Ultrafine Particles and the Occurrence of Heavy Rain: Model-Based Search for a Causal Relationship on Base of Open Data

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SNE 35(3), 2025, 137-142, DOI: 10.11128/sne.35.tn.10743
Selected ASIM SST 2024 Postconf. Publication: 2024-12-10
Rec. Impr. English version: 2025-06-27; Accepted: 2025-07-15
SNE - Simulation Notes Europe, ARGESIM Publisher Vienna
ISSN Print 2305-9974, Online 2306-0271, www.sne-journal.org

Abstract. Investigating the influence of ultrafine particles (UFP) on heavy rainfall events reveals a nuanced relationship between atmospheric composition and weather phenomena. This paper analyzes heavy rainfall events around the region of Frankfurt Airport and UFP data acquired by the Hessian Agency for Nature Conservation, Environment and Geology, and discusses what influence UFP may have on the hydrologic cycle. While a direct correlation remains inconclusive, daily average analysis suggests a potential link between elevated UFP counts and impending heavy rainfall, affecting the hydrologic cycle. Further in-depth analysis is required to validate this supposition and better understand the effects of UFP´s influence on the hydrologic cycle.

Introduction

Extreme weather events, including heavy rainfall and prolonged drought periods, are on the rise globally. A pioneering study conducted by researchers from the Karlsruhe Institute of Technology and the independent institute Airborne Research Australia explores the connection between ultrafine dust or particles (UFP) in the atmosphere and their disruptive impact on the hydrologic cycle - particularly cloud physics and rainfall formation.

The study underscores that anthropogenic UFP emissions alter precipitation patterns and contribute to heavy rainfall events by serving as cloud condensation nuclei [1]. Moreover, it has already been established that the quantity of UFP has notably increased in recent decades [2].

Particulate matter refers to airborne aerosol particles, including dust particles or droplets of specific sizes, capable of remaining suspended in the atmosphere for several days before settling to the ground [3]. These particles are typically classified based on their aerodynamic diameter into PM10 (particulate matter with a diameter less than 10 µm) and PM2.5 (with a diameter less than 2.5 µm). UFP, measuring up to 100 nm in diameter, are considerably smaller than PM10 particles. They are primarily produced by the combustion of fossil fuels in exhaust gas purification systems, large combustion plants, as well as from air and maritime traffic. Due to their small size, UFP can deeply penetrate into the human body, reaching lung tissue and the bloodstream, where they have been shown to cause respiratory and cardiovascular diseases along with neurodegenerative diseases such as dementia, Alzheimer's and Parkinson's [2][4][5].

Heavy rain, a weather phenomenon characterized by substantial amounts of precipitation in a short period of time and small geographical area, typically originates from convective clouds like cumulonimbus clouds.

This precipitation can lead to floods, landslides, or flash floods, causing significant harm to the environment, buildings and infrastructure. Therefore, the German Meteorological Service (Deutscher Wetterdienst, DWD) issues severe weather warnings when expected rainfall reaches 15 liters per square meter within an hour or 20 liters within six hours [6].

The impacts of climate change are significantly shaping the frequency and intensity of these extreme precipitation events. Research from the World Weather Attribution indicates that heavy rainfall occurrences in Germany and some neighboring countries have seen a surge, with probabilities increasing by 1.2 to 9 times due to human-induced global warming.

Additionally, the studied areas have shown that heavy rainfall intensity has risen by 3 to 19% [7]. Carbon dioxide drives warming and increases water vapor capacity of the atmosphere. However, due to its long lifespan and uniform atmospheric distribution, carbon dioxide cannot solely account for the observed uptick and high variability in frequency and distribution of heavy rainfall occurrences. An understanding of the hydrologic cycle´s dynamics is therefore essential to comprehending these changes [8].

1 Problem Statement

Due to their impact on both the quantity and size of water droplets in cloud formation in the atmosphere, UFP can disrupt the hydrologic cycle by impeding precipitation. Typically, water droplets ranging from approximately 0.01 to 0.25 mm in diameter coalesce around a cloud condensation nucleus (CCN) measuring roughly 0.0002 mm. Once the combined total size of droplets and CCN has reached 1 to 2 mm, they can descend to the earth as raindrops, surpassing the updraft speed within a cloud.

