However, in the rest of the
 465 Carpathian region, the 2020 flood peaks were lower than those recorded during the floods of July 2008 and 2010.

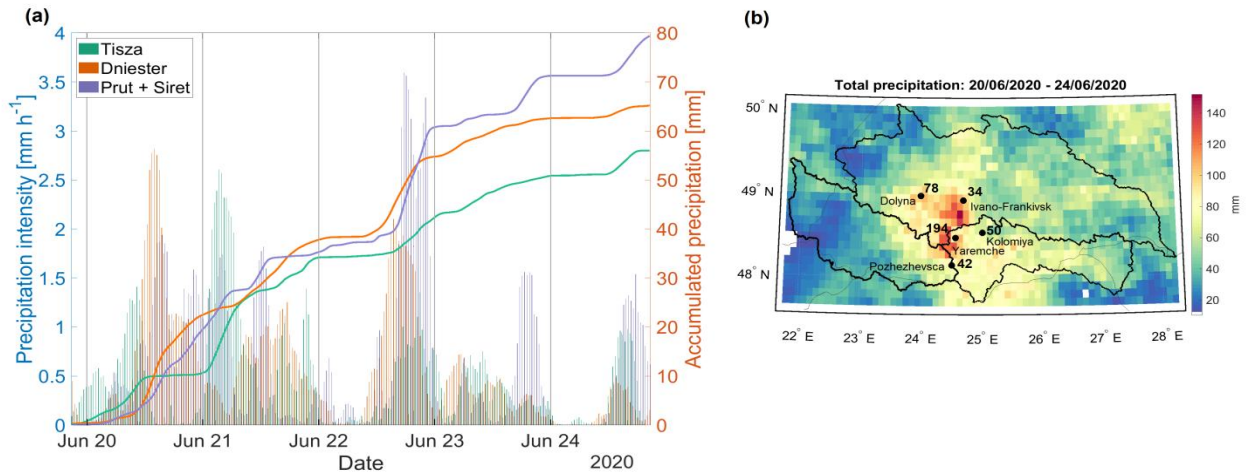
466



467
 468
 469 **Figure 10. As Fig. 3, but for the event on 20–24 June 2020.**

470 **3.4.2 Observed precipitation**

471
472 The precipitation registered between 20 and 24 June 2020 in the western region of Ukraine led to flooding, but one
473 should keep in mind that this event was preceded by a prolonged period of rainfall since late May. According to IMERG
474 data, the highest accumulated precipitation totals during this period were recorded in the Prut and Siret River
475 catchments, with values reaching approximately 80 mm in the Ivano-Frankivsk region (Fig. 11a). In comparison,
476 precipitation totals in the Dniester and Tisza River basins were approximately 65 mm and 57 mm, respectively.
477



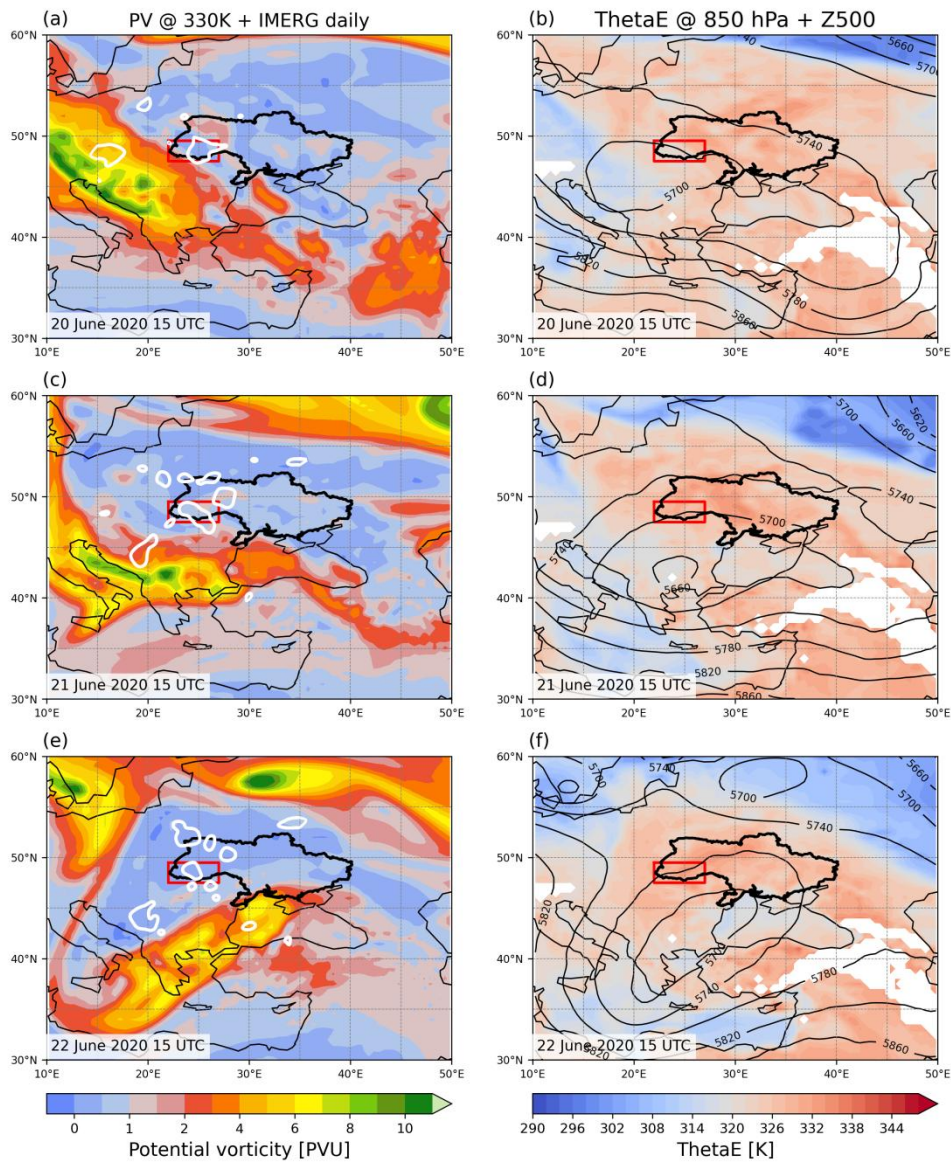
478
479

480 **Figure 11. As Fig. 4, but for the flood event on 20–24 June 2020.**

481
482 On 20 June, the first peak in rainfall intensity was recorded across all three catchments, triggering a rapid rise in water
483 levels and intensified streamflow, especially in the mountainous regions of the Carpathians, except for the left-bank
484 tributaries of the Dniester. The largest rainfall intensities occurred two days later, on the night from 22 to 23 June.
485 The spatial distribution of five day accumulated precipitation reveals two maxima, one located in the Chernivtsi region
486 and another in the Ivano-Frankivsk region (Fig. 11b). This result is consistent with observations at surface stations. In
487 the Ivano-Frankivsk region, several stations recorded extreme daily precipitation totals. For instance, at Kolomyia and
488 Dolina, approximately 50% of the climatological June rainfall fell within a single day. Furthermore, at Yaremche, the
489 three-day accumulated rainfall reached 194 mm, which exceeded the monthly climatology by 23% (Fig. S3c).
490

491 **3.4.3 Synoptic and PV analysis**

492
493 The synoptic situation on 20 June 2020 featured an upper-level trough that extended from northern Europe across
494 southeastern Europe into Asia Minor, while a high-pressure ridge stretched from the Caspian Sea toward Scandinavia
495 (Fig. 12a,b). This large-scale flow configuration enabled the advection of warm and moist air from Asia Minor and the
496 Black Sea toward Ukraine. To the west of the upper-level trough, cold air was advected from the northwest to Slovakia,
497 Hungary, and western Ukraine. This intrusion of cold air was associated with a meridionally elongated and narrow PV
498 streamer, with PV values ranging between 8 and 11 PVU on 330 K. The northern edge of this PV streamer was located
499 over the Tisza catchment, inducing a southeasterly flow at low levels and triggering convection along an elongated band
500 clearly identifiable in IR-image (Fig. S6a).



