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Summary of the Doctoral thesis

RELATIONSHIP AMONG MOISTURE FLUX ANOMALIES, EXTREME PRECIPITATION, AND FLOODS IN CENTRAL EUROPE

VZTAH ANOMÁLIÍ TOKŮ VLHKOSTI, EXTRÉMNÍCH SRÁŽEK A POVODNÍ VE STŘEDNÍ EVROPĚ

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Abstract

Floods associated with extreme precipitation are one of the most serious natural hazards, which produce substantial human and socio-economic losses in central Europe. One way to reduce the impact of flooding is by increasing preparedness with better flood forecasts and warnings, which is not possible without a proper understanding of physical processes leading to a flood hazard. However, frequent research on floods in relation to causal precipitation and synoptic conditions is usually carried out regionally, although some events often affect areas of a size of entire countries or even larger.

The thesis was focused exactly on these large-scale precipitation and flood events that occurred in the second half of the 20th century and then until 2013, for which the size of the affected area is as crucial in the extremity assessment as the magnitude of flood discharges or precipitation totals. The extremity indices used for the assessment of extreme precipitation and flood events connected both aspects. The larger area of interest defined within central Europe then allowed examining the spatial structure of events, the differences between them, and their relation to conditions in the atmosphere. To connect the extremes of precipitation with extremes in atmospheric conditions, the causal circulation was evaluated quantitatively, based on the characteristics of the moisture flux at 850 hPa isobaric level in the area of extra high upward vertical velocity, which are both important ingredients for the occurrence of extreme precipitation in central Europe.

As a result, the different types of moisture flux conditions corresponded perfectly with specific seasonal and spatial patterns of extreme precipitation. There were only two main types of extreme precipitation events in central Europe, the difference between them can be explained by the seasonal distribution of anomalies of moisture flux from the respective sectors: (i) warm half-year events with prevailing northern moisture flux and affecting mainly eastern central Europe, and (ii) events with prevailing western moisture flux occurring in the west and exclusively from September to March.

Only in case of events with northern moisture flux, a close connection existed between moisture flux anomalies and precipitation extremeness. This fact allowed to consider the application of moisture flux anomalies from the northern sector in forecasting and extreme weather warnings. However, the question remained whether the predictability of moisture flux anomalies is good enough to support the correct prediction of extreme precipitation events. The results showed that the general use is probably not possible due to worse vertical velocity forecast; the approach based on moisture flux anomalies could be applied only to the largest summer precipitation events, for which the forecast was very good and stable. Therefore, predicting moisture flux anomalies potentially could help to increase preparedness for the same type of precipitation events that produced the most damaging central European summer floods, such as in July 1981 and 1997, August 2002 or June 2013.

Keywords: floods, extreme precipitation, extremity index, moisture flux, predictability, central Europe

Abstrakt

Povodně spojené s extrémními srážkami jsou jedním z nejzávažnějších přírodních ohrožení ve střední Evropě, které mají značné ekonomické dopady na společnost. Jedním ze způsobů, jak dopady zmírnit, je zvyšovat připravenost pomocí lepších předpovědí a včasných varování před povodněmi, což ale není možné bez dokonalého pochopení fyzikálních procesů, které k povodňovému ohrožení vedou. Mnoho studií se věnuje výzkumu povodňových událostí ve vztahu k příčinným srážkám a synoptickým podmínkám, často je ale tento výzkum zaměřen jen regionálně, ačkoli některé události postihují oblasti srovnatelné s rozlohou samostatných států nebo dokonce i větší.

Tato práce byla zaměřena právě na tyto rozsáhlé srážkové a povodňové události druhé poloviny 20. století a dále až do roku 2013, u nichž je pro hodnocení extremity stejně důležitá plocha zasažené oblasti jako velikost povodňových průtoků nebo úhrny srážek. Indexy extremity použité pro hodnocení extrémních srážkových a povodňových událostí kombinovaly oba aspekty. Větší zájmové území v rámci střední Evropy pak umožnilo zkoumat prostorovou strukturu událostí, rozdíly mezi různými typy událostí a jejich vztah k podmínkám v atmosféře. Aby bylo možné určit souvislost mezi srážkovými extrémy a anomálními cirkulačními podmínkami v atmosféře, byla cirkulace hodnocena kvantitativně na základě charakteristik toku vlhkosti v izobarické hladině 850 hPa v místech s mimořádnou rychlostí vzestupných pohybů vzduchu, což jsou důležité složky pro vznik extrémních srážkových událostí ve střední Evropě.

