Success Rate Evaluation of Severe Storm Phenomena and Flash Floods Forecasting

DAVID ŠAUR
Regional research centre CEBIA-Tech
Tomas Bata University in Zlin
Faculty of Applied Informatics, Nad Stranemi 4511,760 05, Zlin
CZECH REPUBLIC
saur@utb.cz

Abstract: - This article focuses on proposal new methods to predict strong convective storms that can cause flash floods. Flash flood is determined by the interaction of a number of factors such as the very intense convective precipitation (torrential rainfall accompanied by hail and strong wind gusts), slow motion of convective storms and the soil saturation. These factors have been included in the Algorithm of Storm Prediction, whose prediction results are presented in the two outcome of this article. The result section contains an assessment of the success rate of predictions of convective precipitation and storm intensity, which is complemented by the evaluation of the prediction success rate of severe storm phenomena. Primarily, the goal of the algorithm is to provide predictive information about risk of flash floods that comprise all the above mentioned outputs. Secondarily, the orieintally overview of other forecast outputs is part of the second result section.

Key-Words: - Weather forecasting; convective storm; torrential rainfall; hailstorm; strong wind gusts; flash floods; meteorological radars; crisis management; NWP models.

1 Introduction

Natural disasters are one of the most significant threats to contemporary society, particularly disasters caused by the weather in the Czech Republic and the world. These are mainly floods, storms, and gales. Floods represent one of the most significant direct hazards for the Czech Republic, where there are significant losses in life and economic losses. Floods caused by steady rain significantly affected the Czech Republic in years of 1997, 2002 and 2006. Flood damage amounted to nearly 150 billion. Moreover, dozens of people were killed as a result of heavy rainfall. Floods caused by torrential rainfall (called "Flash floods") have started to occur regularly in the Czech Republic since 2007. Nevertheless, this type of floods has become a current issue of crisis management. At the same time a threat to our entire society due to their high frequency of intensity and short duration of severe storm phenomena, especially torrential rainfall, which are one of the leading causes of the flash floods [1, 2, 3].

Severe storm phenomena associated with strong severe storms are one of the impacts of global climate change with a natural uneven occurrence [5]. Typical consequences of global climate change are the global increase of surface temperature and atmospheric humidity caused by the melting of glaciers, frozen land and sea ice [4, 6], which contributes to growing the frequency of these extreme weather events and also flash floods.

The possibilities of flash floods prediction are still insufficient due to a large number of parameters that affect the formation of flash floods. The reason for the low success rate of predicting intense torrential rainfall and other dangerous phenomena is their local occurrence in a tiny area of several km^2 with a short duration (approximately ten of minutes). Current forecasting systems such as numerical weather prediction models (NWP models), nowcasting systems and expert meteorological systems allow predicting the occurrence of torrential rainfall with relatively low success and short lead times. The prediction of intense convective precipitation by NWP models has been investigated in many studies [7, 8, 9]. The fundamental problem of NWP models lies in the lack of horizontal resolution, the amount of input data, including the absence of the effect of orography on the initiation of convection. Nowcasting systems work with data from radar rainfall measurements to calculate the motion field of precipitation using extrapolation methods [10, 11, 12] with a very short lead time (approximately

---

60 minutes). These systems do not predict variability of rainfall in time including orographic influences. Expert meteorological systems combine previous systems, including conceptual and statistical models of orography, the use of which is documented in some papers [13, 14, 15].

Limitations of expert systems are based on the disadvantages of applied methods. None of these forecasting tools provide relevant prediction information with higher prediction accuracy. For these reasons, the Algorithm of Storm Prediction was developed to solve these problems. The goal of the algorithm is to provide a more accurate predictive information on convective precipitation and dangerous severe phenomena for the early warning of flash floods with the possibility of deploying preventive flood control measures.

2 Methods

The prediction of intense convective precipitation, which is one of the leading causes of the flash floods, is solved through these systems and algorithms with forecast lead time:

1. System Integrated Warning Service of CHMI with forecast lead time 24 hours.
2. The algorithm of Storm Prediction with lead time 6-24 hours.

System Integrated Warning Service of CHMI provides prediction warning information on dangerous phenomena related to severe storms for the territory of the regions and districts, shown below in Table 1:

Table 1. Classification of dangerous phenomena [16]

Colour	The degree of storm intensity	Rainfall intensity, dangerous phenomena
🟩	Weak storms	below 29 mm/hr., heavy rainfall
🟨	Strong storms	30-49 mm/hr., heavy rainfall, hail and strong wind gust
🟧	Very strong storms	50-89 mm/hr., heavy rainfall, hail, strong wind gust and tornadoes
🟥	Extremely strong storms	above 90 mm/hr., heavy rainfall, hail, strong wind gust and tornadoes

However, the territory of regions and districts is relatively large, so it is essential to use a predictive tool to provide more accurate predictive information on the occurrence of convective precipitation and other dangerous phenomena. This predictive tool is the Algorithm of Storm Prediction proposed in the dissertation work of the author of this article.

2.1. Algorithm of Storm Prediction

The Algorithm of Storm Prediction was developed as a desktop application to provide predictive information on severe convective storms. This algorithm uses the principles of analysis and evaluation of predictive meteorological elements and parameters from NWP models, including the evaluation of orography effects and the use of a database of approximately 200 historical weather situations [3].

The output of the algorithm is a report that contains prediction information:

- precipitation occurrence - municipalities with extended powers (MEP) and its regions,
- time of precipitation occurrence and
- forecast lead time with 6-24 hr [3].

Fig. 1 demonstrate that predictive algorithm outputs are computed through ten phases. The null phase is focused on converting input data from NWP models and other sources (database of historical situations and relief characteristics, alerts from CHMI and ESTOFEX) to coefficient values in the interval 0-3.