Due to their diminutive size and highly curved surface, which hastens water evaporation, UFP are poor CCN. As a result, the droplets which accumulate around an UFP remain too small to overcome air resistance for an extended period of time. This process generates an additional energy reservoir in the mid-troposphere, promoting extreme rainfall. When these highly enriched clouds eventually precipitate, the resulting rainfall events are notably more intense and moisture-laden. Regions exhibiting significantly heightened UFP levels increasingly experience extreme heavy rainfall and decreasing overall precipitation [1][2][9].

For this investigation an analysis was conducted, using a specific example to explore the potential link between elevated UFP concentrations in the atmosphere and the occurrence of particularly intense heavy rainfall events in a chosen region.

The Frankfurt Airport region served as the study area, because turbine exhaust emissions from aircrafts have been identified as a major source of UFP emissions when operating on the ground [10]. Furthermore, this region stands out as one of the few in Germany where continuous monitoring of UFP concentration is carried out. This lack of data collection is primarily attributed to the absence of legal regulations concerning UFP emissions [11].

The objective of this study is to investigate the connection between UFP and heavy rainfall occurrences using freely accessible data, with the aim of implementing automated analysis and visualization techniques through a GIS dashboard in the near future. This approach could facilitate more extensive analyses of relationships and enhance the presentation of results in a visually engaging manner.

2 Data Material

Measuring UFP values requires special techniques, as the particles, owing to their diminutive size, contribute minimally to the particle masses of coarser fine dust categories such as PM2.5 and PM10 [12]. Instead of mass determination, devices for particle counting are employed [13].

This study sourced UFP data from the Measuring Data Portal of the Hessian Agency for Nature Conservation, Environment and Geology (HLNUG), which has been collecting UFP data at varying numbers of air monitoring stations in and around Frankfurt Airport since 2015 [14]. Categorization is based on particle size ranging from 10 to 500 nm. For this study, particle sizes ranging from 10 to 100 nm were considered, aligning with the common definition of UFP. Aircraft emissions are primarily associated with the release of UFP sized between 10 and 30 nm [13].

The heavy rainfall data used in this study is sourced from the DWD’s catalog of radar-based heavy rainfall events (CatRaRE) [15]. This comprehensive catalog encompasses all heavy rainfall events in Germany dating back to 2001. Unlike large-scale, prolonged precipitation, locally and temporally limited heavy rainfall events pose a challenge for measurement. To acquire reliable data, the DWD employs weather radars capable of extensively scanning the areas surrounding the radar device, effectively capturing duration and intensity of precipitation, even beyond regular measuring stations. Thereafter, the collected datasets undergo a multi-stage quality control process, to ensure their suitability for climatological analysis [16].

3 Combined Methods

Initially, the heavy rainfall data was imported into ArcGIS and filtered based on the chosen observation period. To ensure data consistency, the period from May 1, 2020, to December 23, 2022, was selected for investigation.