Různé podmínky toku vlhkosti ve výsledku dokonale odpovídaly konkrétním sezónním a prostorovým charakteristikám extrémních srážek. V zásadě se ve střední Evropě vyskytují dva hlavní typy extrémních srážkových událostí, které lze definovat na základě sezónního rozložení anomálií toku vlhkosti z příslušných sektorů: (i) události teplého půlroku s převládajícím severním tokem vlhkosti, které postihují hlavně východ střední Evropy, a (ii) události s převládajícím západním tokem vlhkosti, které se vyskytují spíše na západě a výlučně v období od září do března.

Pouze v případě událostí se severním tokem vlhkosti existovala úzká souvislost mezi anomáliemi toku vlhkosti a extrémy srážek, což by mohlo mít potenciální využití v předpovědích a ve vydávání výstražných informací před extrémními srážkovými a povodňovými událostmi. Otázkou ale zůstává, jestli předpověď anomálií toku vlhkosti je dostatečně kvalitní, abychom jí mohli podpořit předpověď extrémních srážkových událostí. Z výsledků vyplývá, že obecné využití zřejmě není možné vzhledem k horší prediktabilitě vertikálních rychlostí; přístup založený na anomáliích toku vlhkosti lze aplikovat jen v případě největších letních srážkových událostí, kdy je předpověď anomálií toku vlhkosti stabilní. Potenciálně to může znamenat zlepšení připravenosti na tento typ srážkových událostí, které vždy vyústily ve velké středoevropské povodně, jakými byly události v červenci 1981 a 1997, srpnu 2002 nebo červnu 2013.

Klíčová slova: povodně, extrémní srážky, index extremity, tok vlhkosti, prediktabilita, střední Evropa

1 Introduction

Floods caused by extreme precipitation are among the costliest natural hazards in central Europe (EEA, 2019) with the costs still increasing. It is partly a matter of the higher exposure of people and assets to extreme weather events (IPCC, 2014), but it has also been reported that the frequency and intensity of extreme precipitation events have likely increased in Europe in the last decades (IPCC, 2014; van den Besselaar et al., 2013). For a better preparedness against flood risk, good flood forecasts and warnings are important, which is not possible without a sufficient skill of the quantitative precipitation forecast. However, the forecast often fails due to high spatial and temporal variability of precipitation (Sukovich et al., 2014).

Although we experience two types of flooding in central Europe – river and flash floods – this work primarily concentrated on large-scale events that often hit different basins or even countries at the same time, and therefore usually cause much more damage than flash floods (Barredo, 2007). Within river floods, those caused by extreme large-scale rainfall are of major concern, so they can be directly associated with causal synoptic-scale circulation.

In addition to the event magnitude, duration and particularly the spatial extent of the event are crucial for the evaluation of such large-scale flood and precipitation events (Müller and Kašpar, 2014). The involvement of the affected area in the evaluation of the event extremity is common not only for floods (Uhlemann et al., 2010) and extreme precipitation (Müller and Kašpar, 2014) but also in the case of other meteorological phenomena like heat waves (Lhotka and Kyselý, 2014) or windstorms (Kašpar et al., 2017).

In central Europe, large-scale precipitation and flood extremes are associated with moisture supply mainly from the Atlantic and Mediterranean (Hofstätter et al., 2017). Cyclones moving along the Vb track (van Bebber, 1891) often bring the warm and moist air from the region of Genoa. This situation is the most relevant for summer extreme precipitation over large parts of central Europe (Messmer et al., 2015) and especially significant parts of the Elbe, Oder and Danube basins (Nissen et al., 2014). Towards western central Europe, the frequency of Vb cyclones decreases, and extreme precipitation and flooding primarily occur during the cold half-year due to zonal westerly circulation patterns associated with Atlantic frontal systems (Beurton and Thieken, 2009; Jacobeit et al., 2003). Central Europe thus forms a kind of transitional zone between the more frequent winter hydrometeorological extremes in the west and summer extremes in the east.

The connection between hydrometeorological extremes in central Europe and synoptic types is relatively well discussed in the literature (e.g. Jacobeit et al., 2006; Wypych et al., 2018). In connection with extreme precipitation and floods, the synoptic classifications are often qualitative, i.e. the circulation patterns are classified based on similar fields of sea level pressure or geopotential height (Jacobeit et al., 2003; Ustrnul and Czekierda, 2001), cyclone tracks (Hofstätter et al., 2017), etc. However, when associated with extreme events, Müller and Kašpar (2010) emphasized the need to add a quantitative aspect to the classification process, which allows expressing the extremity of circulation conditions at different places.