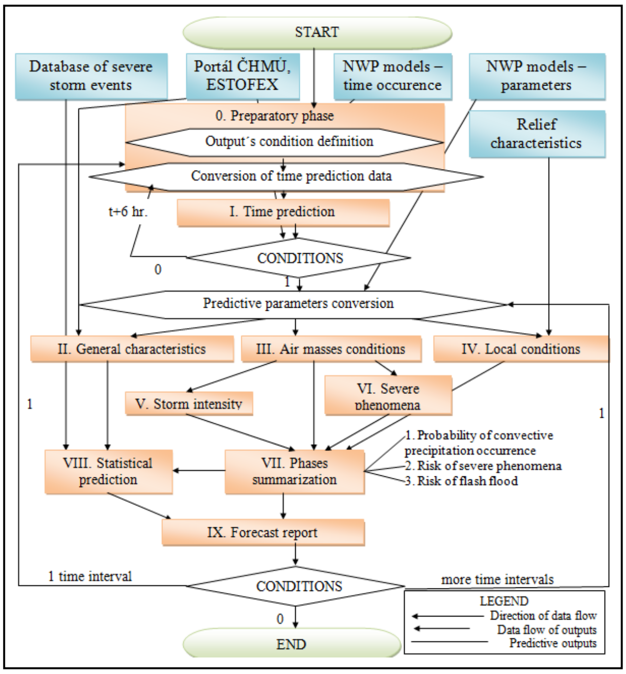


Fig. 1. Flowchart of Algorithm of Storm Prediction [3]

Forecasting outputs are computed for each 3-hour interval separately. In the first phase, 3-hour intervals are determined on the forecast of precipitation from seven NWP models with a horizontal resolution of fewer than 11 km. The second phase summarizes crucial predictive information, in particular about the warnings of the CHMI and ESTOFEX. The third phase predicts conventional properties in the atmosphere. The fourth stage predicts conditions of temperature, humidity and airflow in the boundary layer of the atmosphere including orographic effects to predict the conditions for the initiation of atmospheric convection. This phase forms the core of a precision forecast of the probability of convective precipitation. The fifth phase predicts the storm intensity, which is compared with the warnings of the CHMI and ESTOFEX. The occurrence probability of dangerous phenomena such as torrential rainfall, hail, strong wind gusts and tornadoes are predicted in the sixth phase. The aim of the seventh phase is merging outputs from third to sixth phases, which are accompanied by a statistical prediction of convective precipitation in the eighth phase. The ninth phase summarizes and visualizes these forecast outputs to maps for the MEP and regions:

- general characteristics of the predicted situation (alg.)
- **forecast of the probability of convective precipitation occurrence (alg.),**
- **forecast of storm intensity (alg.),**
- **forecast of the risk of flash floods (alg.),**
- forecast of time probability and precipitation occurrence (NWP models) and
- **forecast of the risk of dangerous phenomena (alg.).**
- statistical prediction of the probability of convective precipitation (alg.) [3, 4].

The situation associated with flash floods are analyzed and evaluated by boldly marked prediction outputs.

Predictive outputs are calculated as their probability values, which is recalculated to coefficient values in the range from 0 to 3 according to the formula:

$$P_{h_i} = \frac{\sum_{j=1}^{k} v_j y_{ij}}{3\sum n}, \qquad (1)$$

where *yij* are values of the critical matrix *Y* (values of coefficients, converted predictive parameters from NWP models) and v_j is the weight of the j-th criterion which is weighted coefficient values of predictive parameters. Σn represents the sum of predictive parameters in a partial or main output [3].

2.1.1 Forecast of the probability of the rainfall intensity and its occurrence

This forecast output is calculated from outputs of the fourth and fifth phase (Storm Intensity + Local Conditions) according to formula 1. Verification of this output is performed with data from the stationary measurement of CHMI network [3].

2.1.2 Forecast of storm intensity

Storm intensity forecast is calculated from partial outputs of the third phase according to formula 1:

- day or night atmosphere instability,
- comprehensive support for convection mechanisms,
- deep layer shear in levels 0 - 6 km,
- propagation, and motion of storms.

This output is compared with the CHMI alerts for a dangerous Storm phenomenon for its verification [3].

2.1.3 Forecast of the risk of flash floods

Risk of flash floods is calculated by combining the critical prediction algorithm outputs (formula 1):

- the degree of soil saturation,
- the number of potential risk precipitations in 1 hour,
- the probability of convective precipitation,
- the storm intensity,
- the propagation and motion of storms,
- the summary of dangerous phenomena [3].

The risk of flash floods is verified by the Czech Hydrometeorological alerts, data from the radar and station measurement of precipitation and flood events reported by the Fire Rescue Service of the Czech Republic.

As can be seen in Table 2, coefficients shown in bold represent high to the very high risk of flash floods, when the determination would be possible to start the implementation of flood prevention measures.

Table 2. Classification of evaluated algorithm outputs [3]

Coefficients	**Rainfall probability**	**Storm intensity (mm/hr.)**	**Risk of flash flood**
0	0-0,24	Weak (0 - 29)	Very low
1	0,25-0,49	Strong (30 - 49)	Low
2	0,50-0,74	Very strong (50 - 89)	High
3	0,75-1	Extremely strong (nad 90)	Very high

Verification of predicted outputs is performed by the Accuracy fundamental verification criterion using the pivot table according to the equation:

$$A = \frac{a+d}{a+b+c+d} \times 100\ (\%), \qquad (2)$$

where a is the number of cases where the phenomenon was predicted and actually occurred; b is the number of cases where the phenomenon was not predicted and actually occurred; c is the number of cases where the phenomenon was predicted and did not actually occur, and d is the number of instances when the phenomenon was not predicted and did not actually occur.

The Accuracy verification criterion is calculated for each three-hour interval separately, both for municipalities with extended powers and their regions according to the equation:

$$\bar{X} = \frac{1}{n} \sum_{i=1}^{n} x_i, \qquad (3)$$

where $\sum x_i$ is the sum of categories $a, b, c, d,$ which is evaluated for each situation separately [3].

2.1.4 Forecast of risk of severe storm phenomena

The prediction of the risk of severe storm phenomena is the seventh predictive phase of Algorithm of Storm Prediction. This output is designed to calculate summaries of severe storm phenomena, which is one of significant predictive outputs for determining the risk of flash floods.

Coefficients values of the risk of severe storm phenomena are calculated according to formula 1. The weights of coefficients values of forecast parameters for individual severe storm phenomena were experimentally determined on:

- the Check-list document from the Czech Hydrometeorological Institute,
- the percentage of prediction parameters of severe storm phenomena,
- weight parameters determined on the basis of literature.

The Algorithm predictive output classification is shown in Table 3. The intensity of the torrential rainfall corresponds to the predicted output Storm Intensity from the first result section. Classification of Hail forecasting is based on the document [17]. Classification of the prediction output Strong wind gusts were taken from the classification of severe storm phenomena of the Integrated Warning Service System of the Czech Hydrometeorological Institute [18].

Table 3. Prediction outputs classification of the second result chapter [17].