501

502 **Figure 12. As Fig. 5, but for the flood event on 20–22 June 2020.**

503

504 In the next 36 hours, the PV streamer changed its orientation, moved south, and weakened in intensity (Fig. 12c,e),
 505 which is also visible in the position of the COL (Fig. 12d,f). This led to a weakening of dynamical forcing for ascent
 506 over western Ukraine and increased static stability in the region, and, consequently, precipitation reduced in all three
 507 considered catchments (Fig. 11a). Late on 22 June, a next PV feature started to move south from the Baltic Sea towards
 508 Poland. Its southern tip was characterized by very high PV values on 330 K (>10 PVU at 15 UTC on 23 June),
 509 widespread clouds (Fig. S6b) and intense precipitation over western Ukraine (Fig. 11a). Most likely this process was
 510 enforced by the continuous advection of warm and moist air at low levels (note the high values of equivalent potential
 511 temperature over Ukraine, induced by the remnants of the former PV streamer, now located over the Black Sea (not
 512 shown).

513 In summary, the cause of heavy and prolonged precipitation during the flood period in June 2020 was a combination of
 514 two Rossby wave breaking events and intense transport of warm and moist air to the affected region. Although the main
 515 forcing originated from comparatively remote PV features, they provided the large-scale advection of humid and warm

516 air from the Black Sea region to the Carpathian. Locally, orographic lifting contributed to the development and
517 organization of convective systems in the flood region.

518

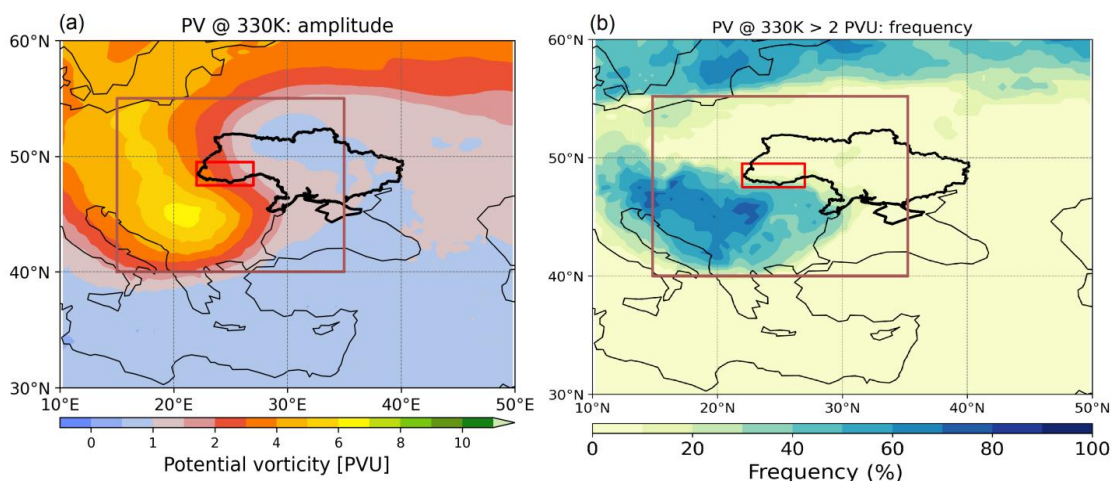
519 4 Anomalous PV structures during cases

520

521 The investigation of the upper-level dynamics in terms of PV of the three flood events in the previous sections revealed
522 the importance of PV streamers and PV cutoffs that were affecting western Ukraine near the peak times of precipitation.
523 This finding is per se not surprising, as it is consistent with the results from our climatological analysis of heavy
524 precipitation events in Ukraine (Agayar et al., 2024) and from many former studies about the dynamics of heavy
525 precipitation events in other parts of the world, as summarized in the introduction. However, our impression was that
526 the PV features related to the three catastrophic flood events studied here, were particularly intense. To check this
527 hypothesis, we performed an additional climatological analysis. To quantify how unusual the PV structures during the
528 flood events *were*, we studied the temporal evolution of summer (JJA) precipitation in the target domain in western
529 Ukraine and the associated PV structures in the period from 2000 to 2022 (Fig. S.2).

530 First, heavy precipitation events were identified as days when the accumulated precipitation averaged in the domain,
531 indicated again by the red box in Fig. 13, exceeded the 99th percentile of *all daily precipitation in summer*. This
532 approach identified 22 heavy precipitation days during the 23 summers, including the three case-study floods. Next, we
533 identified PV streamers and PV cutoffs associated with these events on 330 K, which covered at least 20% of the
534 extended domain shown by the brown box in Fig. 13. The rationale for using a much larger box to identify associated
535 PV features is the fact that they have a far-field effect and as shown for the detailed case studies above, PV features
536 outside of the flood area can affect precipitation in the flood area via advection and forcing for ascent.

537



538

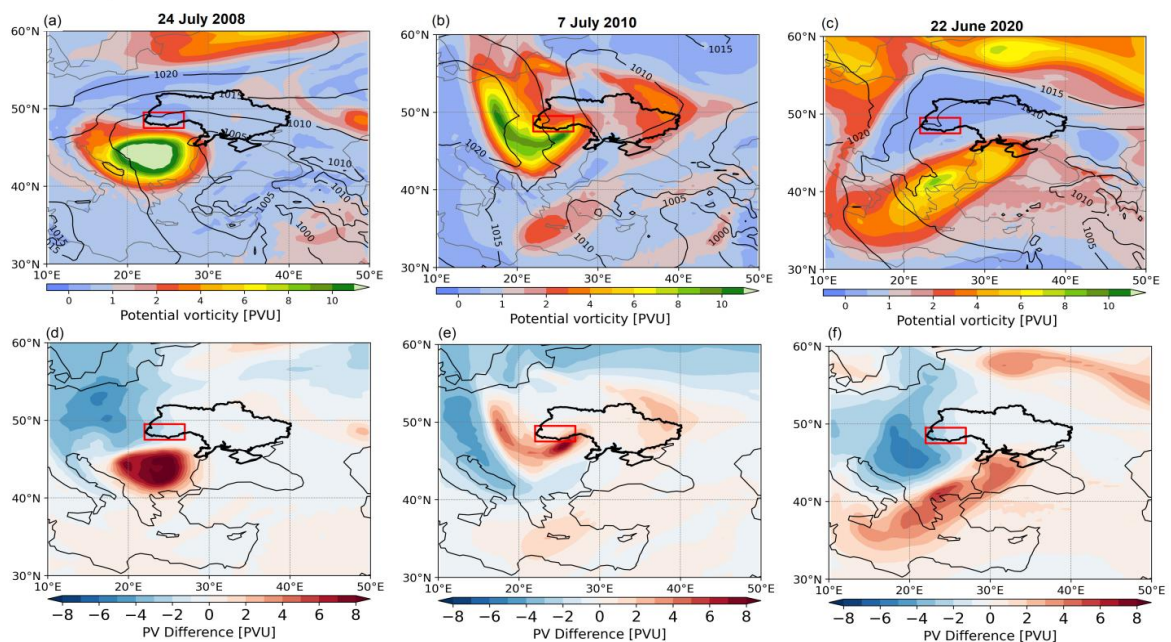
539

540 **Figure 13. Composites of PV cutoffs and streamers on 330 K related to 22 heavy precipitation events in western**
541 **Ukraine (red box) in summer; (a) shows the mean PV field (amplitude, in PVU) and (b) the frequency of PV**
542 **streamers/cutoffs in %. The brown box is used for the selection of PV features (see text for details).**

543

544 This analysis of precipitation and PV features shows that 67% of all summer days with precipitation were related to an
545 upper-level PV structure on 330 K (when using our criterion of 20% coverage of the larger box). However, all 22 heavy
546 precipitation events were linked with a PV structure: 23% with a cutoff only, 64% with only a streamer, and 13% with
547 both a streamer and a cutoff. A day is defined as “both” when at least one cutoff event and one streamer event, each
548 exceeding a cover threshold of 20%, occur on the same calendar day.