Such a quantitative evaluation of the synoptic–dynamical conditions can be based on anomalies of some meteorological variables (Martius et al., 2006) or their combinations (Kašpar and Müller, 2014). Most notably the transport of moisture seems to be essential for the occurrence of precipitation and flood extremes in central Europe (Froidevaux and Martius, 2016; Müller and Kašpar, 2011). However, the moisture supply is probably not sufficient because only sustained ascent of moist air provides suitable conditions for extreme precipitation (Doswell et al., 1998).

In any case, if some circulation anomalies are connected to extreme precipitation and floods, they can be used also for forecasting those events. Given that some circulation anomalies, e.g. moisture fluxes, are related to a larger-scale circulation, we can assume that their predictability will be better than in the case of precipitation, which is driven by more complex small-scale atmospheric processes (Lavers et al., 2016). There is already evidence from the previous research that integrated vapour transport is more predictable than precipitation (Lavers et al., 2014), so it could support extreme precipitation forecasts even at longer lead times and improve preparedness for precipitation and flood extremes.

2 Aims of the study

The general aim of this work was to study hydrometeorological extremes in complex from the consequences, i.e. floods, to meteorological causes including heavy precipitation and the causal conditions in the atmosphere. Hladný (2007) emphasized the need to examine all these components together in the so-called hydro-synoptic continuum. The focus was on the large-scale flood and precipitation extremes that occurred in the second half of the 20th century and then until 2013 in central Europe. Therefore, a study area of five main river basins in central Europe (Fig. 1) was examined so that the entire events or their substantial parts could be captured. The other part of the work was more practically focused on the use of the acquired knowledge about circulation causes in forecasting extreme precipitation and floods, which could possibly improve preparedness for these events.

Altogether, the thesis had several partial objectives:

- Compilation of the list of extreme floods in central Europe, objectively evaluated by an index combining the discharge magnitudes with lengths of the affected rivers. Determination of the spatial and temporal distribution of extreme flood events.
- Compilation of the list of extreme precipitation events in central Europe, objectively evaluated with respect to the areal precipitation extremity. Comparison of the lists of extreme floods and precipitation events. Evaluation of events hierarchically, on different spatial levels, to cluster the events according to spatial patterns of precipitation. Assessment of the seasonal occurrence of precipitation events.
- Explanation of the circulation causes of extreme precipitation events in central Europe by the combined evaluation of anomalies of the atmospheric moisture flux and the upward vertical velocity, which are both important ingredients required for the extreme precipitation

occurrence. Comparison of the types of events obtained with regard to similar circulation anomalies with the event clusters generated according to spatial patterns of precipitation.

- Verification of the ability to use moisture flux anomalies as an additional forecasting tool, which could potentially help to predict the occurrence of extreme precipitation events in central Europe.