Coefficients	**Intensity of torrential rainfall (mm/hr.)**	**Radar reflectivity (dBZ) measured by the radar network CZRAD, converted on rainfall intesity (mm/hr.)**	**Strong wind gusts (m/s)**
0	0 - 29	48 (37)	<20
1	30 - 49	52 (65)	20-24
2	50 - 89	56 (115)	25-29
3	above 90	60 (200)	>30

Table 3 show the evaluation of Hail forecast based on the radar precipitation measurements. The hourly rainfall intensity is calculated by the Marshall-Palmer formula:

$$Z = aI^b \qquad (4)$$

$$I = 10(Z-10\log(a))/10b. \qquad (5)$$

Where Z is the radar reflectivity in dBZ, I is the rainfall intensity in mm / h, a and b are experimentally determined constants (a = 200, b = 1.6) for medium latitudes. Hourly rainfall intensity values have an exponential trend of the growth depending on the radar reflectivity [3].

The radar measurement data was obtained from the CZRAD radar network and the MMR50 X-band meteorological radar of the Zlín Region.

2.1.3.1 Forecast of risk of torrential rainfall

"The torrential rainfall is a rain of high intensity, which is predominantly short in the order of several tens of minutes to hours, and a small area in km2 in our regions" [19].

Fig. 2 Torrential rainfall

As can be seen in Fig. 2, the torrential rainfall is caused by a strong rainfall effect of convective storm due to favorable temperature, humidity and wind conditions in the atmosphere, especially high Convective avalaible potential energy (CAPE) values and Deep layer shear (DLS). The massive vertical range of the convective cell (over 10 km) and the terrain orography that can significantly enhance this phenomenon in terms of upslope triggering in combination with the ground-level convergence of air flow are at the same time other important conditions for the formation of this severe storm phenomenon (Řezáčová, 2007).

The risk of torrential rainfall is calculated according to these partial forecast outputs:

- speed of storm motion
- conditions for the occurrence of severe storm phenomena (mechanisms to support the occurrence of severe storm phenomena, storm intensity and probability of precipitation)
- probability of occurrence of torrential rainfall (6th prediction phase of the algorithm)

The probability of the occurrence of torrential rainfall is determined on the above-mentioned forecast parameters [3].

2.1.3.2 Forecast of risk of hailstorm

Hailstorm is precipitation contained by hails, which is spherical, conical or irregular pieces of ice. It takes a few minutes and hits very small areas. Meteorological radars are used for early identification of the occurrence of this severe storm phenomenon [19].

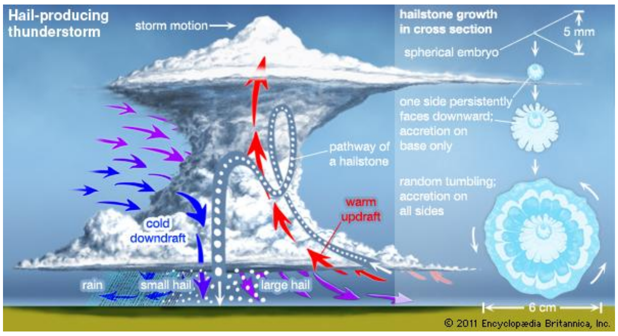


Fig. 3 Principle of hailstorm

Fig. 3 illustrate the hailstorm, which is occurred in the massive vertically convective clouds with characteristic high velocity air flow of its updraft, where are applied same conditions as a torrentiall rainfall. For example, high values of combination indices convection CAPE and DLS, favorable temperature and humidity surroundings, e.g. the zero isotherm level must lie very high, over 4-5 km. The risk of hailstorm is calculated according to these partial forecast outputs:

- conditions for the occurrence of hailstorm
- probability of occurrence of hailstorm [3].

2.1.3.2 Forecast of risk of strong wind gusts

Wind gust is a short-term increase in wind speed, or a short-term deviation from a more permanent wind direction, with values wind speed higher than 20 ms-1. Strong wind gusts are the result of strong downdraft inside the convective storm which is most often occured in the vicinity of atmospheric and gust fronts [19].

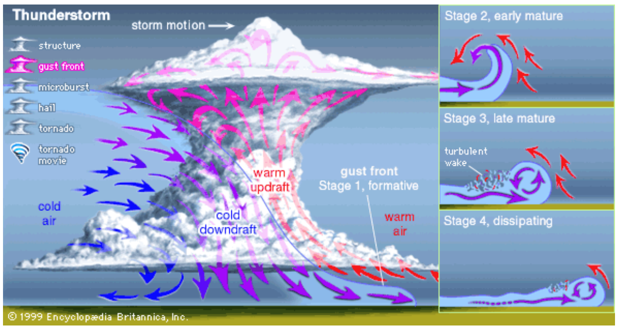


Fig. 4 Principle of strong wind gusts

As can be seen in Fig., the formation of downburst caused strong wind gusts is due to favorable downdraft conditions in the convective storm. The basic parameters of the downburst are the vertical temperature gradient at the middle atmospheric levels, high humidity in lower atmospheric levels, high CAPE, DLS, Low layer shear (LLS) combined with Storm relative helicity (SREH) 0-3 km and SREH 0-1 km, including a low-level jet at 850 hPa and Downdraft CAPE (DCAPE).

Strong wind gusts are caused by the flow of a downdraft when it lands on the earth's surface, which is also associated with a gust front (the interface between cold and ambient air). This phenomenon may take a few minutes, and in exceptional cases up to half an hour. The result of this dangerous phenomenon is the high material damage to property (especially damaged, roofed roofs and houses).

The risk of strong wind gusts is calculated according to these partial forecast outputs:

- conditions for the occurrence of strong wind gusts
- probability of occurrence of strong wind gusts[3].

3 Evaluation of the success rate of flash floods forecast

This chapter focuses on results of verification algorithm outputs with the measured radar and station data of CHMI associated with flash floods in the Zlín Region:

- July 24, 2015,
- August 5, 2016,
- July 22, 2017.

3.1. Flash flood on July 24, 2015

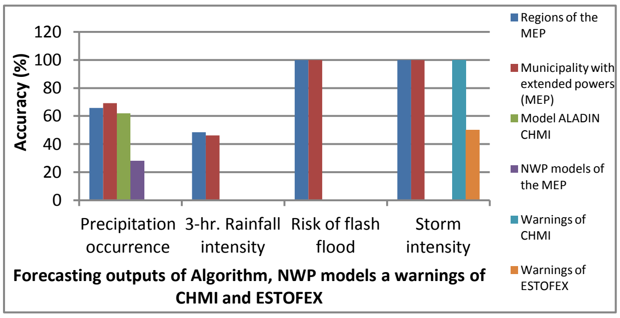
Flood event of July 24, 2015, was characterized by its unexpected emergence and rapid progression. The leading cause of flash floods was cold front above western Slovakia to create favorable conditions in the atmosphere because of its high instability and significant wind shear [3].

