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Wind speed estimation for the correction of wind-caused errors in historical precipitation data

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Abstract— The wind has a significant impact on the accuracy of precipitation measurement in the case of collecting gauges. As widely known, the velocity field of wind suffers a deformation over and around the precipitation gauges, which causes deviations in the measured quantities. This error must be corrected if it is possible. Thanks to numerous researches, correction formulas give tools for adjusting precipitation data in the function of the wind speed and raindrop distribution (DSD) relationship, gauge parameters, and for the case of snow and temperature. The measured intensity of precipitation in historical data allows estimating the DSD, but in most cases, there are no simultaneously measured wind speed data coupled to the historical precipitation data.

Characteristic data of wind speed can be estimated based on the wind speed statistics, and these data can be utilized for the statistical correction of the precipitation measurements. The statistical correction means that the rainfall data can be adjusted with the expected value of the wind speed for a more extended observation period, assuming a stationarity of wind speed statistics for the given location. After the statistical correction, the unique data will not be unbiased, but statistically they will be closer to the actual value, and the correction will be statistically correct in inherited perecipitation cheracteristics, as for example the IDF curves. For this correction, an investigation is necessary to find the adequate wind statistics for the rainfall correction. This paper shows the results of a study about the relation of statistics of wind speeds during precipitation, based on a 10-minute sampling period. The wind speed data were independent of the rain depth (or intensity) data. The result of the study shows that the distribution of wind speeds differs of the wind speed distribution measured in the precipitation events. This difference can be treated easily using the stable rate of the means of these distributions. This result gives a step toward correcting the wind-affected error of historical precipitation data.

Key-words: rainfall, rainfall measurement, historical data, wind-caused error, correction

1. Introduction

The measurement of precipitation, and especially the rainfall intensity, has a significant role in hydrology with relevant effects on technical, agrotechnical and other fields. A lot of research have been performed worldwide related to the adjustment of the data collected in the past decades by some measurement devices.

For some kinds of systematic errors, there are correction procedures, mainly for tipping bucket rain gauges (*Vuerich et al.,* 2009; *Luyckx* and *Berlamont*, 2001) and for the level-measurement-based gauges (*Luyckx* and *Berlamont,* 2002), or also for their partially processed, selected data (*Rácz,* 2021a). These processes target the systematic errors coming from the construction of the gauge. Researchers have studied the under-measurement phenomena caused by the wind in daily or longer sampling period data; meanwhile, this kind of investigation is rare for the sub-daily historical rainfall data. (The adjective 'historical' covers here the data measured before 2000 with several minutes sampling or with analogous, continuously registering devices.)

In 1769, Heberden called attention to the phenomenon that the result of a rain depth measurement in the same site, but in different heights, differ in most of cases. The differences were explained by Jevons in 1861, who proved that deviations occur by a wind-caused error, and since the wind speed changes with the heights, the deviation in precipitation measurements diverge similarly. (*Strangeways*, 2010). The wind-caused error can be disappear by prevention or correction.

The prevention can be achieved by arranging a measurement site (pit gauge) free from wind disturbance or using some solution to diminish the wind effect on the measurement, like the Nipher shield (*Strangeways,* 2010), or as the most advanced result, using an aerodynamically neutral gauge (*Strangeways*, 2010; *Rodda et al.,* 1985; *Folland,* 1985, 1988).

The correction shows a significant advance in daily or longer sampling data from the 1950s (*Sevruk*, 1982, 1985). Intercomparisons and field measurements have been performed in the late 1900s and in the first decades of the 2000 (*Pollock et al.,* 2015, 2018). As the sampling period shortens, the actual rainfall intensity and the drop-size distribution (DSD) have growing importance. The DSD shows a relation with the character of the rainfall and the rainfall intensity, as it was constated in the middle of the 20th century (*Laws* and *Parsons,* 1943; *Marshall* and *Palmer,* 1948). Later, the approach was modified for more detailed temporal models, using Gamma distribution in the DSD (*Ulbrich*, 1983; *Ulbrich* and *Atlas*, 1984; *Williams et al.*, 2014).

The wind effect depends on the aerodynamical character of the rain gauges, so it is different in the case of different devices. The loss or correction function should be determined to correct the historical rainfall data at least for the most extensively used gauges. These functions can be determined by wind tunnel experiments and by computational fluid dynamics (CFD) modeling. These experiments were done for a limited group of gauges during the past decades. Many researchers have studied this field, and they took steps forward in the research on the wind effect (*Strangeways*, 2010). In the 1980s, Folland reached significant results using a simplified mathematical model of the wind-caused loss in 2D and 3D cases (*Folland,* 1985, 1988). Particle transport process was investigated in wind tunnels and by CDF models to determine the relation to approach the losses of devices (*Ralph* and *Barret*, 1984; *Nešpor,* 1996; *Nešpor* and *Sevruk,* 1999; *Habib et al.,* 1999; *Cauteruccio* and *Lanza*, 2020).