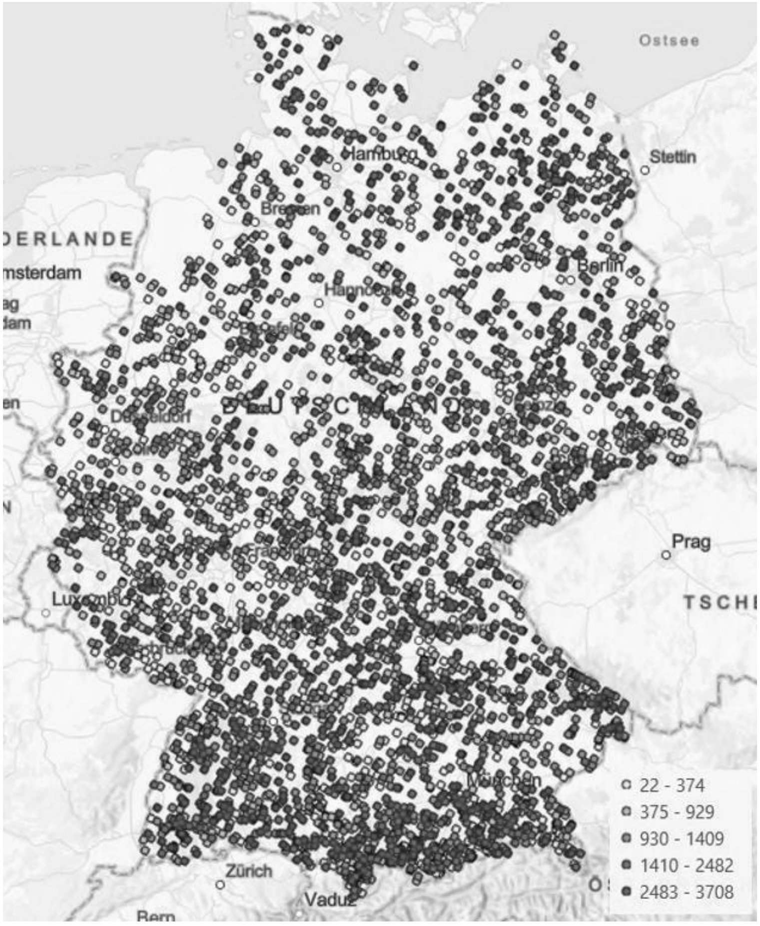

Figure 1: Number of most intense heavy rainfall events in Germany from May 1, 2020, to December 23, 2022.

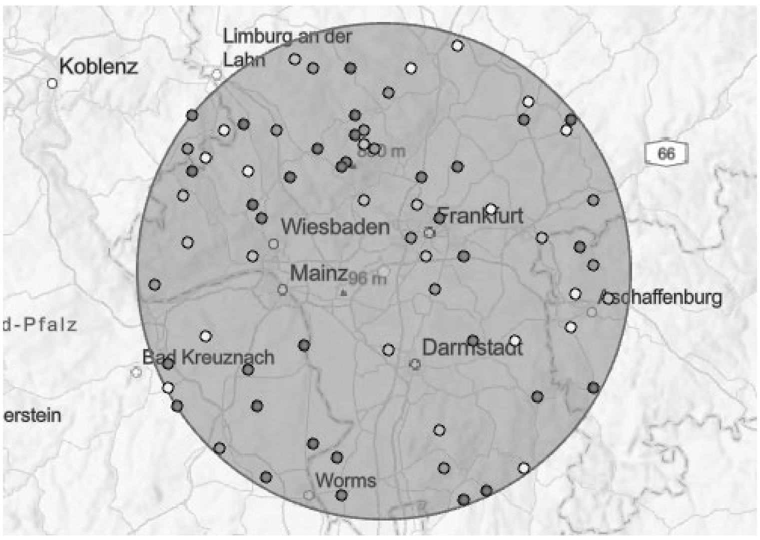

Figure 2: Intersect of buffer layer (50 km around Frankfurt Airport) and heavy rainfall events.

Furthermore, the most intense heavy rainfall events were identified and selected using criteria such as the maximum precipitation within the event zone (RRmax), the maximum heavy rainfall index (SRImax), and duration stage of the event (Duration) (see Figure 1).

A 50 km buffer was then centered on Frankfurt Airport, creating a polygon layer that was pairwise intersected with the point layer representing the selected heavy rainfall events (see Figure 2).

From the most intense heavy rainfall events identified in the studied region, two events per year from 2020, 2021, and 2022 were selected for sample analysis. The UFP data from the seven days preceding each heavy rainfall event was imported, with the heavy rainfall event occurring on the last day (Day 0). For each particle size category, the upper and lower quartiles along with the respective daily mean value, were determined for each measurement period. This analysis enabled insights into the distribution of higher and lower UFP measurements in the days leading up to the heavy rainfall event (see Figure 3 to Figure 6).

4 Results

In the exemplary illustrated measuring periods from May 28, 2021, to June 3, 2021 (see Figures 3 and 4), and from September 8, 2022, to September 14, 2022 (see Figure 5 and 6), the UFP values across all particle size categories indeed exhibited a distribution pattern. Lower concentrations were predominantly observed at the beginning of the period, indicated by a left-skewed chart in the lower quartile, while higher concentrations tended to occur towards the end of the period, as indicated by the right-skewed chart in the upper quartile.

This phenomenon was also noted in some of the other analyzed samples, albeit not consistently enough to establish a clear trend or regularity. The behavior of quartile captures appeared rather unpredictable, given the varied distribution of data captures in each dataset.