Table 3 shows that a low risk of flash floods was predicted for the central, western, northern and northeastern territory of the Zlin region. High risk was calculated for MEP Zlín, where actual floods occurred and caused damage to property and infrastructure in the order of tens of millions of crowns.

Table 3. Verification of flood event on July 24, 2015 [3]

24.7.2015 (18-21:00)	**Predi-ction**	**Reality**	**Predi-ction + reality**	**Predi-ction**
MEP of the Zlín region, *reported flash flood event*	Rainfall intesity (mm/ 3hr.)	Rainfall in mm (the name of station)	Rain-fall inten-sity (mm/ hr.)	Risk of flash flood
Uh.Hradiště	0	7 - Staré Hutě	0-29	0
Otrokovice	3-9	0	0-29	low
Kroměříž	3-9	6 - Kroměříž	0-29	low
Holešov	3-9	6 - Holešov	0-29	low
Zlín	*10-29*	*23 - Zlín*	*0-29*	*high*
Bystřice	3-9	4 - Bystřice	0-29	low
Valašské Meziříčí	0	0	0-29	low
Rožnov	3-9	0	0-29	low
Vsetín	3-9	12 - (Maruška)	0-29	low
Vizovice	3-9	4 Vizovice	0-29	low
Valašské Klobouky	3-9	0	0-29	0
Luhačovice	3-9	0	0-29	0
Uh. Brod	0	0	0-29	0

Table 3 provide a more detailed verification where the most intense rainfall was measured in the Zlin region at the Zlin station (23 mm), where local floods were reported by the authorities of the region's crisis management and Fire Rescue System of Czech Republic.



Graph 1. The accuracy of predictive outputs on July 24, 2015 [3]

Graph 1 provide the results of verification by Accuracy for flood event July 24, 2015. The risk of flash floods reached the highest value in comparison with the Czech Hydrometeorological Institute, which did not issue the alert, very favorable assumption of correct configuration algorithm for prediction of flash floods.

3.2. Flash flood on August 5, 2016

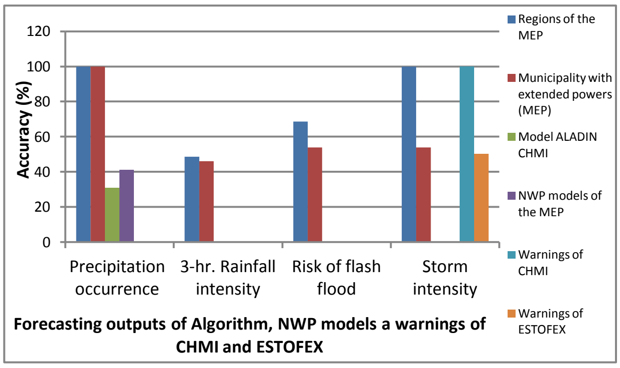
This flood event occurred at a time when it rained in the whole territory of the Zlín Region in previous days. The primary cause of flash floods was the cold front [3].

Table 4. Verification of flood event on August 5, 2016 [3]

5.8.2016 (21-24:00)	**Predi-ction**	**Reality**	**Predi-ction + reality**	**Predi-ction**
MEP of the Zlín region, *reported flash flood event*	Rainfall intesity (mm/ 3hr.)	Rainfall in mm (the name of station)	Rain-fall inten-sity (mm/ hr.)	Risk of flash flood
Uh.Hradiště	10-29	11 - Staré Hutě	30-49	0
Otrokovice	3-9	8 - Košíky	0-29	0
Kroměříž	3-9	8 - Kroměříž	0-29	0
Holešov	3-9	9 - Holešov	0-29	0
Zlín (povodeň)	3-9	6 - Zlín-Štípa	0-29	low
Bystřice	10-29	9 - Bystřice	30-49	low
Valašské Meziříčí	3-9	7 -Valašské Meziříčí	30-49	low
Rožnov	3-9	15 - Horní Bečva	30-49	low

Vsetín	10-29	24 - Val. Senice	30-49	low
Vizovice	0-3	9 - Vizovice	30-49	low
Valašské Klobouky	*10-29*	*21 - Brumov-Bylnice*	*30-49*	*high*
Luhačovice	10-29	14 - Luhačovice	30-49	low
Uh. Brod	10-29	14 - Strání	30-49	low

As can be seen in Table 4, high risk was predicted for the Vsetín and Valašské Klobouky regions, where a local flash flood occurred on the Brumovka river between 22 and 23 o'clock. This flood has caused enormous damage mainly to the infrastructure and property of the population. The intensity of strong storms was predicted for nearly two-thirds of the region, but only in the Valašské Klobouky region, there was a flash flood where the second highest rainfall was measured at the Brumov-Bylnice station (21 mm).

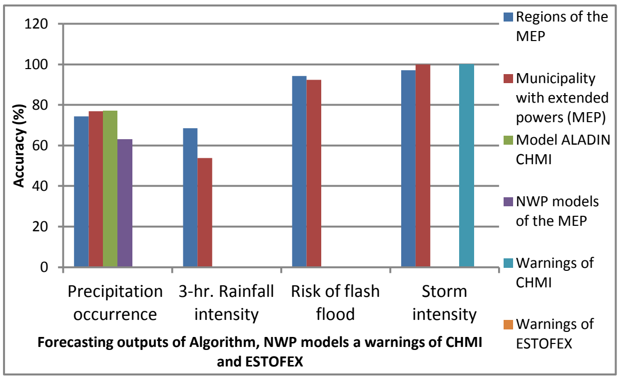


Graph 2. The accuracy of predictive outputs on August 5, 2016 [3]

Graph 2 shows the very high success rate of convective rainfall occurring throughout the Zlín Region. On the contrary, lower values were at the storm intensity. Predicting the risk of flash floods correspond with reality, which was reported flash flood in the MEP of Valašské Klobouky. On the other hand, the Czech Hydrometeorological Institute again did not issue a warning, even though the presence of some factors (for example extreme soil saturation) recorded a probable flood event in the eastern of the Czech Republic.

3.3. Flash flood on July 22, 2017

The last evaluated flood event was the situation on July 22, 2017, when there were very intense convective precipitation between villages of Horní Lhota and Luhačovice in a concise time (approximately 60-90 minutes). The leading cause of flash floods was occluded front, where there was rainfall intensity of 30 mm/hr. in combination with strong wind shear. Just wind shear caused the stationary movement of the severe storm, which led to the formation of the flash flood [3].