549 Figure 13 shows maps of the mean PV cutoff and streamer amplitude and frequency on 330 K for the 22 periods. The
550 amplitude reveals the averaged PV structure and intensity (Fig. 13a), while the frequency indicates the percentage of
551 heavy precipitation time steps that are associated with a PV structure at a particular grid point (Fig. 13b). The
552 climatological PV pattern on 330 K resembles cyclonic wave breaking and has a coherent meridionally-aligned spatial
553 structure extending from northern Europe towards the Balkans (Fig. 13a). The target region in western Ukraine is
554 located east of the averaged stratospheric PV structures. The shape of the averaged PV pattern implies that the
555 tropospheric flow induced by this pattern has a strong southerly component towards the Carpathian Mountains. The PV
556 amplitude is relatively high, ranging from 6 to 7 PVU, and has a clear maximum over eastern Europe that is co-located
557 with the frequency peak (Fig. 13b). The mean frequency of PV features attains values of 60–70% in this region, with
558 local peaks over Romania and Slovenia, where values reach 80% (Fig. 13b). These results confirm the strong influence
559 of PV dynamics on extreme precipitation, suggesting that PV streamers and cutoffs are typical dynamical precursors of
560 heavy precipitation episodes in eastern Europe, and in particular in western Ukraine. It is worth noting that according to
561 the climatological investigation by [Portmann \(2020\)](#), the Baltic Sea region is a primary genesis area for the formation of
562 PV cutoffs. Our study shows that they are of primary importance for heavy precipitation in western Ukraine and in
563 particular for the three flood events discussed in detail.
564 For all heavy precipitation events (Fig. S7), including three flood cases, the associated PV features have a more intense
565 amplitude than the PV climatological composite related to HPE (Fig. 13a). Therefore, the difference fields in Fig. 14d-f
566 reveal marked positive PV anomalies with values up to 8 PVU relative to the climatology for all 22 heavy precipitation
567 events (Fig. 13a).
568



569
570
571 **Figure 14. (a,b,c) PV on 330 K on the peak precipitation day and MSLP (black contours, every 5 hPa), and (d,e,f)**
572 **differences of (a,b,c) and the PV climatology for 22 extreme precipitation events in western Ukraine shown in Fig.**
573 **13a.**

574 Here, for each event, we focus on the time of maximum precipitation. At this stage, the upper-level PV field shows PV
575 cutoffs on 330 K in all three cases. Despite this common feature, the location, intensity, and shape of the PV anomalies
576

577 substantially differ between the cases, thus also highlighting the different ways how the cutoffs influences precipitation
578 formation.

579 The PV cutoff for the case in July 2008 – the most intense in terms of precipitation and river discharge – shows the
580 largest PV anomaly (with a circular shape) exceeding 8 PVU south of the target region over Romania (Fig. 14a,d). A
581 PV cutoff anomaly is clearly localized over Romania and has a quasi-circular shape. The heavy precipitation in the
582 flood area is related to the destabilizing effect of the northern flank of the PV cutoff anomaly. In July 2010, the PV
583 anomaly is more elongated and amounts to 7–8 PVU in a narrow band extending directly to the flood-impacted area,
584 thereby providing strong dynamical forcing for the event through both baroclinicity and the Carpathian orography (Fig.
585 14b,e). By contrast, in June 2020, the differences in location and shape between the composite PV structure and the case
586 (Fig. 14c,f) are significant and dynamically meaningful. The PV cutoff has a lower amplitude, an elongated shape and it
587 is shifted southeastward. This displacement suggests a more indirect role of the southern PV cutoff in triggering
588 precipitation during this case. It facilitated a more zonally oriented transport of moisture toward the flood-affected
589 region, while the direct dynamic influence of the upper-level PV anomaly on vertical ascent was limited or negligible.
590 In the detailed discussion above, we however highlighted also the potential role of the next PV cutoff, which starts to
591 form northwest of the target area.

592

593 **5 Discussion**

594

595 Severe flooding is often caused by one or multiple episodes of heavy precipitation. According to Breugem et al. (2020),
596 the severity of flood events depends on several rainfall characteristics, like accumulated precipitation, rainfall duration,
597 peak rainfall intensity, average rainfall rate, and the spatial scale. Despite the moderate hourly rainfall intensities
598 averaged over the catchments (not exceeding 4.5 mm h^{-1}) observed during all three flood events, the prolonged duration
599 of precipitation and also high rainfall intensity in specific points resulted in significant cumulative rainfall and
600 ultimately caused flooding. At some gauging stations, total rainfall amounts during the five-day flood episodes in July
601 2008 and June 2020 exceeded the average July precipitation by more than a factor of two. Notably, the flood of 2008
602 was generated by one five-day period of heavy precipitation, while the 2010 and 2020 floods were produced by a
603 sequence of several but less intense rainfall episodes, leading to soil saturation and a gradual increase in river water
604 levels.

605 The scale of heavy precipitation events is an essential characteristic because it affects the scale of the flooding potential
606 (Konrad, 2001, Morin and Yakir, 2014; Boers et al., 2016; Armon et al., 2022). An analysis of the spatial distribution
607 of precipitation during the three flood events, based on the IMERG dataset, revealed that the area with precipitation
608 exceeding 100 mm was significantly more extensive during the 2008 flood than in July 2010 and June 2020. However,
609 as Brunner (2023) pointed out, the relationship between the spatial distribution of precipitation and the flood extent and
610 location is not one-to-one. Evidence of this is seen in the differing spatial impacts of each event: while all three basins
611 experienced flooding, the 2010 event was largely confined to the Tisza basin and as well as in the upper Dniester region,
612 whereas in 2020, flooding predominantly affected the Prut and Siret basins, as well as part of the Dniester catchment.
613 The most significant increases in river levels occurred in July 2008, when the highest levels approached historical
614 records, while the flood at the end of June 2020 did not surpass the inundation levels seen in 2008 and 2010. The
615 negative impacts of the three floods were not only due to the heavy precipitation but were likely exacerbated by human
616 activities in the river catchments and on the slopes of the Carpathians. Issues such as the development of riverside areas
617 without compliance with current regulations, clogging of riverbeds, especially in the primary hydrographic network

618 (including streams and streams within settlements), and reduced capacity of drainage systems contributed to the severity
619 of the flooding (State Agency of Water Resources of Ukraine).