Duchon and Essenberg compared the results of a free-standing tipping bucket gauge, a weight measurement-based gauge, Nipher-shielded gauges, and a pit gauge (*Duchon* and *Essenberg*, 2001).

Vuerich and his colleagues performed intercomparison measurements during the fourth campaign of the WMO, focusing mainly on the systematic errors of the unique gauges (*Vuerich et al*., 2009). According to their experimental results, they found the wind-caused error lower than the sum of the measurement inaccuracy of the given rain gauge and the pit gauge used as a reference. This consideration can be satisfying for highly accurate, ultimately used gauges, but in the case of the historical data and the less accurate devices, efforts must be made to adjust the wind-caused errors. Adjusting historical data would be important to ensure more accurate reference data to the investigation of crucial issues such the climate change.

Since 2010, there has been continued field experiment in Norway by Wolff and his colleagues to determine the measurement issues of solid and fluid precipitation. They constructed a correction formula using standard meteorological stations' precipitation, wind speed, and air temperature data (*Wolff et al.*, 2015). As the result of the experiment, a correction factor, *CF* and a catch efficiency value, *CE* have been developed. Kochendorfer's research team used this result to process a data series registered between 2009–2014 (*Kochendorfer et al.,* 2017a). Based on the results, they proposed a less complex correction equation. The investigation has also been performed on six further rain gauges (*Kochendorfer et al*., 2017b).

As a general formula, the correction factor can be written as the function of the w wind speed, the *DSD*, the p set of device-dependent aerodynamical parameters, and the t temperature. The air temperature data is to separate the solid and fluid phases of precipitation, in the formulas adequate to make this distinction:

$$CF = F(w, DSD, p, t) \ . \tag{1}$$

As it can be considered, there has been a significant development in the field of wind-caused rainfall measurement issues, but for the devices used in the 20th century, the determination of the *CF* is not performed yet.

To achieve an adequate correction in the application of Eq.(1), it is necessary to have highly detailed temporal resolution wind speed data (highly detailed wind speed, HDWS) and rain depth data with a similar (or better) sampling. In the case of historical data, there is no way to complement the data series with wind speed in the necessary resolution, so the adjustment of the high temporal resolution precipitation data is going to be performed with statistical methods.

The statistical correction results in an adjusted dataset from the point of view of statistical parameters, but it does not result in a corrected time series, since the wind data can only be assumed. Corrections can be used for the processed data products, such as the IDF curves, where the corrected data can provide more realistic information. The statistical correction can be applied for a unique gauge, using the locally measured wind speed's statistics to the locally measured historical data, or using a regionally accepted wind statistics of another station, assuming the temporal and spatial stationarity of the wind speed statistics.

2. Materials and method

2.1. Mathematical considerations

Let t be a 1–30 minutes long sampling period of rain and wind speed observations. Let w be the wind speed data of some t (HDWS data), as an independent and identically distributed (iid) random variable with a probability density function (PDF) as its $f(w)$ function. Let, furthermore, r be the wind speed of those t periods when rainfall has occurred (P-HDWS data) with its PDF $f(r)$. Let us assume that the probability distributions of both variables are time-invariant. For the t intervals of precipitation more than 0 mm, a conditional PDF can be written as

$$f(w|r) = (f(wr))/(f(r)) \ . \tag{2}$$

If w and r are independent, then

$$f(w|r) = f(w) \ . \tag{3}$$

In this case, the cumulative distribution function (CDF) of the wind speed measured in the t sampling period is identical to the CDF of wind speed data of every t period, and the correction can be performed with the statistics of w data, regarding Eq.(3).

If the independence of both variables cannot be verified, further analysis is necessary to find some statistical relationship between the statistics of w and r variables. In this case, some kind of proportional relation is to be found, so

$$f(w|r) \quad \propto \quad f(w) \tag{4}$$

The only remaining question is, in this case, the mathematical character of proportionality.

In practice, samples of w and r are available. Let us assume, that the data were recorded in the same sampling period. The arithmetic means of the w and r variables can be calculated.