Graph 3. Accuracy of predictive outputs on July 22, 2017 [3]

As can be seen in the Graph 3, algorithm and NWP models have the high predictability of convective precipitation. The highest success rate was achieved in predicting the risk of flash floods and storm intensity (the algorithm and warnings of the CHMI). The forecast of the flash flood risk corresponded to the fact that a flood in the Luhačovice MEP was reported. Czech Hydrometeorological warnings were issued for the entire territory of the Zlin Region and despite that flash flood occurred in only one district.

Table 5. The accuracy of predictive outputs on July 22, 2017 [3]

22.7.2017 (15-18:00)	**Prediction**	**Reality**	**Prediction + reality**	**Prediction**
MEP of the Zlín region, *reported flash event*	Rainfall intesity (mm/ 3hr.)	Rainfall in mm (the name of station)	Rain-fall inten-sity (mm/ hr.)	Risk of flash flood
Uh.Hradiště	0	3 - Hluk	0-29	0
Otrokovice	0	0	0-29	0
Kroměříž	0	0	0-29	0
Holešov	0	0	0-29	0
Zlín (povodeň)	10-29	0	0-29	low
Bystřice	0	0	0-29	0
Valašské Meziříčí	0	0	0-29	0
Rožnov	0	0	0-29	0
Vsetín	3-9	3 - Val. Polanka	0-29	0

Vizovice	3-9	0	0-29	0
Valašské Klobouky	3-9	0	0-29	0
Luhačovice	*30-49*	*36 - Horní Lhota*	*30-49*	*high*
Uh. Brod	0	0	0-29	0

Table 5 show that this situation was characterized by the presence of strong local precipitations measured at Horní Lhota station (36 mm / hour), which had a significant influence on the formation of the flash flood. The forecast corresponded to the actual state. High risk was predicted only for the Luhačovice region, where 58 mm / 2 hours precipitation was measured. The flash flood affected the isolated area and damaged the transport infrastructure.

4 Evaluation of success rate of severe storm phenomena forecast

This chapter focuses on results of verification algorithm outputs with the measured station and radar data of CHMI and MMR50 X-band meteorological radar of the Zlin Region associated with severe storm phenomena, which is caused flash floods in the Zlín Region:

- July 24, 2015,
- August 5, 2016,
- July 22, 2017.

4.1. Flash flood on July 24, 2015

The cause of severe storm phenomena, especially torrential rainfall, which was one of significant factors of the flash flood in the central part of the Zlín Region, was the undulated cold front. The formation of torrential rainfall, hailstorm and strong wind gusts have been supported by very favorable thermal, humidity and especially wind conditions, which was a strong wind shear caused by the ground northeast and high-rise southwest winds. Another initiating factor was the orography of Hostýnsko-Vsetínské Highland in terms of the effect of their upslope triggering and leeward effects.

Initially, intense convective precipitation occurred over western Slovakia. The strongest precipitation began to return from Slovakia to the northeast and east of the Czech Republic during the afternoon and evening hours due to the influence of the warm sector of the undulated cold front. As a result, the convective storm slowed down and at the same time to increase precipitation.

Table 7 show that the torrential rainfall with the highest intensity, including the occurrence of hailstorms and strong wind gusts, were predicted and measured especially for MEP Zlín and Holešov. MEP Zlín was actually hit by a local flash flood.

Table 7. Verification of severe storm phenomena 24.7.2015 [3].

24.7.2015 (18-21:00)	**Forecast**	**Real stste**	**Forecast**	**Real stste**
MEP of the Zlín region, *reported flash event*	Intensity of torrential rainfall (mm/ hr.)	Rainfall in mm (station)/ Radar reflectivity v dBZ (radar network CZRAD)	Strong wind gusts (m/s)	Maximal strong wind gusts (m/s)
Uh.Hradiště	0-29	7 - Staré Hutě/ 56	0-19	18
Otrokovice	0-29	0	0-19	12
Kroměříž	30-49	6 – Kroměříž/ 56	20-24	13
Holešov	30-49	6 – Holešov/ 56	20-24	20
Zlín (povodeň)	*30-49*	*23 – Zlín/ 60*	*20-24*	*20*
Bystřice	30-49	4 – Bystřice/ 56	0-19	11
Valašské Meziříčí	0-29	0	0-19	10
Rožnov	0-29	0	0-19	7
Vsetín	0-29	12 - (Maruška) / 60	0-19	15
Vizovice	30-49	4 Vizovice/ 56	0-19	10
Valašské Klobouky	0-29	0	0-19	7
Luhačovice	0-29	0	0-19	8
Uh. Brod	0-29	0	0-19	8

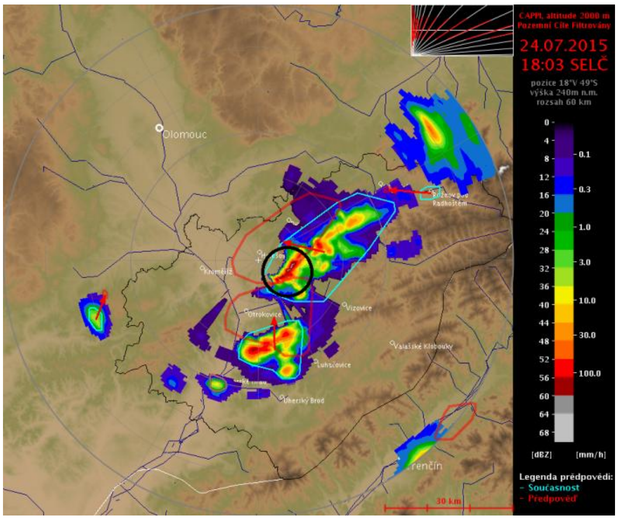
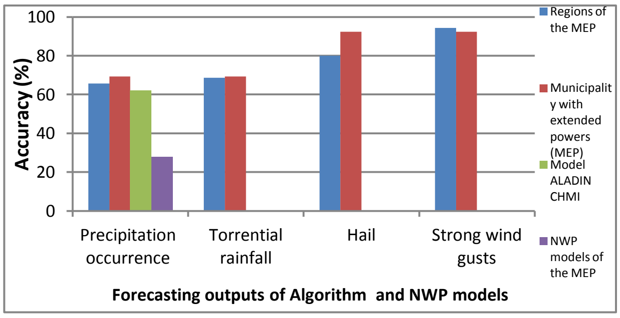


Fig. 5 The most intense rainfall measured by the MMR50 X-band meteorological radar of the Zlín Region (July 24, 2015 at 18: 03 CEST).