620 To understand the large-scale processes and PV dynamics underlying the three major flood events in western Ukraine, it
621 is useful to first consider the climatological context. As already noted in Sect. 4, the contribution of PV structures to
622 summer precipitation and precipitation extremes is rather high in the study domain. This is consistent with several
623 studies. For example, Rimbu et al. (2016) investigated the reasons for the high frequency of extreme summer
624 precipitation in Romania and the eastern Mediterranean. Porcú et al. (2007) also emphasized that PV cutoffs are highly
625 relevant for precipitation in the Mediterranean and surrounding regions. Agayar et al. (2024) found that during summer
626 extreme precipitation events in Ukraine, a moderately intense positive PV anomaly is typically located over
627 southeastern Europe. [Since the horizontal moisture transport is a major factor distinguishing precipitation severity \(e.g.,
628 Froidevaux and Martius, 2016\), extreme rainfall events in western Ukraine typically occur when the PV structure
629 directly interacts with enhanced local moisture and regional orography, leading to strong localized convection.](#) Thus, the
630 findings from the regional climatology of PV streamers and cutoffs conditional on heavy precipitation events presented
631 in Sect. 4, are consistent with previous studies. This climatology served to assess the extremity of the PV structures
632 related to our selected flood cases.

633 The synoptic storylines of the devastating floods presented in Sect. 3 included PV streamers, PV cutoffs (or COLs), and
634 blocking anticyclones. The atmospheric flow in the 2008 and 2020 flood events was shaped by the interaction between
635 a trough from the northeast and two blocking systems upstream and downstream of the trough: the anticyclone to the
636 north and a ridge over the East European Plain to the east of the target region. In July 2010, a synoptic configuration
637 similar to the two other cases was observed during the first few days, however, with a less intensive impact of the high-
638 pressure system northward from the study region. However, the amplification of the western Russian anticyclone led to
639 a reversal of the trough orientation from northeast to northwest, which ensured the stationarity of the blocking
640 anticyclone against the mean flow. These large-scale configurations in all three cases induced Rossby wave breaking,
641 which is known to occur frequently in such synoptic conditions (Kautz et al., 2022). The resulting high-amplitude PV
642 streamers, followed by cutoff formation, established a sustained easterly low-level flow against the Carpathian barrier,
643 potentially forcing orographic lifting. Combined with large-scale forcing for ascent due to the PV cutoffs, this led to a
644 favorable mesoscale environment for convection and prolonged heavy rainfall over western Ukraine. Such
645 amplification of heavy precipitation by the interaction between Rossby wave breaking and low-level moist flow toward
646 an orographic barrier frequently results in heavy precipitation, which is also reported from flood events in other regions,
647 for instance, in Central Europe (Hofstätter et al., 2018) and in the Alps (Piaget et al., 2015).

648

649 **6 Conclusions**

650

651 In this study, we investigated the hydrometeorological and large-scale atmospheric dynamic factors contributing to three
652 catastrophic flooding events in western Ukraine in July 2008, July 2010, and June 2020. Additionally, we analysed the
653 regional summer climatology of upper-level PV structures and precipitation, to put the three case studies in a broader
654 context. To this end, three different analyses were performed, which address: (1) the hydrometeorological causes of the
655 floods; (2) the surface weather evolution and upper-level PV structures associated with the events; and (3) a composite
656 analysis of stratospheric PV streamers and PV cutoffs on the 330K isentropic surface during 22 heavy precipitation
657 events in western Ukraine, identified between 2000 and 2022. The questions posed in the introduction can now be
658 answered as follows:

659 1. The floods of 2008, 2010, and 2020 in the Carpathian region were driven by heavy precipitation events of varying
660 intensity, spatial extent and duration. The 2008 flood was the most severe, with river levels surpassing historical records
661 at several hydrological stations and five-day accumulated rainfall amounts reaching extreme values, exceeding the July
662 average by a factor of two in some areas. The 2010 flood, although less widespread, heavily affected the Tisza
663 catchment and the upper Dniester basin. The 2020 flood did not reach the levels seen in 2008 in most areas, except at
664 two gauge stations, where river levels exceeded previous peaks by up to 50%. Both the 2010 and 2020 events were
665 preceded by several episodes of prolonged precipitation, resulting in saturated soil, gradually increasing river levels and
666 creating favorable conditions for subsequent flooding. The duration and high cumulative precipitation amounts, despite
667 moderate area-mean hourly intensities, were one of the key factors in all three floods, highlighting the importance of
668 their assessment for flood prediction.

669 2. A key synoptic feature contributing to the initiation of heavy precipitation during the flood events was the presence
670 of an upper-level trough extending from the north or northeast of the East European Plain toward southeastern Europe.
671 In all three cases, the large-scale configuration induced Rossby wave breaking, resulting in the development of high
672 amplitude PV streamers, followed by the formation of PV cutoffs (cutoff lows) over the target region. Remote blocking
673 anticyclones, both upstream and downstream, most likely played a role in impeding the eastward movement of these
674 cutoff cyclones, allowing them to remain quasi-stationary over the region for an extended period (flood of 2008) or to
675 occur repeatedly within a few days in the same region (floods of 2010 and 2020). The interaction of the larger-scale
676 flow with the Carpathian Mountains oriented and anchored the low-tropospheric moist air flow towards the topographic
677 barrier, significantly increasing the likelihood of prolonged and intense precipitation over the flood-prone regions in
678 western Ukraine.

679 3. While all three flood events shared a common upper-level PV pattern leading to large-scale forcing for ascent and
680 low-level moisture advection, the involved PV cutoffs differ substantially in terms of shape, amplitude, and evolution.
681 The most severe flood in 2008 was associated with a particularly intense PV cutoff, whose PV values exceeded the
682 composite mean of the PV features associated with all heavy precipitation events in more than two decades by more
683 than 8 PVU. It remained fairly stationary and led to intense rainfall in western Ukraine on four consecutive days. In
684 contrast, the PV cutoffs associated with the two other flood events were less stationary, less intense, and less circular in
685 shape, and indeed the 2010 and 2020 flood events featured the passage of two consecutive upper-level PV cutoffs
686 during the considered five-day precipitation phase.

687 4. The climatological analysis of the PV structures associated with 22 heavy precipitation events in western Ukraine in
688 the summers of 2000-2022 confirms the expected strong link. Notably, 67% of all days with precipitation in the target
689 region were associated with a PV streamer or PV cutoff, while all heavy precipitation events were linked with a
690 prominent PV structure: 23% were related to a PV cutoff, 64% to a PV streamer, and 13% to a combined occurrence of
691 PV streamer and PV cutoffs. The amplitude of the composite PV structure on 330 K over Eastern Europe is relatively
692 high (6–7 PVU) and shows a robust geographical pattern, with frequency peaks reaching up to 80% in Romania and
693 Slovenia (indicating relatively weak spatial variability of the PV structures). The PV anomalies related to the three
694 catastrophic flood events support this pattern: in July 2008, a strong, localized PV cutoff over Romania exceeded
695 climatological values by over 8 PVU; in July 2010, an elongated PV anomaly extended across the flood region,
696 surpassing climatology by 7–8 PVU; in June 2020, the weaker and southeast-shifted PV anomaly did not directly
697 overlay the flood zone, indicating a more remote influence.

698 Overall, the findings of this study confirm that upper-level PV streamers and cutoffs are key drivers of extreme summer
699 precipitation in the Carpathian region, and their structure, amplitude, and spatial alignment play a critical role in
700 determining the location and intensity of flood-inducing rainfall events.

701 **Data availability**

702 ERA5 data is openly available at <https://cds.climate.copernicus.eu> (Hersbach et al., 2020). IMERG data is openly
703 available at <https://doi.org/10.5067/GPM/IMERG/3B-HH/07>, (Huffman et al., 2024). The observational data used for
704 this study can be requested from the Ukrainian Hydrometeorological Center ([https://www.meteo.gov.ua/en/Dani-
705 avtomatichnikh-hidrolohichnikh-postiv](https://www.meteo.gov.ua/en/Dani-avtomatichnikh-hidrolohichnikh-postiv)).