The arithmetic mean of a specific data population's sample is the unbiased estimation of the expected value of the real probability distribution of the given population. When we got a wind speed time series of a given station, we have only one sample for the data population, because some 10 km distance stations' wind speed data can show a statistically significant difference. It means that we have only one sample for every station, although the number of elements can be in the magnitude of 10^4–10^5. The consequence of Glivenko's theorem is that if the number of elements is high enough, the arithmetic mean of the sample is a good estimation of the real CDF's expected value (*Reimann*, 1989). Similarly, the median is a good estimation of the real CDF's median. However, the standard deviation (SD) is a biased estimation of the variation, in such a high number of the elements, the estimation with SD can be accepted too.

Following the above described way, data series of the investigated stations with similar length can be analyzed, and inferences can be found between the general wind statistics and the rainy wind speed statistics.

Since there are several ways of modeling the real CDF of the wind speed data (*Shi et al*., 2021), and the selection of method depends on specific targets or toolkits of a well defined task, in this study the distribution fitting was not performed.

2.2. The planned steps of the research

As mentioned in the Section 1, for the historical data, the possible way of adjusting wind-caused error is the statistical correction of data. The correction cannot restore the realistic rainfall data for every investigated moment, but it modifies the data to set them closer to the most probable (realistic) value. The correction will be precise in the statistical parameters of the resulting dataset.

The primary hypothesis for the statistical correction comprises the following surmises:

1. A database with high temporal resolution wind speed and rain depth data is available.
2. Let us surmise that the wind statistics are robust; they change in time slowly, if they change at all.
3. Let us surmise that the conditional probability relation between statistics of wind speed (HDWS) and wind speed during rainfall events (P-HDWS) is robust.

This way, the expected value of the wind speed for the rainfall adjustment is estimable.

From the HDWS data series, the P-HDWS data subseries can be selected by the similar sampling period of a known data series. It is given in the majority of the presently used meteorological stations. The further steps are detailed in this Section. In the investigation, some of the statistical parameters of the homogenized data series have been studied, and a conclusion can be made. The flow chart of the research is shown in *Fig. 1*:

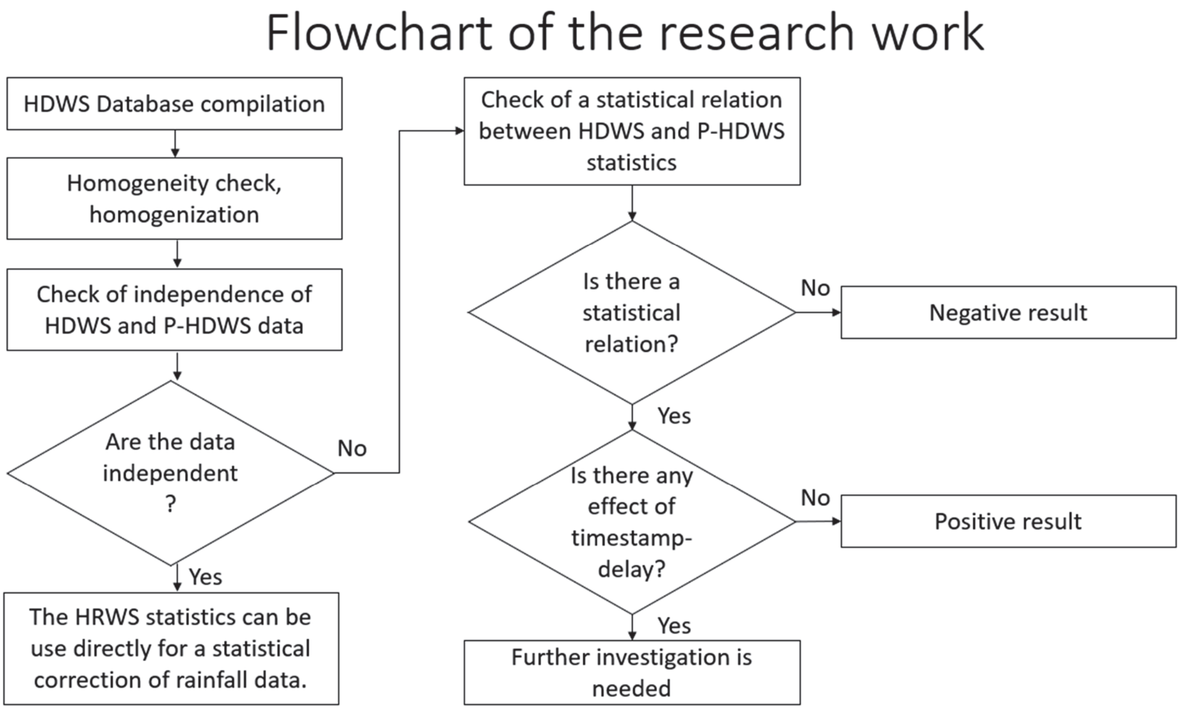

Fig. 1. Flowchart of the present research.