As can be seen in Fig. 5, the most intense rainfall was measured for the central area of the Zlín Region in the evening hours. The rainfall intensity has reached the radar reflectivity approximately 60 dBZ (converted to rainfall intensity with value of 200 mm/hr.). This means that there was torrential rainfall in combination with hail, which led to the formation of flash flood.



Graph 4 Verification of severe storm phenomena for the flash flood of 24.7.2015 [3].

Graph 4 indicate that the success rate of torrential rainfall predictions was slightly lower than the success rate of predictions of hailstorm and strong wind gusts. The reason was the local occurrence of torrential rainfall in the MEP Zlín.

4.2. Flash flood on August 5, 2016

The frequency of severe storm phenomena was not as high as in the previous situation. The reason was the undulated cold front of weaker intensity. Nevertheless, the two most important causes of the flash floods were the intermittent and, at the same time, protracted occurrence of weaker convective precipitation combined with extreme soil saturation.

Table 8 document that the occurrence of severe storm phenomena was not predicted for a single MEP. The forecast corresponded to the measured data, with the exception that the most intense precipitation with the radar reflectivity of 60 dBZ was measured by the CZRAD radar network in the MEP Valašské Klobouky. However, torrential rainfall and strong wind gusts did not occur in this area, although local flash flood was registered in this area.

Table 8. Verification of severe storm phenomena 5.8.2016 [3].

5.8.2016 (21-24:00)	**Forecast**	**Real stste**	**Forecast**	**Real stste**
MEP of the Zlín region, *reported flash event*	Intensity of torrential rainfall (mm/ hr.)	Rainfall in mm (station)/ Radar reflectivity in dBZ (radar network CZRAD)	Strong wind gusts (m/s)	Maximal strong wind gusts (m/s)
Uh.Hradiště	0-29	11 - Staré Hutě/48	0-19	10
Otrokovice	0-29	8 – Košíky/ 48	0-19	7
Kroměříž	0-29	8 – Kroměříž/ 48	0-19	8
Holešov	0-29	9 – Holešov/ 52	0-19	14
Zlín	0-29	6 - Zlín-Štípa/ 52	0-19	5
Bystřice	0-29	9 - Bystřice/ 52	0-19	10
Valašské Meziříčí	0-29	7 -Valašské Meziříčí/ 48	0-19	6
Rožnov	0-29	15 - Horní Bečva/ 48	0-19	4
Vsetín	0-29	24 - Val. Senice/ 52	0-19	6
Vizovice	0-29	9 - Vizovice/ 48	0-19	8
Valašské Klobouky (povodeň)	*0-29*	*21 - Brumov-Bylnice/ 60*	*0-19*	*8*
Luhačovice	0-29	14 - Luhačovice/ 48	0-19	7
Uh. Brod	0-29	14 – Strání/ 52	0-19	7

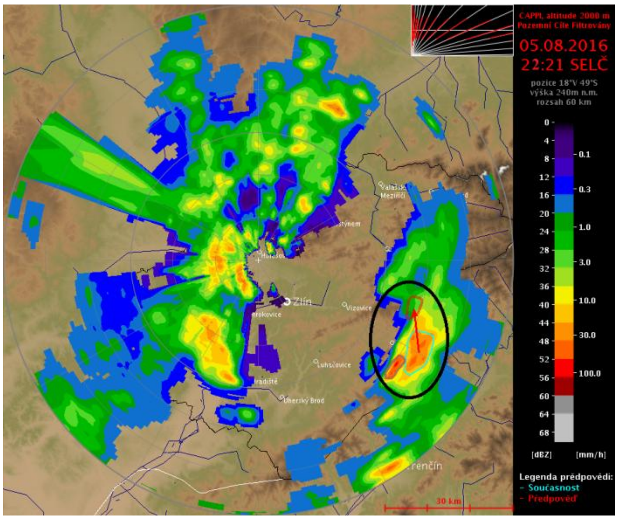
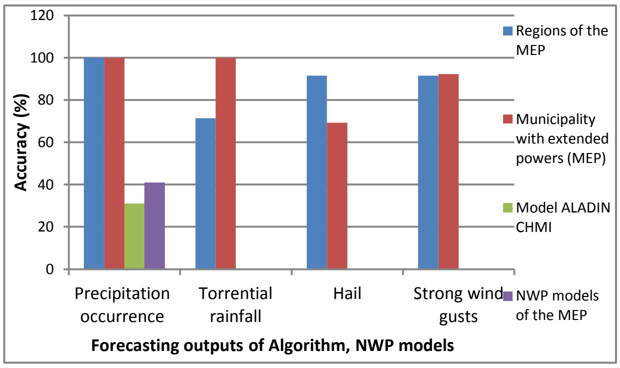


Fig. 6 The most intense rainfall measured by the MMR50 X-band meteorological radar of the Zlín Region (5.8.2016 v 22:21 CEST).

It is clear from Figure 6 that the most intense rainfall occurred in the southeast of the Zlín Region in the MEP Valašské Klobouky. The precipitation progressed from the south with a low intensity (48-52 dBZ), but in the MEP Valašské Klobouky was occurred several times within three hours. Simultaneously, there was an extreme soil saturation, which resulted in the local flash flood on the Brumovka stream between 22:00 and 23:00 CEST.



Graph 5 Verification of severe storm phenomena for the flash flood of 5.8.2016 [3].

Graph 5 illustrate that results of verification of the forecast of severe storm phenomena and convective precipitation. The high values of the forecast of convective precipitation and strong wind gusts were due to the flatness of the convective storm. The lower success rate of torrential rainfall and hailstorm forecast was given by the inaccuracy of the algorithm calculation due to insufficient quantity of prediction parameters from NWP models.

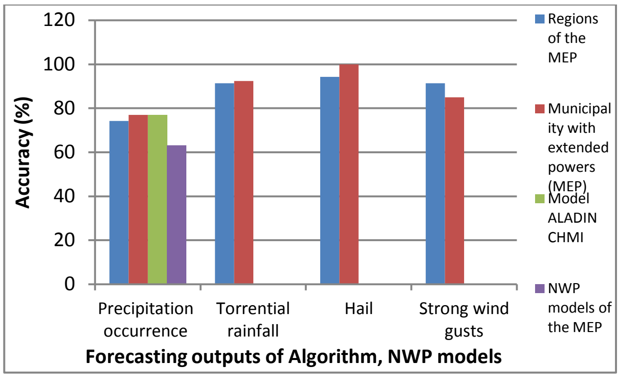
4.3. Flash flood on July 22, 2017

The reason of the formation of the torrential rainfall and hailstorm was the occlusal front, which slowly moved from the southwest to the northeast. Significant wind shear resulted in the deceleration of the intense precipitation and it led to emergence of the local flash flood in the southeastern and central part of the Zlín Region.