706

707 **Video supplement**

708 To illustrate the RWB lifecycle and synoptic-scale development, we show upper-level PV distributions and 850 hPa
709 equivalent potential temperature at 6-hour intervals throughout each case. Video supplements are available online at the
710 AV Portal of TIB Hannover:

711 <https://doi.org/10.5446/73098> THE_2020 (Agayar, 2026)

712 <https://doi.org/10.5446/73097> THE_2010 (Agayar, 2026)

713 <https://doi.org/10.5446/73096> THE_2008 (Agayar, 2026)

714 <https://doi.org/10.5446/73095> PV_2020 (Agayar, 2026)

715 <https://doi.org/10.5446/73094> PV_2010 (Agayar, 2026)

716 <https://doi.org/10.5446/73093> PV_2008 (Agayar, 2026)

717

718 **Author contributions**

719 EA, MS and HW designed the study, EA performed the analysis, and wrote the manuscript with support from HW.
720 Visualizations were produced by EA and MA. All authors contributed to the interpretation and discussion of the results.

721

722 **Competing interests**

723 The authors declare that they have no conflict of interest.

724

725 **Acknowledgements**

726 EA would like to extend its sincere appreciation to Perevozchikov Illia, the head of the Department of Hydrological
727 Forecasts at the Ukrainian Hydrometeorological Center, for providing hydrological observation data for the river
728 catchments.

729

730 **Financial support**

731 EA was supported by the Swiss National Science Foundation (grant no. 212026 and 216775). MA was supported by the
732 Swiss National Science Foundation (grant no. TMPFP2_216989), by the Med World Consortium, funded by the
733 Council for Higher Education in Israel, and by Israel Science Foundation research grant (ISF's No. 4089/25) and the
734 Maimonides Fund's Future Scientists Center.

735

736 **References**

737

738 Agayar, E., Aemisegger, F., Armon, M., Scherrmann, A., and Wernli, H.: Precipitation extremes in Ukraine from 1979
739 to 2019: climatology, large-scale flow conditions, and moisture sources, *Nat. Hazards Earth Syst. Sci.*, 24, 2441–2459,
740 <https://doi.org/10.5194/nhess-24-2441-2024>, 2024.

741 Alberton, M., Andresen, M., Citadino, F., Egerer, H., Fritsch, U., Götsch, H., Hoffmann, C., Klemm, J., Mitrofanenko,
742 A., Musco, E., Noellenburg, N., Pettita, M., Renner, K., Zebisch, M.: Outlook on climate change adaptation in the
743 Carpathian mountains, United Nations Environment Programme, GRID-Arendal and Eurac Research, Nairobi, Vienna,
744 Arendal and Bolzano, [https://gridarendal-website-live.s3.amazonaws.com/production/documents/:s_
745 document/368/original/MP_Carpathians_lores.pdf?1507791467](https://gridarendal-website-live.s3.amazonaws.com/production/documents/:s_document/368/original/MP_Carpathians_lores.pdf?1507791467), 2017.

746 Armon, M., Marra, F., Enzel, Y., Rostkier-Edelstein, D., Garfinkel, C. I., Adam, O., Dayan, U., and Morin, E.: Reduced
747 Rainfall in Future Heavy Precipitation Events Related to Contracted Rain Area Despite Increased Rain Rate, *Earth's
748 Futur.*, 10, 1–19, <https://doi.org/10.1029/2021ef002397>, 2022.

749 Armon, M., Shmilovitz, Y., and Dente, E.: Anatomy of a Foreseeable Disaster: Lessons from the 2023 Dam-Breaching
750 Flood in Derna, Libya, *Sci. Adv.*, 11, <https://doi.org/10.1126/sciadv.adu2865>, 2025.

751 Berghuijs, W. R., Harrigan, S., Molnar, P., Slater, L. J., and Kirchner, J. W.: The relative importance of different flood-
752 generating mechanisms across Europe, *Water Resour. Res.*, 55, 4582–4593, <https://doi.org/10.1029/2019WR024841>,
753 2019.

754 Bissolli, P., Friedrich, K., Rapp, J., and Ziese, M: Flooding in eastern central Europe in May 2010 – reasons, evolution
755 and climatological assessment, *Weather*, 66: 147-153, <https://doi.org/10.1002/wea.759>, 2011.

756 Blöschl, G., Hall, J., Parajka, J., Perdigão, R.A.P., Merz, B., Arheimer, B., Aronica, G.T., Bilibashi, A., Bonacci, O.,
757 Borga, M., Čanjevac, I., Castellarin, A., Chirico, G.B., Claps, P., Fiala, K., Frolova, N., Gorbachova, L., Gül, A.,
758 Hannaford, J., Harrigan, S., Kireeva, M., Kiss, A., Kjeldsen, T.R., Kohnová, S., Koskela, J.J., Ledvinka, O., Macdonald,
759 N., Mavrova-Guirguinova, M., Mediero, L., Merz, R., Molnar, P., Montanari, A., Murphy, C., Osuch, M., Ovcharuk, V.,
760 Radevski, I., Rogger, M., Salinas, J.L., Sauquet, E., Šraj, M., Szolgay, J., Viglione, A., Volpi, E., Wilson, D., Zaimi, K.,
761 Živković, N.: Changing climate shifts timing of European floods, *Science*, 357(6351), 588-590,
762 <https://doi.org/10.1126/science.aan2506>, 2017.

763 Blöschl, G., Hall, J., Viglione, A., Perdigão, R.A.P., Parajka, J., Merz, B., Lun, D., Arheimer, B., Aronica, G. T.,
764 Bilibashi, A., Boháč, M., Bonacci, O., Borga, M., Čanjevac, I., Castellarin, A., Chirico, G. B., Claps, P., Frolova, N.,
765 Ganora, D., Gorbachova, L., Gül, A., Hannaford, J., Harrigan, S., Kireeva, M., Kiss, A., Kjeldsen, T. R., Kohnová, S.,
766 Koskela, J. J., Ledvinka, O., Macdonald, N., Mavrova-Guirguinova, M., Mediero, L., Merz, R., Molnar, P., Montanari,
767 A., Murphy, C., Osuch, M., Ovcharuk, V., Radevski, I., Salinas, J. L., Sauquet, E., Šraj, M., Szolgay, J., Volpi, E.,
768 Wilson, D., Zaimi, K., and Živković, N.: Changing climate both increases and decreases European river floods, *Nature*
769 573, 108–111, <https://doi.org/10.1038/s41586-019-1495-6>, 2019.

770 Boers, N., Bookhagen, B., Marwan, N., and Kurths, J. : Spatiotemporal characteristics and synchronization of extreme
771 rainfall in South America with focus on the Andes Mountain range, *Clim. Dynam.*, 46, 601–617,
772 <https://doi.org/10.1007/s00382-015-2601-6>, 2016.

773 Borys Sreznjevskiy Central Geophysical Observatory, Ukraine: <https://cgo-sreznjevskiy.kiev.ua/>, last access:
774 20 December 2024.

775 Breugem, A. J., Wesseling, J. G., Oostindie, K., Ritsema, C. J.: Meteorological aspects of heavy precipitation in
776 relation to floods – An overview, *Earth-Science Reviews*, 204, 103171, <https://doi.org/10.1016/j.earscirev.2020.103171>,
777 2020.