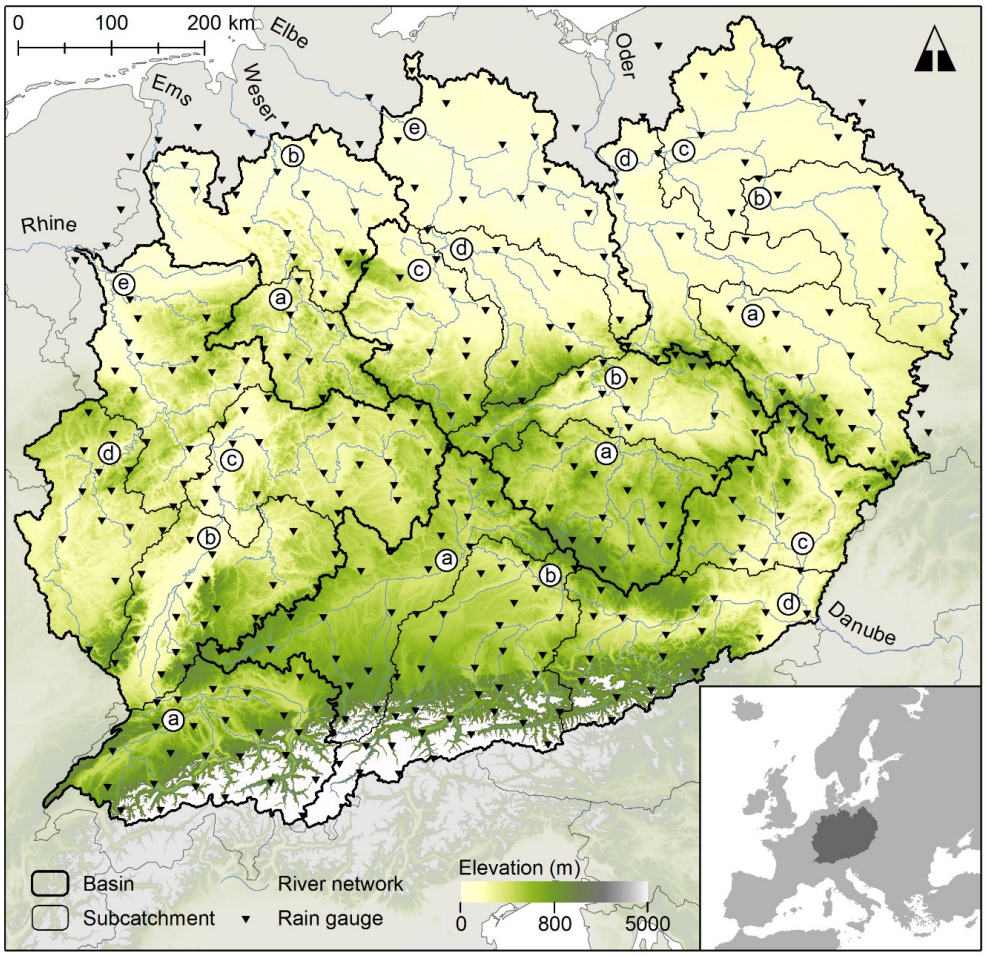

Figure 1: Rain gauges and the study area of central Europe divided into basins and subcatchments. The letters indicating subcatchments correspond with Figure 3.

3 Material and methods

The data used in the thesis were of four types: (i) time series of mean daily discharges at selected gauge stations; (ii) daily precipitation totals at selected rain gauges (Fig. 1); (iii) mean daily reanalysis of zonal and meridional moisture flux at the isobaric level of 850 hPa, vertical velocity at 700 hPa level and precipitation from ERA5 and ERA-Interim reanalyses; (iv) and the ERA-Interim prognostic fields of the same variables. The evaluated period initially ranged from 1951 to 2013, but due to data availability, the assessment of circulation causes was carried out only from 1979.

The methodology for the identification of extreme large-scale floods was primarily based upon the approach of Uhlemann et al. (2010), when both the spatial extent of floods – given by the length of the affected river segments – and the aspect of the discharge magnitudes was incorporated into an extremity index, which evaluated flood events. Similarly, an index for the evaluation of extreme precipitation events was established by Müller and Kašpar (2014). The index combines the information about the rarity of precipitation totals, the area affected by precipitation and the event duration, which are optimized for each event. To determine the spatial patterns of extremity of large-scale precipitation events, the index calculation was applied also to smaller parts of the study area defined in Fig. 1.

As heavy precipitation is mainly a result of ascending low-level moist air (Doswell et al., 1998), the information about magnitude and direction of moisture fluxes over areas of extra high upward vertical velocity was used for the evaluation of circulation conditions during large-scale precipitation events. To each of the reference precipitation events, it was possible to assign one of the four variant of moisture flux conditions (i.e. west, east, south and north), which showed the largest anomaly with respect to its climatology.

To assess the predictability of moisture flux anomalies, the actual size of the moisture fluxes in the area of extra high upward vertical velocity was calculated for both reanalysis and forecast and compared day by day, when the numbers of hits, false alarms, misses and correct negatives were determined. For the comparison of the predictability of vertical velocity, moisture fluxes and precipitation, the anomaly correlation between the grid points of a single pair of reanalysis/forecast fields was computed according to Wilks (2011).

4 Results and discussion

4.1 Extensive floods

According to various studies, the number of extreme precipitation events is increasing and probably will increase in the future, but this is not so certain in the case of extreme floods. This thesis cannot approve or reject the statement, as the study period was quite short for analysing trends of very rare events. Generally, the flood events did not occur regularly over time and they rather accumulated in certain periods.

In the list of extreme flood events from 1951 to 2013, those of the cold half-year predominated with peaks in January and March. The secondary frequency maximum occurred in July, but in general, summer events accounted for only one-third of the major floods (Fig. 2). Nevertheless, the flood of June 2013 was the first in the ranking and the August 2002 flood was the third. Such a high ranking may be related to the wet conditions before flooding events (Grams et al., 2014; James et al., 2004) and also to the unusually large affected area in 2013.