There are three possible favorable outputs of the research. The most favourable would be if the independence of HDWS and P-HDWS data were verified. If the data are not independent, a further investigation is needed to find some mathematical (statistical) relation between the relevant parameters (mean, median, standard deviation) of both data series. There is also a possible negative output if a later detailed problem of data would not be solvable.

2.3. Data description

The origin of the data is the Climate Data Center of the German Weather Service. The selected data comprise 10 minutes sampled wind speed and rain depth. The length of the time series could have reached 30 years, but for better homogeneity of a later analysis of rain depth data, the 2010–2019 years were selected, only because a similar type of rain gauge was used for all stations. The metadata of the time series is available, and papers show the applied methods of the data quality check process (*Kaspar et al.*, 2013). The quality check has occured in several steps, using manual and automatized procedures. The wind speed measurement was performed by Windsensor Classic 4.3303 and 3D Ultrasonic Anemometers.

The homogeneity testing could not have been performed for the higher resolution then one month, and the better-detailed data were homogenized using the correction of the monthly inhomogeneities. The available metadata is adequate to surmise some inhomogeneities, such as the change of instrument or the moving of the meteorological station.

According to the metadata, there is a delay between the wind speed and rain depth data, so its probable effect is to be investigated. The cause of this delay is that the rain depth measurement in these time series was performed with a real-time (RT) or a non-real-time (NRT) method. Before 2008, the applied rain gauges used the RT method, where the delay depended on the rainfall intensity. The delay of data registration in high-intensity rain has been some seconds only, but by the decreasing of the intensity, the time delay could have grown even to several minutes, in some situations reaching the 30 minutes value. Since 2008, the rain gauges were changed to OTT Pluvio devices, which follows the NRT method of measurement with 5 minutes delay, so the time delay has become constant.

The investigated data were collected in 116 stations. The location of the stations is shown in *Fig. 2*.

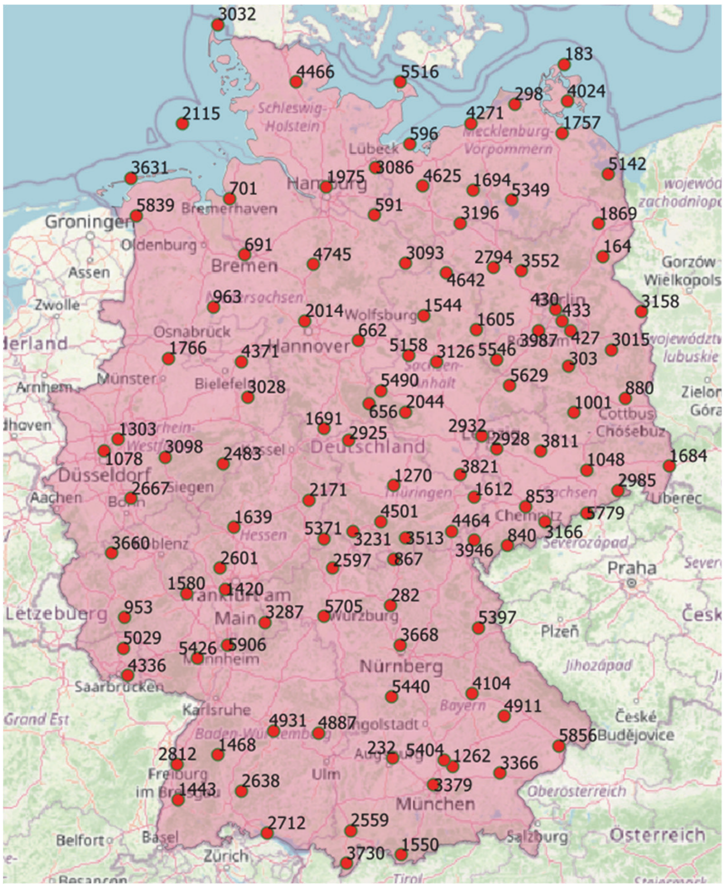

Fig. 2. Map of examined wind speed stations and their ID numbers in Germany.

2.4. Homogeneity and homogenization of data

For testing the homogeneity and for correction of the casual inhomogeneities, the MASH package was used (*Szentimrey*, 2014). The MASH is a relative homogeneity test, so the investigation is based on a simultaneous analysis of several time series measured in the same period but in different stations. For the test, in the case of homogeneity, the similarity of changes in statistical parameters is assumed in the meteorological station close to each other. The analysis takes into consideration the relative distance of the investigated stations. If any inhomogeneity can be observed, its position in time and its measure can be known, so the necessary correction can be performed. The analysis was done for the monthly average wind speed values, and the corrections were redistributed onto the 10-minute data.