Table 9 indicate a successful forecast of torrential rainfall and hailstorm for the MEP Luhačovice, where the local flash flood occurred. Intensive precipitation was also registered in the southern region of the MEP Zlín; however, the predicted precipitation intensity was lower than in the first area. This was also confirmed by the radar and station measurement (no station measured precipitation in this MEP).

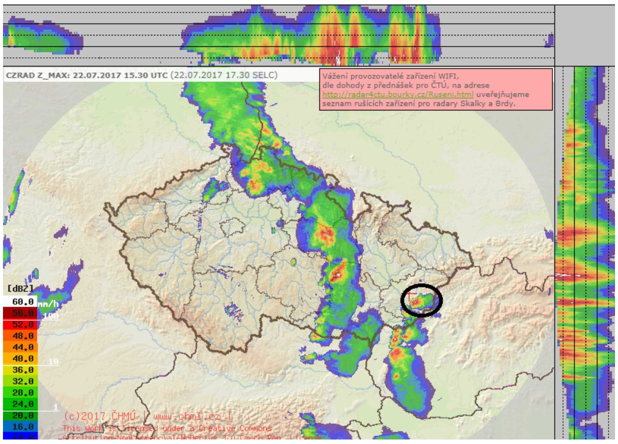
Table 9. Verification of severe storm phenomena 22.7.2017 [3].

22.7.2017 (15-18:00)	**Forecast**	**Real stste**	**Forecast**	**Real stste**
MEP of the Zlín region, *reported flash event*	Intensity of torrential rainfall (mm/ hr.)	Rainfall in mm (station)/ Radar reflectivity v dBZ (radar network CZRAD)	Strong wind gusts (m/s)	Maximal strong wind gusts (m/s)
Uh.Hradiště	0	3 – Hluk/ 56	0-19	8
Otrokovice	0	0	0-19	5
Kroměříž	0	0	0-19	13
Holešov	0	0	0-19	10
Zlín	0-29	0/56	20-24	13
Bystřice	0	0	0-19	8
Valašské Meziříčí	0	0	0-19	14
Rožnov	0	0	0-19	10
Vsetín	0-29	3 - Val. Polanka	0-19	12
Vizovice	0-29	0	0-19	12
Valašské Klobouky	0-29	0	0-19	6
Luhačovice (povodeň)	*30-49*	*36 - Horní Lhota/ 60*	*25-29*	*14*
Uh. Brod	0	0/ 52	0-19	11



Graph 6 Verification of severe storm phenomena for the flash flood of 22.7.2017 [3].

As can be seen in the Graph 4, the high success rate predictions was in all severe storm phenomena, which is paradoxically higher than the prediction of convective precipitations calculated by the Algorithm and NWP models. This case has again confirmed the importance of rare phenomena that occur very locally.



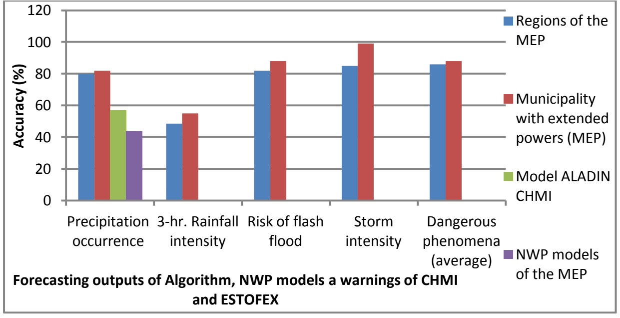
Vážení provozovatelé zařízení WIFI,
dle dohody z přednášek pro ČTÚ, na adrese
http://radar4ctu.bourky.cz/Ruseni.html uveřejňujeme
seznam rušících zařízení pro radary Skalky a Brdy.

Fig. 7 The most intense rainfall measured by meteorological radars of the network CZRAD (22.7.2017 v 17 :30 CEST) [20].

Fig. 7 document and confirm the occurrence of the strongest precipitation in the south-eastern part of the Zlín Region between 17:00 and 18:00. The local flash flood did not cause significant damage to property as in previous situations. Property damage related only to the flooding of the local main road and the roundabout between the village Dolní Lhota and the town Luhačovice, which resulted in traffic constraints due to the occurrence of mud and debris flooded from surrounding hills and fields. Fortunately, human lives were not threatened in connection with this flood event.

5 Success rate evaluation of the Algorithm and NWP models

The average success rate outputs of Algorithm of Storm Prediction and NWP models are shown in Graph 7:



Graph 7 Verification of forecast outputs [3].

It can be seen in Figure 7 that the success rate of the risk of flash floods, storm intensity and severe storm phenomena reached average higher values than predicted probability of convective precipitation. The higher average success rate of these forecasting outcomes was due to the fact that significant parameters of flash floods with their characteristic rare occurrence were evaluated. Generally, NWP models have achieved the lowest success rate due to problematic modeling of convective precipitation, because these models use the hydrostatic core rather determined for modeling stratiform precipitation.

6 Conclusion

This article aimed to provide information on the new forecasting tool (Algorithm of Storm Prediction) regarding its evaluation success rate in three flash flood events that hit the Zlín Region in years of 2015-2017.

The first result section is focused on the verification predictive Algorithm outputs such as probability of convective precipitation, storm intensity and risk of flash floods, which was calculated to a high level for all flood events.

Verified predicted outputs of the algorithm were the probability of the precipitation occurrence, storm intensity, and the flash flood risk, which was calculated to a high degree for all flood events. It corresponded to the fact that there were floods occurred in the regions. On the contrary, the CHMI issued warnings on dangerous phenomena of severe strong storms in only one case (July 22, 2017), which is a severe problem regarding inaccurate information on early warning of flash floods.

The second parts of results document the verification of severe storm phenomena such as torrential rainfall, hailstorms and strong wind gusts for the same flood situations. The success rate of predictions of severe storm phenomena was high in all flood situations due to its rare occurrence. The exception was only the flood situation of 5 August 2016, as the heavy rainfall and hailstorm were almost absent, only very shortly in the MEP Valašské Klobouky. The higher success rate of predictions of these phenomena was also confirmed the higher success rate of risk of flash flood forecast as individual forecasts of these phenomena are simultaneously included in the calculation of the risk of flash flood.