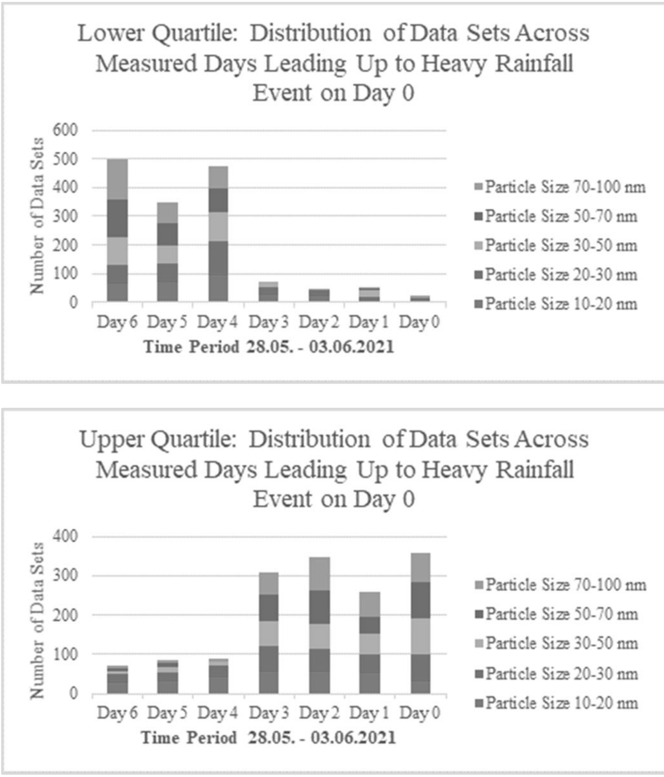

Figure 3: Charts depicting the distribution of data sets per measurement day in the lower quartile (proportion of measurements with lowest UFP values) and in the upper quartile (proportion of measurements with highest UFP values) for the measurement period from May 28, 2021, to June 3, 2021, for each particle size category.

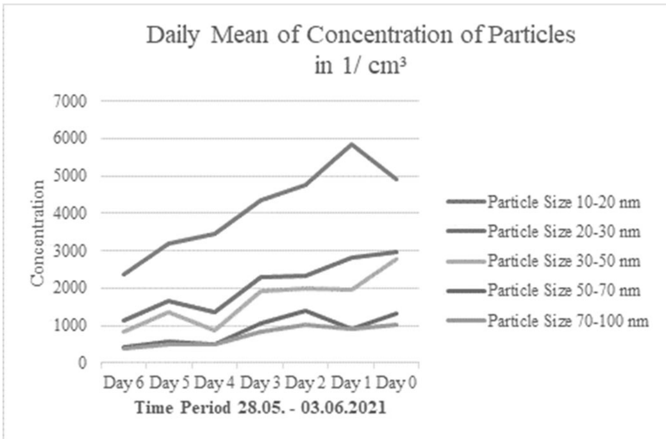

Figure 4: Time series plot of daily mean values per particle size category for the measurement period from May 28, 2021, to June 3, 2021.

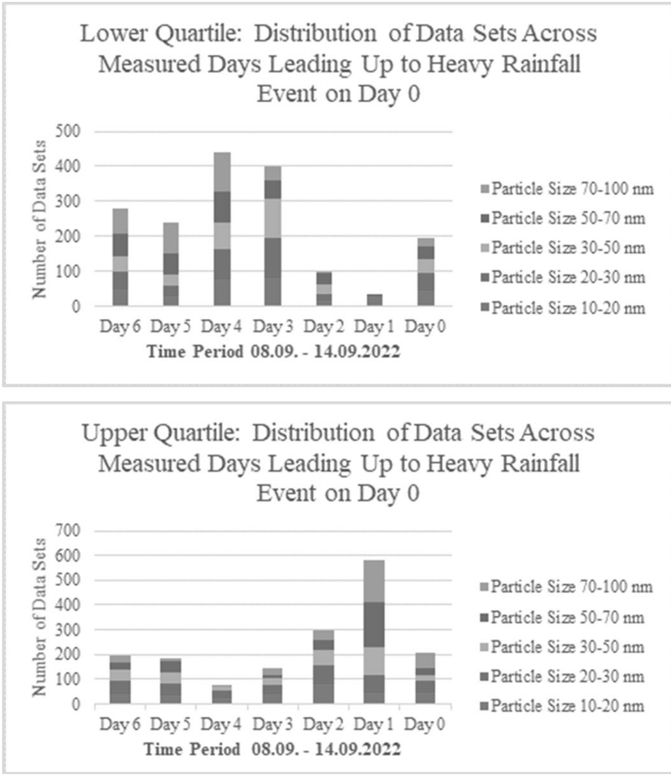

Figure 5: Charts depicting the distribution of data sets per measurement day in the lower quartile (proportion of measurements with lowest UFP values) and in the upper quartile (proportion of measurements with highest UFP values) for the measurement period from Sept. 8, 2022, to Sept. 14, 2022, for each particle size category.