The size of the affected area largely controls the value of the flood extremity index of Uhlemann et al. (2010). Therefore, some events that occurred on the edge of the study area could be underestimated. The flood of July 1997 is an example of the underestimation, as in addition to the Oder River basin, the flood also affected the Vistula basin to the east of the study

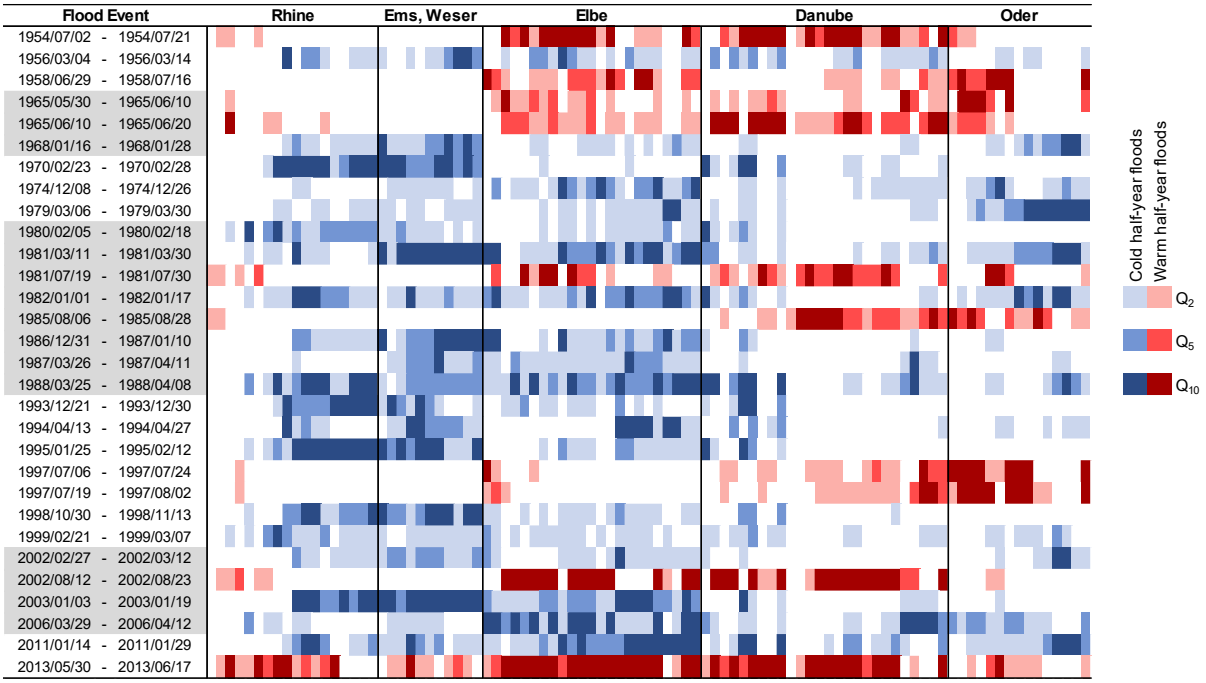

Figure 2: The occurrence of discharges equal to or greater than 2-, 5- and 10-year flood at individual stations during each of the 30 maximum floods between 1951 and 2013. The basins are indicated at the top of the chart; the stations are arranged according to their position downstream.

area (Kundzewicz et al., 1999). In the list of extreme floods, the 1997 event was at the 18th position and its rating would likely be higher if we consider the Vistula basin.

Regarding the spatial distribution of floods, there were regions affected by extreme floods only in the cold half-year, i.e. Weser, Ems, and the lower part of the Rhine River basin including the Main, or in the warm half-year, i.e. most of the Alpine rivers. By contrast, other regions were prone to extreme floods in both the cold and warm halves of the year: the Oder, Elbe and Danube River basins, apart from the Alpine tributaries (Fig. 2). In general, the number of cold half-year floods decreases towards the east, whereas the number of warm half-year floods increases in the same direction.

4.2 Extreme precipitation events

Although assessed in a similar way combining event magnitude and spatial extent, the lists of large-scale precipitation and flood extremes overlapped only to a limited extent. Central European extreme precipitation events were distributed over the whole year but with higher concentration and extremity in its warmer half. The discrepancy between the lists can be justified by the large number of winter floods that were partially caused by snowmelt and did not depend only on extreme precipitation (Uhlemann et al., 2010). Although these floods have lower return periods of discharge values, they may be very extensive (Brázdil et al., 2005), causing their frequent representation among the major flood events. On the other hand, the two lists corresponded in the summer extremes in July 1981 and 1997, June 2013 and August 2002, which in this order represented the maximum recorded precipitation events.