778 Brunner, M. I.: Floods and droughts: a multivariate perspective, *Hydrol. Earth Syst. Sci.*, 27, 2479–2497,
779 <https://doi.org/10.5194/hess-27-2479-2023>, 2023.

780 Chow, Van Te: *Open-Channel Hydraulics*, New York: McGraw-Hill, 350 pp., 1959.

781 Chu, L., Warren, J.L., Spatz, E.S., Lowe, S., Lu, Y., Ma, X., Ross, J.S., Krumholz, H.M., and Chen, K.: Floods and
782 cause-specific mortality in the United States applying a triply robust approach, *Nat. Commun.* 16, 2853,
783 <https://doi.org/10.1038/s41467-025-58236-0>, 2025.

784 Didovets I., Krysanova, V., Bürger, G., Snizhko, S., Balabukh, V., Bronstert, A.: Climate change impact on regional
785 floods in the Carpathian region, *J. Hydrol.*, 22, 100590, <https://doi.org/10.1016/j.ejrh.2019.01.002>, 2019.

786 Dole, R., M. Hoerling, J. Perlwitz, J. Eischeid, P. Pegion, T. Zhang, X.-W. Quan, T. Xu, and D. Murray: Was there a
787 basis for anticipating the 2010 Russian heat wave?, *Geophys. Res. Lett.*, 38, L06702,
788 <http://dx.doi.org/10.1029/2010GL046582>, 2011.

789 Dorrington, J., Wentz, M., Grazzini, F., Magnusson, L., Vitart, F., and Grams, C. M.: Precursors and pathways:
790 dynamically informed extreme event forecasting demonstrated on the historic Emilia-Romagna 2023 flood, *Nat.*
791 *Hazards Earth Syst. Sci.*, 24, 2995–3012, <https://doi.org/10.5194/nhess-24-2995-2024>, 2024.

792 Francipane, A., Pumo, D., Sinagra, M., La Loggia, G., and Noto, L. V.: A paradigm of extreme rainfall pluvial floods in
793 complex urban areas: the flood event of 15 July 2020 in Palermo (Italy), *Nat. Hazards Earth Syst. Sci.*, 21, 2563–2580,
794 <https://doi.org/10.5194/nhess-21-2563-2021>, 2021.

795 Froidevaux, P. and Martius, O.: Exceptional integrated vapour transport toward orography: an important precursor to
796 severe floods in Switzerland, *Quart. J. Roy. Meteor. Soc.*, 142, 1997–2012, <https://doi.org/10.1002/qj.2793>, 2016.

797 Givon, Y., Hess, O., Flaounas, E., Catto, J. L., Sprenger, M., and Raveh-Rubin, S.: Process-based classification of
798 Mediterranean cyclones using potential vorticity, *Weather Clim. Dynam.*, 5, 133–162, <https://doi.org/10.5194/wcd-5-133-2024>, 2024.

800 Grams, C. M., Binder, H., Pfahl, S., Piaget, N., Wernli, H.: Atmospheric processes triggering the Central European
801 floods in June 2013, *Nat. Hazards Earth Syst. Sci.*, 14, 1691–1702, <https://doi.org/10.5194/nhess-14-1691-2014>, 2014.

802 Gudmundsson, L., Boulange, J., Hong X. Do, Gosling, S. N., Grillakis, M. G., Koutroulis, A. G., Leonard, M., Liu, J.,
803 Schmied, H. M., Papadimitriou, L., Pokhrel, Y., Seneviratne, S. I., Satoh, Y., Thiery, W., Zhang, S. W. X., Zhao, H.:
804 Globally observed trends in mean and extreme river flow attributed to climate change, *Science*, 371, 1159–1162,
805 <https://doi.org/10.1126/science.aba3996>, 2021.

806 Hersbach, H., and Coauthors: The ERA5 global reanalysis, *Quart. J. Roy. Meteor. Soc.*, 146, 1999–2049,
807 <https://doi.org/10.1002/qj.3803>, 2020.

808 Hofstätter, M., Lexer, A., Homann, M., Blöschl, G.: Large-scale heavy precipitation over central Europe and the role of
809 atmospheric cyclone track types. *Int. J. Climatol.*, 38, e497–e517, <https://doi.org/10.1002/joc.5386>, 2018.

810 Holton, J. R. and Hakim, G. J.: *An Introduction to Dynamic Meteorology, 5th Edition, Academic Press, Cambridge, 552*
811 *p.*, <https://doi.org/10.1016/C2009-0-63394-8>, 2013.

812 Hoskins, B., McIntyre, M., and Robertson, A.: On the use and significance of isentropic potential vorticity maps, *Q. J.*
813 *Roy. Meteorol. Soc.*, 111, 877–946, <https://doi.org/10.1256/smsqj.47001>, 1985.

814 Houze, R. A., Rasmussen, K. L., Medina, S., Brodzik, S. R. and Romatschke, U. : Anomalous Atmospheric Events
815 Leading to the Summer 2010 Floods in Pakistan, *Bull. Amer. Meteor. Soc.*, 92, 291–298,
816 <https://doi.org/10.1175/2010BAMS3173.1>, 2011.

817 Huffman, G.J., Stocker, E.F., Bolvin, D.T., Nelkin, E.J., Tan, J.: GPM IMERG Final Precipitation L3 Half Hourly 0.1
818 degree x 0.1 degree V07, Greenbelt, MD, Goddard Earth Sciences Data and Information Services Center (GES DISC),
819 <https://doi.org/10.5067/GPM/IMERG/3B-HH/07>, 2023.

820 ICPDR 2012: Floods in the Danube River Basin 2010. Brief overview of key events and lessons learned,
821 https://www.icpdr.org/sites/default/files/nodes/documents/icpdr_flood_report_2010.pdf, (last access: 5 September 2024),
822 2012.

823 Ionita, M., Nagavciuc, V.: Extreme Floods in the Eastern Part of Europe: Large-Scale Drivers and Associated
824 Impacts, *Water*, 13, 1122, <https://doi.org/10.3390/w13081122>, 2021.

825 Kautz, L.-A., Martius, O., Pfahl, S., Pinto, J., Ramos, A., Sousa, P., and Woollings, T.: Atmospheric Blocking and
826 Weather Extremes over the Euro-Atlantic Sector – A Review, *Weather Clim. Dynam.*, 3, 305–336,
827 <https://doi.org/10.5194/wcd-3-305-2022>, 2022.

828 Kholiavchuk, D., Cebulska, M.: The highest monthly precipitation in the area of the Ukrainian and the Polish
829 Carpathian Mountains in the period from 1984 to 2013, *Theor. Appl. Climatol.*, 138, 1615–1628,
830 <https://doi.org/10.1007/s00704-019-02910-z>, 2019.

831 Konrad, C. E.: The Most Extreme Precipitation Events over the Eastern United States from 1950 to 1996:
832 Considerations of Scale, *J. Hydrometeor.*, 2, 309–325, [https://doi.org/10.1175/1525-7541\(2001\)002<0309:TMEPEO>2.0.CO;2](https://doi.org/10.1175/1525-7541(2001)002<0309:TMEPEO>2.0.CO;2), 2001.

834 Kovalets, I.V., Kivva, S.L. and Udovenko, O.I.: Usage of the WRF/DHSVM model chain for simulation of extreme
835 floods in mountainous areas: a pilot study for the Uzh River Basin in the Ukrainian Carpathians, *Nat. Hazards*, 75,
836 2049–2063, <http://dx.doi.org/10.1007/s11069-014-1412-0>, 2015.