In analyzing the daily mean values of the UFP concentrations, it was noted that 20 out of 30 generated curves exhibited an increase in values in temporal proximity to the heavy rainfall event.

However, the curves displayed varying patterns. For instance, some curves showed peaks at the beginning of the observed period and then a dip in the middle of the period. Others displayed a continuous increase, only to decrease again towards the end of the period.

Nonetheless, a common observation was that the majority of curves featured the highest daily mean value within the measurement period one to two days before the occurrence of the heavy rainfall event.

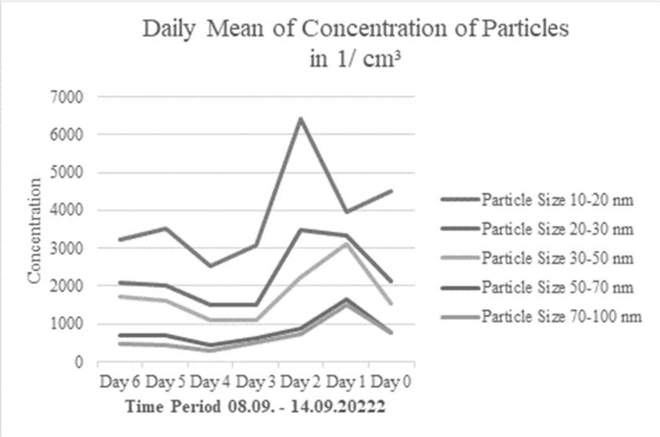

Figure 6: Time series plot of daily mean values per particle size category for the measurement period from September 8, 2022, to September 14, 2022.

5 Conclusions

The present study did not find sufficient evidence to establish a direct correlation between increased UFP pollution in the atmosphere and the occurrence of heavy rainfall events. Given the complexity of weather and climate phenomena, more extensive analysis is necessary. This analysis should encompass influencing factors such as altitude data, terrain profiles, temperature, general precipitation, air pressure and wind movements. For instance, wind and precipitation can impact local UFP concentrations. Clouds can disperse depending on wind strength and velocity, moving the potentially correlated heavy rainfall event to an area away from the region with increased UFP concentrations [We22].

The analysis of daily mean value did indeed provide suggestive evidence of a potential increase in determined UFP emissions leading up to a heavy rainfall event. However, to solidify this assumption, a study of significantly larger scope would be required. Additionally, analyses at various locations are essential for a more precise investigation. This would not only facilitate local comparisons but also enable the correlation of results from different regions with similar geographical conditions.

In order to facilitate a comprehensive analysis of the relationship between UFP pollution and heavy rainfall events, the implementation of an automated system for evaluating and visualizing freely available data via a GIS dashboard could be highly beneficial. This approach would not only enable the examination of individual data points but also facilitate the identification of complex patterns and trends within the data.

Moreover, it would allow for the adoption of various spatial and temporal scales for modeling, thus enhancing the understanding of relationships and providing a more robust foundation for further research and decision-making. Furthermore, such a system could foster communication and information exchange among different interest groups, which is vital for developing measures to mitigate the potential impact of UFP on the hydrologic cycle and the environment as a whole.

In conclusion, as UFP pollution continues to rise steadily over time, this study endeavors to establish an initial foundation and impetus for further analysis. The ultimate goal is to ascertain the potentially significant impact of UFP on the hydrologic cycle and subsequently implement measures to mitigate them. This could include the establishment of an official UFP limit to regulate emissions.

Publication Remark

This contribution is the revised English version of the (German) conference version published in
Tagungsband Langbeiträge ASIM SST 2024,
ARGESIM Report AR 47, vol. DOI 10.11128/arep.47,
ISBN ebook: 978-3-903347-65-6
article DOI 10.11128/arep.47.a4712, p 67-72.

References

[1] Junkermann W, Hacker J. Unprecedented levels of ultrafine particles, major sources, and the hydrological cycle. Sci Rep 12, 7410, 2022. DOI 10.1038/s41598-022-11500-5

[2] Freund A. Ultrafeinstaub für Wetterextreme mitverantwortlich. Deutsche Welle. https://www.dw.com/de/ultrafeinstaub-f%C3%BCr-wetterextreme-mitverantwortlich/a-61903127, Accessed: 06.09.2023, 2022.