The limitation of this study is the insufficient number of evaluated flood events. Future research will focus on testing and verification of dozens of flood events not only for the Zlín Region but the whole of the Czech Republic.

Acknowledgement

This work was supported by the project No. CEBIA-Tech LO1303, A2.4 – ICT for support of crisis management.

References:

[1] ZDENEK, S., DUSAN, V., JAN, S., IVAN, M., MIROSLAV, M. Protection from flash floods (2015) Proceedings of the 26th International Business Information Management Association Conference - Innovation Management and Sustainable Economic Competitive Advantage*: From Regional Development to Global Growth, IBIMA 2015*, pp. 1359-1363. https://www.scopus.com/inward/record.uri?eid=2-s2.0-84976391745&partnerID=40&md5=923aa2f309578593d8b5e2cc503d02de

[2] OBRUSNÍK, I. (2006): *Rizikové situace způsobené počasím*, http://iris.env.cz/ris/ekodisk-new.nsf/e75c7074f3a42826c1256b0100778c9a/4ab2c3258d4743aac12576410026f2b0/$FILE/MZ%202006_6.pdf

[3] ŠAUR, D. *Informační podpora krizového řízení kraje z hlediska hodnocení výskytu povodní*. Zlín: Academia Centrum UTB ve Zlíně, 2017. 172s. ISBN 978-80-7454-712-6. Disertační práce. Univerzita Tomáše Bati ve Zlíně. Fakulta aplikované informatiky, Ústav řízení procesů.

[4] GARCÍA-ESPARZA J. A., ALACANIZ E. To Rehabilitate the Habitability. Scenario Simulation for Consolidated Urban Areas in Warm Regions. *WSEAS Transactions on Environment and Development*, ISSN / E-ISSN: 1790-5079 / 2224-3496, Volume 13, 2017, Art. #30, pp. 291-303

[5] LU, J., VECCHI, G. A., REICHLER, T (2007): Expansion of the Hadley cell under global warming. *Geophysical Research Letters*. 34 (6). DOI:10.1029/2006GL028443.

[6] ŠILHÁNKOVÁ V., PONDĚLÍČEK M. Agenda 2030 and Settlement Adaptation to Climate Change Impacts. *WSEAS Transactions on Environment and Development*, ISSN / E-ISSN: 1790-5079 / 2224-3496, Volume 13, 2017, Art. #20, pp. 181-188.

[7] YU, W., NAKAKITA, E., KIM, S., YAMAGUCHI, K. Improvement of rainfall and flood forecasts by blending ensemble NWP rainfall with radar prediction considering orographic rainfall (2015), *Journal of Hydrology*, 531, pp. 494-507. DOI: 10.1016/j.jhydrol.2015.04.055

[8] ZHANG, X., ANAGNOUSTOU, E.N., FREDIANI, M., SOLOMOS, S., KALLOS, G. Using NWP simulations in satellite rainfall estimation of heavy precipitation events over mountainous areas (2013), *Journal of Hydrometeorology*, 14 (6), pp. 1844-1858. Cited 6 times. DOI: 10.1175/JHM-D-12-0174.1

[9] VINCENDON, B., DUCROCQ, V., NUISSIER, O., VIÉ, B. Perturbation of convection-permitting NWP forecasts for flash-flood ensemble forecasting (2011) *Natural Hazards and Earth System Science*, 11 (5), pp. 1529-1544. DOI: 10.5194/nhess-11-1529-2011

[10] SIMONIN, D., PIERCE C., ROBERTS N., et al. Performance of Met Office hourly cycling NWP-based nowcasting for precipitation forecasts. *Quarterly Journal of the Royal Meteorological Society* [online]. 2017, 143(708), 2862-2873. DOI: 10.1002/qj.3136. ISSN 00359009. http://doi.wiley.com/10.1002/qj.3136

[11] DAS, S., Rohit CHAKRABORTY A., MAITRA. A random forest algorithm for nowcasting of intense precipitation events. *Advances in Space Research* [online]. 2017, **60**(6), 1271-1282. DOI: 10.1016/j.asr.2017.03.026. ISSN 02731177. Dostupné z: http://linkinghub.elsevier.com/retrieve/pii/S0273117717302144

[12] CASERI, A., JAVELLE, P., RAMOS, M.H., LEBLOIS, E. Generating precipitation ensembles for flood alert and risk management (2016), *Journal of Flood Risk Management*, 9 (4), pp. 402-415. DOI: 10.1111/jfr3.12203

[13] BAKER, L. H., A. C. RUDD, S. MIGLIORINI, et al. Representation of model error in a convective-scale ensemble prediction system. *Nonlinear Processes in Geophysics* [online]. 2014, **21**(1), 19-39 [cit. 2018-03-20]. DOI: 10.5194/npg-21-19-2014. ISSN 1607-7946. Dostupné z: http://www.nonlin-processes-geophys.net/21/19/2014/

[14] L. NISI, AMBROSETI P., Clementi L. Nowcasting severe convection in the Alpine region: the COALITION approach.Quarterly" *Journal of the Royal Meteorological Society* [online]. 2014, vol. 140, issue 682, s. 1684-1699 DOI: 10.1002/qj.2249.

[15] LAKSHMANAN, V., CROCKETT, J., SPEROW, K., BA, M., XIN, L. Tuning AutoNowcaster automatically (2012) *Weather and Forecasting*, 27 (6), pp. 1568-1579. Cited 4 times. DOI: 10.1175/WAF-D-11-00141.1

[16] ŠAUR, D. *Algoritmus předpovědi bouří: Technická specifikace*. Univerzita Tomáše Bati ve Zlíně, Fakulta aplikované informatiky, CEBIA-Tech, 2018.

[17] ŠAUR, D. *Metodika využití meteorologického radaru Zlínského kraje pro potřeby krizového řízení*. Zlín, Zlínský kraj, 2016.

[18] SIVS - kód V. Bouřkové jevy: *Český hydrometeorologický ústav.* 1997 - 2018. Avalaible at: http://portal.chmi.cz/files/portal/docs/meteo/om/vystrahy/napoveda/bourky.html

[19] *Meteorologický slovník výkladový a terminologický (eMS)*. 1993 -2017. Avalaible at: http://slovnik.cmes.cz

[20] JSRadView – radar data browser *CHMI,* 2010 - 2018 Avalaible at: http://portal.chmi.cz/files/portal/docs/meteo/rad/data_jsradview.h