837 Lau, W. K. M., and Kim, K.-M.: The 2010 Pakistan flood and Russian heat wave: Teleconnection of hydrometeorologic
838 extremes, *J. Hydrometeorol.*, 13, 392–403, <https://doi.org/10.1175/JHM-D-11-016.1>, 2012.

839 Lin, Y.-L., Chiao, S., Wang, T.-A., Kaplan, M.L., Weglarz, R.P.: Some common ingredients for heavy orographic
840 rainfall, *Weather Forecast.*, 16, 633–660, [https://doi.org/10.1175/1520-0434\(2001\)016<0633:SCIFHO>2.0.CO;2](https://doi.org/10.1175/1520-0434(2001)016<0633:SCIFHO>2.0.CO;2), 2001.

841 Lenggenhager, S., Croci-Maspoli, M., Brönnimann, S., Martius, O.: On the dynamical coupling between atmospheric
842 blocks and heavy precipitation events: A discussion of the southern Alpine flood in October 2000, *Quarterly Journal of*
843 *the Royal Meteorological Society*, 145, 719, <https://doi.org/10.1002/qj.3449>, 2018.

844 Lenggenhager, S., Martius, O.: Atmospheric blocks modulate the odds of heavy precipitation events in Europe, *Clim.*
845 *Dynam.*, 53, 4155–4171, <https://doi.org/10.1007/s00382-019-04779-0>, 2019.

846 Lehner, B., Verdin, K., Jarvis, A.: New global hydrography derived from spaceborne elevation data, *Eos, Transactions,*
847 *AGU*, 89(10), 93-94, <https://hdl.handle.net/10568/88952>, 2008.

848 Madsen, H., Lawrence, D., Lang, M., Martinkova, M., and Kjeldsen, T. R.; Review of trend analysis and climate
849 change projections of extreme precipitation and floods in Europe, *J. Hydrol.*, 519, 3634–3650,
850 doi:10.1016/j.jhydrol.2014.11.003, 2014.

851 [Massacand, A. C., Wernli, H. and Davies, H. C.: Heavy precipitation on the Alpine southside: An upper-level precursor,](#)
852 [Geophys. Res. Lett., 25, 9, 1435-1438, https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/98GL50869, 1998.](#)

853 Mantovani, J., Alcântara, E., Pampuch, L.A., Baião, C. F. P., Park, E., Custódio, M. S., Gozzo, L. F. and Bortolozzo, C.
854 A.: Assessing flood risks in the Taquari-Antas Basin (Southeast Brazil) during the September 2023 extreme rainfall
855 surge, *Nat. Hazards*, 1, 9, <https://doi.org/10.1038/s44304-024-00009-8>, 2024.

856 Martius, O., Zenklusen, E., Schwierz, C., Davies, H.C.: Episodes of Alpine heavy precipitation with an overlying
857 elongated stratospheric intrusion: a climatology, *Int. J. Climatol.*, 26, 1149–1164, <https://doi.org/10.1002/joc.1295>,
858 2006.

859 Martius, O., Sodemann, H., Joos, H., Pfahl, S., Winschall, A., Croci-Maspoli, M., Graf, M., Madonna, E., Mueller, B.,
860 Schemm, S., Sedláček, J., Sprenger, M., Wernli, H.: The role of upper-level dynamics and surface processes for the
861 Pakistan flood of July 2010, *Q. J. R. Meteorol. Soc.*, 139, 675, <https://doi.org/10.1002/qj.2082>, 2012.

862 Matsueda, M.: Predictability of Euro-Russian blocking in summer of 2010, *Geophys. Res. Lett.*, 38, L06801,
863 <http://dx.doi.org/10.1029/2010GL046557>, 2011.

864 Miri, M., Raziqi, T., Zand, M. and Kousari, M. R.: Synoptic aspects of two flash flood-inducing heavy rainfalls in
865 southern Iran during 2019–2020, *Nat. Hazards*, 115, 2655–2672, <https://doi.org/10.1007/s11069-022-05658-4>, 2023.

866 Moore, B. J., Keyser, D., and Bosart, L. F.: Linkages between extreme precipitation events in the central and eastern
867 United States and Rossby wave breaking, *Mon. Wea. Rev.*, 147, 3327–3349, [https://doi.org/10.1175/MWR-D-19-](https://doi.org/10.1175/MWR-D-19-0047.1)
868 [0047.1](https://doi.org/10.1175/MWR-D-19-0047.1), 2019.

869 Morin, E. and Yakir, H.: Hydrological impact and potential flooding of convective rain cells in a semi-arid environment,
870 *Hydrol. Sci. J.*, 59, 1353–1362, <https://doi.org/10.1080/02626667.2013.841315>, 2014.

871 Morote, Á.-F., Tévar, B., Olcina, J.: The 2024 Floods in Valencia (Spain): Case Study of Flood Risk Education in a
872 Primary Education Setting, *GeoHazards*, 6, 30, <https://doi.org/10.3390/geohazards6020030>, 2025.

873 [Moskalenko, S. and Malytska, L.: Peak maxima on the rivers of the Prut and Siret basins \(within Ukraine\), Acta](#)
874 [Hydrologica Slovaca, 22 \(2\), https://doi.org/10.31577/ahs-2021-0022.02.0021, 2021.](#)

875 Nieto, R., Sprenger, M., Wernli, H., Trigo, R.M. and Gimeno, L.: Identification and Climatology of Cut-off Lows near
876 the Tropopause, *Annals of the New York Academy of Sciences*, 1146, 256-290, <https://doi.org/10.1196/annals.1446.016> ,
877 2008.

878 Pfahl, S., Schwierz, C., Croci-Maspoli, M., Grams, C.M. and Wernli, H.: Importance of latent heat release in ascending
879 air streams for atmospheric blocking, *Nature Geoscience*, 8, 610–614, <https://doi.org/10.1038/ngeo2487>, 2015.

880 Piaget, N., Froidevaux, P., Giannakaki, P., Gierth, F., Martius, O., Riemer, M., Wolf, G. and Grams, C.M. : Dynamics of
881 a local Alpine flooding event in October 2011: moisture source and large-scale circulation, *Q.J.R. Meteorol. Soc.*, 141:
882 1922-1937, <https://doi.org/10.1002/qj.2496>, 2015.

883 Pirnach, G., Belyi, T., Shpyg, V., Dudar, S.: Heavy precipitation in Eastern Carpathian and microphysical mechanisms
884 of their formation, *The 13-th Conference on Cloud Physics*, 28, <https://ams.confex.com/ams/pdfpapers/170141.pdf> ,
885 2010.

886 Pelly, J. L. and Hoskins, B. J.: A new perspective on blocking, *Journal of the atmospheric sciences*, 60, 743–755,
887 <https://doi.org/10.1029/2020JD034082>, 2003a.

888 Porcu, F., Caracciolo, C., Prodi, F.: Cloud systems leading to flood events in Europe: an overview and classification,
889 *Meteorol. Appl.* 10, 217–227, <http://dx.doi.org/10.1017/S1350482703003025>, 2003.

890 Porcú, F., Carrassi, A., Medaglia, C. M., Prodi, F. and Mugnai, A.: A study on cut-off low vertical structure and
891 precipitation in the Mediterranean region, *Meteorol. Atmos. Phys.*, 96: 121–140, doi: 10.1007/s00703-006-0224-5, 2007.

892 Portmann, R.: The life cycles of potential vorticity cut-offs, *Climatology, predictability and high impact weather*,
893 *Doctoral dissertation, ETH Zurich*, <https://doi.org/10.3929/ethz-b-000466735>, 2020.