Many precipitation events resembled each other in where heavy precipitation occurred. Therefore, it was possible to divide the extreme precipitation events according to the similarity in the spatial patterns into two main types of events that basically occurred either in the west or in the east. The finer clustering then divided the events into five groups (Fig. 3). Only two of them, namely ED (Elbe-Danube) and O (Oder), were represented among the top ten central European extreme precipitation events. The events were exceptional in their seasonality too, because they occurred exclusively from the end of May to the beginning of September. Three other groups consisted of generally lower extreme events rather equally distributed throughout the year, so their seasonal pattern was not so obvious. Within the eastern-type events (E-CE), the only winter cases appeared in the RD (Rhine-Danube) group, when mainly the Upper Rhine and the Danube without the Morava basin were affected (Fig. 3). Despite the expectations, the western-type precipitation events (W-CE) were not predominantly of a winter character as were the flood extremes (Beurton and Thieken, 2009), but in fact, a lot of these events occurred during the spring and autumn within the Rhine basin (R group) or even in summer months in case of the northwestern part of central Europe (NW group).

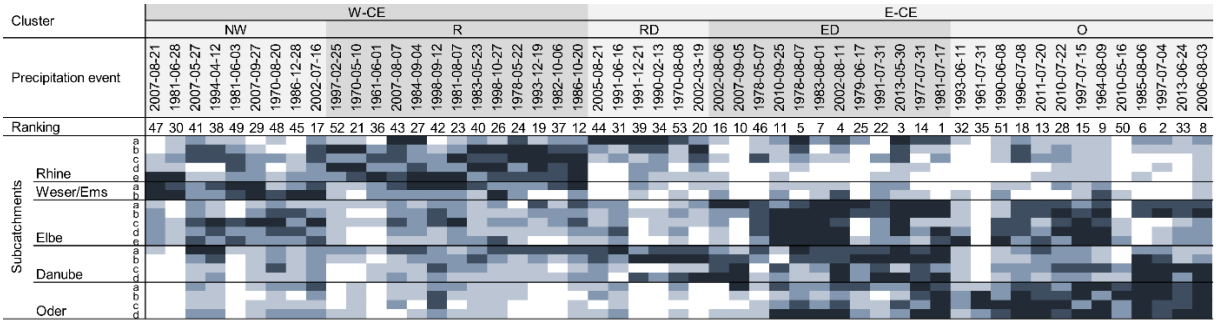

Figure 3: Values of extremity index in individual subcatchments during the 53 maximum precipitation events. Darker colours indicate larger index values.

4.3 Moisture flux anomalies

The circulation conditions during extreme precipitation events were analysed quantitatively by examining moisture flux magnitudes and direction in the area of extra high upward vertical velocity. Three types of events were recognized: (i) events with dominating moisture flux from the northern sector (*Nf*), (ii) events with dominating moisture flux from the western sector (*Wf*), and (iii) weak flux events (*Ot*). Additional analysis showed that these types of moisture flux conditions corresponded perfectly with seasonal and spatial patterns of extreme precipitation (i.e. groups according to spatial patterns, compare Figs. 4a and 4b). Events with prevailing northern moisture flux were concentrated only in the warm half-year and affected mainly eastern central Europe, while events with prevailing western moisture flux occurred in the west