[3] Kinne S, Quaas J. Einfluss der Luftverschmutzung auf den Klimawandel – neue Erkenntnisse aus Satelliten daten und Klimamodellen. https://www.mpg.de/405815/forschungsSchwerpunkt, Accessed: 06.09.2023, 2007.

[4] Initiative Klima-, Umwelt- und Lärmschutz e.V.: Feinstaub und noch feinerer Staub – Ultrafeinstaub. https://www.klima-umwelt-luftverkehr.de/umwelt/ultrafeinstaub/ Accessed: 22.08.2023.

[5] Umweltbundesamt: Feinstaub. https://www.umweltbundesamt.de/themen/luft/luftschadstoffe-im-ueberblick/feinstaub#undefined, Accessed: 22.08.2023, 2022.

[6] Deutscher Wetterdienst: Wetter und Klimalexikon. Starkregen. https://www.dwd.de/DE/service/lexikon/Functions/glossar.html?nn=103346&lv2=102248&lv3=102572, Accessed: 04.09.2023.

[7] Kreienkamp F, et al. Rapid attribution of heavy rainfall events leading to the severe flooding in Western Europe during July 2021. https://www.worldweatherattribution.org/wp-content/uploads/Scientific-report-Western-Europe-floods-2021-attribution.pdf, Accessed: 04.09.2023, 2021.

[8] Karlsruher Institut für Technologie. Klimaforschung: Ultrafeinstaub könnte Wetterextreme verursachen. https://www.kit.edu/kit/pi_2022_044_klimaforschung-ultrafeinstaub-konnte-wetterextreme-verursachen.php, Accessed: 06.09.2023, 2022.

[9] Weishaupt M. Dürre und Starkregen: Fossile Brennstoffe verändern Wasserkreislauf. https://www.nationalgeographic.de/umwelt/2022/05/duerre-und-starkregen-fossile-brennstoffe-veraendern-wasserkreislauf, Accessed: 06.09.2023, 2022.

[10] Umweltbundesamt. Einfluss eines Großflughafens auf zeitliche und räumliche Verteilungen der Außenluftkonzentrationen von Ultrafeinstaub < 100 nm, um die potentielle Belastung in der Nähe zu beschreiben - unter Einbeziehung weiterer Luftschadstoffe. https://www.umweltbundesamt.de/sites/default/files/medien/11850/publikationen/14_2021_texte_grossflughafen_.pdf, Accessed: 25.04.2024, 2021.

[11] Umweltbundesamt. Fragen und Antworten: Ultrafeine Partikel. https://www.umweltbundesamt.de/themen/luft/luftschadstoffe-im-ueberblick/feinstaub/fragen-antworten-ultrafeine-partikel, Accessed: 25.04.2024, 2018.

[12] Hessisches Landesamt für Naturschutz, Umwelt und Geologie. Ultrafeine Partikel. https://www.hlnug.de/themen/luft/luftqualitaet/sonder-messprogramme/ultrafeine-partikel, Accessed: 06.09.2023.

[13] Peil K. Ultrafeine Partikel (UFP): Flugverkehr und Gesundheit. Fakten - kurz und bündig erstellt vom BUND AK Luft/Klima/Lärm Hessen. https://www.bund-hessen.de/fileadmin/hessen/Publikationen/Arbeitskreise/AK-Luft-Klima-Laerm/2021-02_BUND-Hessen_FactSheet_Ultrafeine-Partikel_final.pdf, Accessed: 06.09.2023, 2021.

[14] Hessisches Landesamt für Naturschutz, Umwelt und Geologie. Messdatenportal. https://www.hlnug.de/messwerte/datenportal/ufp, Accessed: 06.09.2023.

[15] Lengfeld K, Walawender E, Winterrath T, Weigl E, Becker A. Starkregenereignisse Version 2023.01 mit Überschreitung der DWD-Warnstufe 3 für Unwetter basierend auf RAD-KLIM-RW Version 2017.002 Parameter und Polygone der Starkregenereignisse in Deutschland version v2023.01. Deutscher Wetterdienst, 2023. DOI 10.5676/DWD/CatRaRE_W3_Eta_v2023.01.

[16] Winterrath T. Niederschlagsklimatologie: Daten und Produkte - Mit Radardaten in die nächste Dimension. Deutscher Wetterdienst. https://www.dwd.de/SharedDocs/broschueren/DE/klima/radklim_broschuere.pdf?__blob=publicationFile&v=2, Accessed: 06.09.2023, 2021.