894 Portmann, R., Sprenger, M., Wernli, H.: The three-dimensional life cycles of potential vorticity cutoffs: a global and
895 selected regional climatologies in ERA-Interim (1979–2018), *Weather Clim. Dynam.*, 2, 507–534,
896 <https://doi.org/10.5194/wcd-2-507-2021>, 2021.

897 Riboldi, J., Noyelle, R., Agayar, E., Binder, H., Federer, M., Hartmuth, K., Sprenger, M., Thurnherr, I., and
898 Vishnupriya, S.: Storm Boris (2024) in the current and future climate: a dynamics-centered contextualization, and some
899 lessons learnt, *Weather Clim. Dynam.*, 7, 65–87, <https://doi.org/10.5194/wcd-7-65-2026>, 2026.

900 Rimbu, N., Stefan, S., Busuioc, A., and Georgescu, F.: Links between blocking circulation and precipitation extremes
901 over Romania in summer, *Int. J. Climatol.*, 36, 369–376, <https://doi.org/10.1002/joc.4353>, 2016.

902 Rinat, Y., Marra, F., Armon, M., Metzger, A., Levi, Y., Khain, P., Vadislavsky, E., Rosensaft, M., and Morin, E.:
903 Hydrometeorological analysis and forecasting of a 3 d flash-flood-triggering desert rainstorm, *Nat. Hazards Earth Syst.*
904 *Sci.*, 21, 917–939, <https://doi.org/10.5194/nhess-21-917-2021>, 2021.

905 Romanescu, G. and Stoleriu, C. C.: Exceptional floods in the Prut basin, Romania, in the context of heavy rains in the
906 summer of 2010, *Nat. Hazards Earth Syst. Sci.*, 17, 381–396, <https://doi.org/10.5194/nhess-17-381-2017>, 2017.

907 Romanescu, G., Miha-Pintilie, A., Stoleriu, C.C., Carboni, D., Paveluc, L.E., Cimpianu, C.I.: A Comparative Analysis
908 of Exceptional Flood Events in the Context of Heavy Rains in the Summer of 2010: Siret Basin (NE Romania) Case
909 Study, *Water*, 10, 216, <https://doi.org/10.3390/w10020216>, 2018.

910 Röthlisberger, M., Scherrer, B., de Vries, A. J., and Portmann, R.: The role of cyclones and potential vorticity cutoffs
911 for the occurrence of unusually long wet spells in Europe, *Weather Clim. Dynam.*, 3, 733–754,
912 <https://doi.org/10.5194/wcd-3-733-2022>, 2022.

913 Schneidereit, A., Schubert, S., Vargin, P., Lunkeit, F., Zhu, X., Peters, D. H. W. and Fraedrich, K.: Large-Scale Flow
914 and the Long-Lasting Blocking High over Russia: Summer 2010, *Mon. Wea. Rev.*, 140, 2967–2981,
915 <https://doi.org/10.1175/MWR-D-11-00249.1>, 2012.

916 Sharma, A., Wasko, C., and Lettenmaier, D. P.: If Precipitation Extremes Are Increasing, Why Aren't Floods?, *Water*
917 *Resour. Res.*, 54, 8545–8551, <https://doi.org/10.1029/2018WR023749>, 2018.

918 Sousa, P. M., Trigo, R. M., Barriopedro, D., Soares, P. M. M., Ramos, A. M., and Liberato, M. L. R.: Responses of
919 European precipitation distributions and regimes to different blocking locations, *Clim. Dyn.*, 48, 1141–1160,
920 <https://doi.org/10.1007/s00382-016-3132-5>, 1280, 2017.

921 Snizhko, S., Bertola, M., Ovcharuk, V., Shevchenko, O., Didovets, I. and Blöschl, G.: Climate impact on flood changes
922 – an Austrian-Ukrainian comparison, *J. Hydrol. Hydromech.*, 71, 3, 271-282, <https://doi.org/10.2478/johh-2023-0017>,
923 2023.

924 Stefanyshyn, D. V. : What could we have learnt from the previous flood data to predict losses caused by the 1980, 1986,
925 and 1998 catastrophic floods in Ukrainian Transcarpathian?, *Environ. Saf. and Nat. Resour.*, 43(3), 81–109,
926 <https://doi.org/10.32347/2411-4049.2022.3.81-109>, 2022.

927 State Agency of Water Resources of Ukraine: Floods of 2008, 2010 and 2020 - consequences and damages,
928 <https://www.davr.gov.ua/news/pavodki-2008-2010-ta-2020-rokiv--naslidki-ta-zbitki>, last access: 27 May 2025.

929 Stucki, P., Rickli, R., Bronnimann, S., Martius, O., Wanner, H., Grebner, D., and Luterbacher, J.: Weather patterns and
930 hydro-climatological precursors of extreme floods in Switzerland since 1868, *Meteorologische Zeitschrift*, 21, 6, 531–
931 550, <https://doi.org/10.1127/0941-2948/2012/368>, 2012.

932 Thayyen, R.J., Dimri, A.P., Kumar, P., and Agnihotri, G.: Study of cloudburst and flash floods around Leh, India, during
933 August 4–6, 2010, *Nat. Hazards*, 65, 2175–2204, <https://doi.org/10.1007/s11069-012-0464-2>, 2013.

934 Torma, C., Giorgi, F.: On the evidence of orographical modulation of regional fine scale precipitation change signals:
935 The Carpathians, *Atmos. Sci. Lett.*, 21:e967, <https://doi.org/10.1002/asl.967>, 2020.

936 Trenberth, K. E., and Fasullo, J. T.: Climate extremes and climate change: The Russian heat wave and other climate
937 extremes of 2010, *J. Geophys. Res.*, 117, D17103, doi:10.1029/2012JD018020, 2012.

938 Ulbrich, U., Brücher, T., Fink, A., Leckebusch, G., Krüger, A., and Pinto, J.: The central European floods in August
939 2002. Part I: rainfall periods and flood development, *Weather*, 58, 371–376, <https://doi.org/10.1256/wea.61.03B>, 2003.

940 Vyshnevskiy, V. I., Kutsiy, A.V.: Long-term changes in the water regim of rivers in Ukraine, Kyiv, *Naukova dumka*,
941 252, <https://er.nau.edu.ua/handle/NAU/56293>, 2022.

942 Ukraine Floods: Final Report, <https://reliefweb.int/report/ukraine/ukraine-floods-final-report-dref-operation-n>-
943 mdrua010, last access: 15 May 2024, 2020.

944 Ukraine Floods: Final Report, <https://reliefweb.int/report/ukraine/ukraine-floods-dref-operation-no-mdrua005-final>-
945 report, last access: 10 May 2024, 2011.

946 Wernli, H., and Sprenger, M.: Identification and ERA15 climatology of potential vorticity streamers and cut-offs near
947 the extratropical tropopause, *J. Atmos. Sci.*, 64, 1569–1586, <https://doi.org/10.1175/JAS3912.1>, 2007.

948 Winschall, A., Pfahl, S., Sodemann, H., Wernli, H.: Comparison of Eulerian and Lagrangian moisture source
949 diagnostics – the flood event in eastern Europe in May 2010, *Atmos. Chem. Phys.*, 14, 6605–6619,
950 <https://doi.org/10.5194/acp-14-6605-2014>, 2014.

951 World Economic Forum: Quantifying the impact of climate change on human health,
952 <https://www.weforum.org/publications/quantifying-the-impact-of-climate-change-on-human-health/>, last access: 11
953 September 2024.

954 World Health Organization: Floods in Moldova, Romania and Ukraine (summer 2008),
955 <https://www.ifrc.org/docs/appeals/08/MDR67003eul.pdf>, last access: 8 September 2024, 2021.