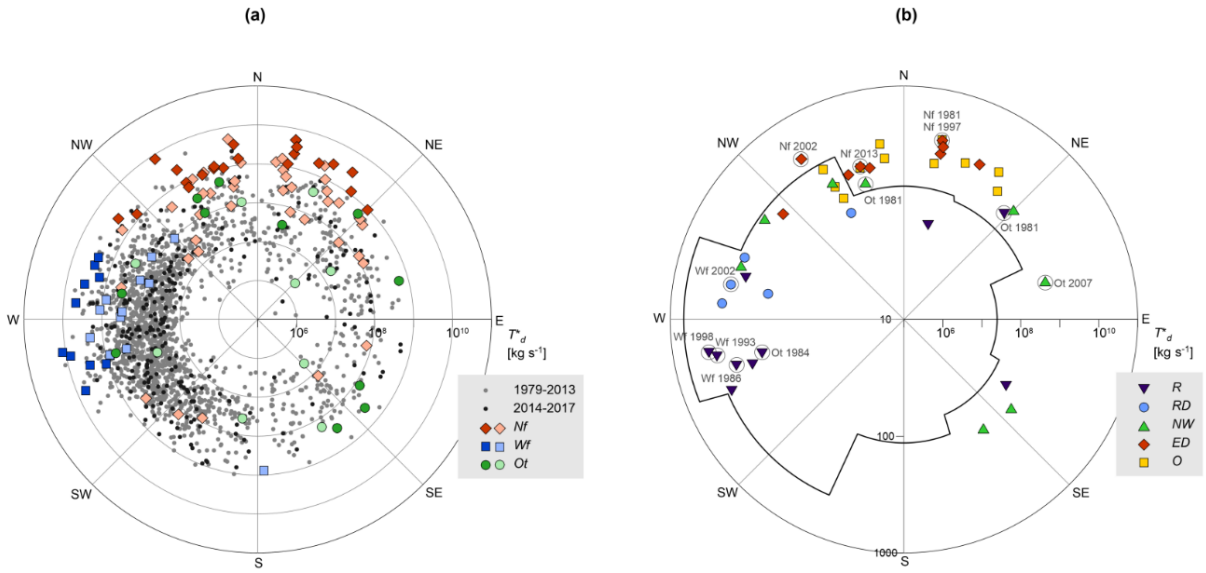

Figure 4: (a) Magnitude and direction of moisture flux accumulated in the area of extra high upward vertical velocity on days between 1979 and 2017. Values measured during the extreme precipitation event are marked with larger symbols differentiated by groups *Wf*, *Nf* and *Ot*; darker symbols indicate the maximum value measured during the event. (b) Only days with maximum moisture fluxes during individual events are presented, differentiated by their membership to spatial clusters R, RD, NW, ED, and O. The numbers of all moisture flux values in each directional sector are only indicated by the solid line. The largest events are labelled.

and exclusively from September to March. In summary, the difference between the two main groups of extreme precipitation events in central Europe can be explained by the seasonal distribution of extra high values of moisture flux from the respective sectors. The last group of weak flux events did not represent the largest precipitation extremes, the group consisted of events of various synoptic causes or even convective events that occurred usually during warm half-year in the western part of central Europe.

Mainly in case of *Nf* events, the extremity of circulation, i.e. anomalies of moisture flux, explained well the occurrence of relevant precipitation extremes (Fig. 4a). In contrast, there was not a clear relationship between anomalies of western moisture flux and the respective precipitation events. Western fluxes were often too large even on days without significant precipitation extremes. The reason could be that the moisture flux is directly proportional to wind velocity, which is usually stronger in the case of western fluxes; this fact allows windstorms to reach high moisture flux values, too. Although wind and precipitation extremes occur relatively often simultaneously during the winter months (Martius et al., 2016), some strong western moisture flux events did not correspond with precipitation extremes.

4.4 Application in forecasting

Due to a close connection between anomalies of northern moisture flux and extreme precipitation of the respective type, we could ask a question whether the predictability of moisture flux anomalies is good enough to support the correct prediction of extreme precipitation events.

In fact, only a few studies have compared the predictability of precipitation and moisture transport; e.g. Lavers et al. (2014, 2016) confirmed the higher predictability of integrated vapour transport compared to precipitation. Similarly, this thesis demonstrated excellent predictability for zonal and meridional moisture fluxes at the 850 hPa level. However, while the predictability of moisture flux itself proved to be very good and more reliable than of precipitation (Fig. 5), generally less accurate forecasts of the vertical velocity negatively affected the predictability of moisture flux accumulated in the area of extra high upward vertical velocity. It produced a large number of false alarms, especially in case of summer precipitation events with prevailing northern moisture flux.

Despite the general inaccuracy, the forecast of moisture flux anomalies in the area of extra high upward vertical velocity was good and stable up to six days in advance in all cases of maximum events that produced major central European summer floods, such as in July 1981 and 1997, August 2002 or June 2013. There was no such continuity for less extreme or false alarm events.

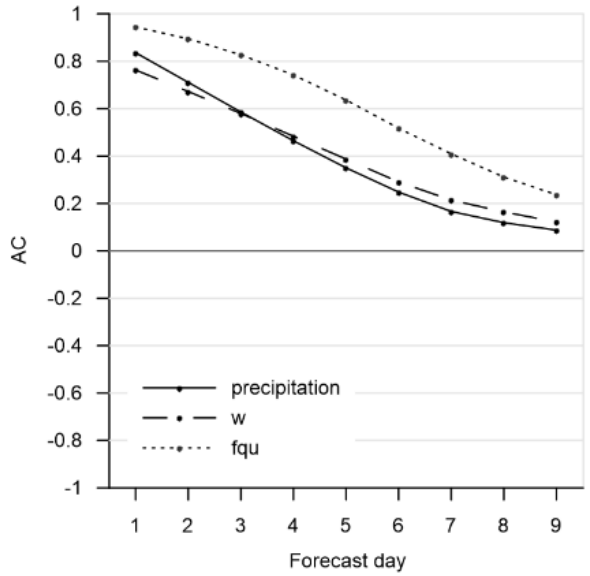

Figure 5: Median values of anomaly correlations for precipitation, vertical velocity (*w*) and zonal moisture flux (*fqu*) forecasts for 1- to 9-day lead times.

5 Conclusions

Through the thesis, all of the parts of the "hydro-synoptic continuum" was considered. Thanks to the larger area of interest, it was possible to examine the spatial structure of events, the differences between them, and their relation to conditions in the atmosphere. The application of the acquired knowledge in the extreme precipitation event forecast is the added value.

Predominantly, the study was focused on large-scale extreme precipitation and floods, for which the size of the affected area is as crucial in the extremity assessment as the magnitude of precipitation totals or flood discharges. The advantage of the extremity indices used is that they

connected both aspects. However, even the same concept produced two different lists of extreme events. The lists matched perfectly only in case of major summer events that affected mainly Elbe, Danube and/or Oder basin and resulted in the largest and most damaging summer floods in central Europe. All of those summer extremes were associated with anomalous northern moisture fluxes in the lower troposphere, which were well predicted already six days in advance. In the future, the forecasts of moisture flux anomalies could complement the quantitative precipitation forecast for the prediction of high-impact summer events and thus support the process of issuing weather warnings and improve preparedness for extreme summer precipitation and flood events.

Although the contribution for summer extreme events is clear, the issue of cold half-year events with a prevailing western moisture flux remains unresolved. The problem is that the correspondence between extreme western moisture flux and the precipitation events of that type was not so strong. Therefore, it is necessary to look for other circulation anomalies or their combinations that would better suit the occurrence of these extremes.

The problematic forecast of vertical velocities is the second issue that should be addressed in further research. Worse vertical velocity forecast negatively affected the predictability of moisture flux anomalies especially in case of less extreme events. Alternatively and independently of the vertical velocity, it would be possible to employ integrated vapour transport, as the variable is often associated with flood and precipitation extremes in other studies. However, its use can be problematic due to the large wind shear that occurs during summer events with the flux of moisture from the northern sector. This statement would need to be confirmed, as well as the results obtained from ERA-Interim forecasts, which should be verified in the future using other numerical weather prediction models with finer horizontal resolution.

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Education

- Since 2015 – Doctoral study program of Physical geography and geoecology, Charles University, Faculty of Science
  PhD project: Relationship among moisture flux anomalies, extreme precipitation, and floods in central Europe
- 2013-2015 Master study program of Physical geography and geoecology, Charles University, Faculty of Science
- 2010-2013 Bachelor study program of Geography and cartography, Charles University, Faculty of Science

Study stays abroad

- 2018/11-2019/01 Erasmus Traineeship at the Institute of Meteorology, Free University of Berlin, Germany
- 2013/09-2014/01 Erasmus study program at Faculty of Life and Health Sciences, University of Ulster, UK

Work experience

- Since 2016/09 – Forecaster at Central forecasting office, Czech Hydrometeorological Institute, Prague
- Since 2019/11 – Meteorologist at Satellite Department, Czech Hydrometeorological Institute, Prague

Conferences and courses

- The EMS Annual Meeting: European Conference for Applied Meteorology and Climatology, 2019, Copenhagen, Denmark (poster presentation)
- Using ECMWF's Forecasts (UEF2019), 2019, Reading, UK (poster presentation)
- International Summer School on Applications with the Newest Multi-spectral Environmental Satellites, 2018, Bracciano, Italy
- The EMS Annual Meeting: European Conference for Applied Meteorology and Climatology, 2017, Dublin, Ireland (poster presentation)
- Weather Radar Application in Nowcasting for Weather Forecasters, 2017, Langen, Germany
- 16th EMS Annual Meeting & 11th European Conference on Applied Climatology (ECAC), 2016, Terst, Italy (oral presentation)

Publications

- **Gvoždíková, B.**, Müller, M. Predictability of moisture flux anomalies indicating central European extreme precipitation events. Submitted to Quarterly Journal of the Royal Meteorological Society.
- **Gvoždíková, B.**, Müller, M., 2021. Moisture fluxes conducive to central European extreme precipitation events. Atmospheric Research, 248. https://doi.org/10.1016/j.atmosres.2020.105182.
- **Gvoždíková, B.**, Müller, M., Kašpar, M., 2019. Spatial patterns and time distribution of central European extreme precipitation events between 1961 and 2013. International Journal of Climatology, 39, 3282−3297. https://doi.org/10.1002/joc.6019.
- **Gvoždíková, B.**, Müller, M., 2017. Evaluation of extensive floods in western/central Europe. Hydrology and Earth System Sciences, 21, 3715–3725. https://doi.org/10.5194/hess-21-3715-2017.
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Additional skills

- Computer skills – Microsoft Office, ArcGIS, basic programming in Python
- Languages – English (Upper-Intermediate), French (Elementary)