2.5. Investigation of HDWS and P-HDWS statistics

Based on the homogenized data, the empirical frequency curve and some chosen statistical parameters of the HDWS data can be determined. The same is to be performed with the P-HDWS data. Comparing the two statistics, the identicalness of the HDWS and P-HDWS data, their independence can be judged, with its consequence, following the flow chart.

2.6. Investigation of the time delay of wind and precipitation measurements

The metadata of the wind and rainfall measurement shows that in reality, the 10-minute rain data is related to a 5 minutes earlier ending 10-minute period. Since this issue can affect the goodness of the investigation, a check was made about it.

The effect of time delay on P-HDWS data was investigated in all data. The comparison was extended to the mean, median, and standard deviation. The examined time shifts were 10 minutes back and forward, and 1440 and 2880 minutes forward.

3. Results and discussion

3.1. Homogeneity examination and homogenization

For the investigation, those data were used only, where both wind speed and rain data were available. Those data, where any of wind or rain data was unavailable (NA signed data), were not considered.

In the examination of the homogeneity, 25 of the 116 investigated time series were found homogenous. The 91 further time series were homogenized.

3.2. *Independence of HDWS and P-HDWS data*

The frequency curve of the HDWS and P-HDWS data were made using 0.1 m/s clusters. The mean, median, and standard deviation of both group of data were determined.

To demonstrate the results, the empirical frequencies of the HDWS and P-HDWS data of station No. 5705 (49.7704 °N, 9.9576 °E, Würzburg) are presented (*Fig. 3*). At the first glance, a difference can be seen between the empirical frequency curves. In P-HDWS data the rate of higher wind speeds is higher, so the mass of the plot is shifted towards the higher values, so the mean and the median are higher than at HDWS data (*Table 1*).

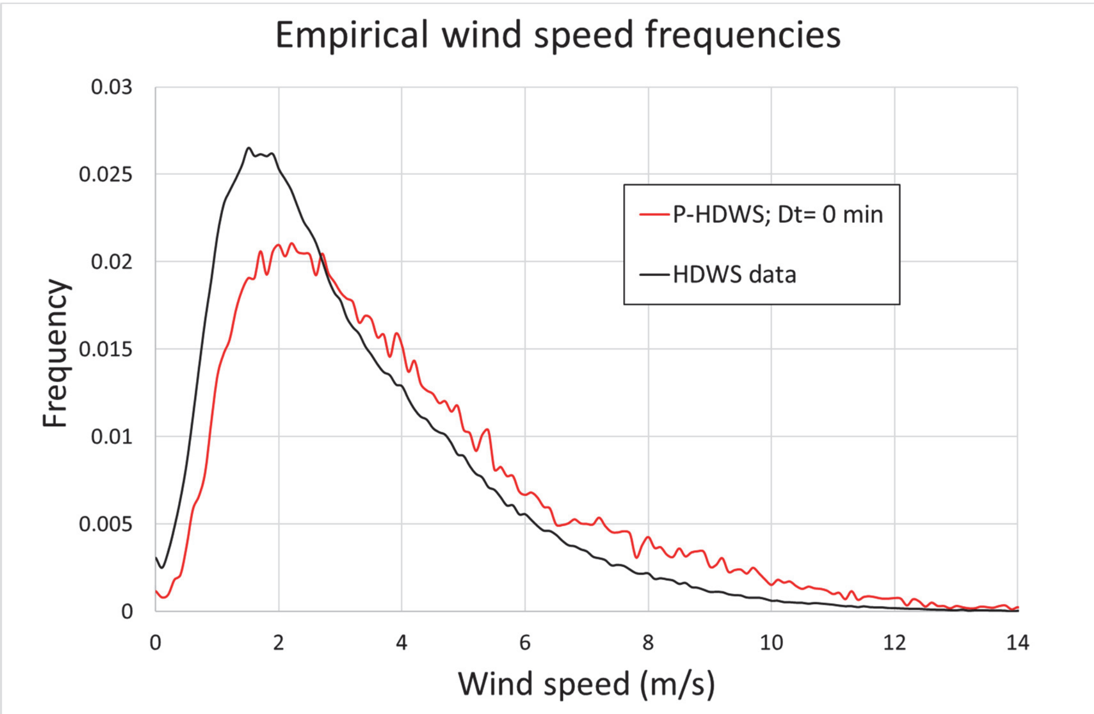

Fig. 3. Wind speed frequencies of station No.5705 (Würzburg) in 2010–2020.

Table 1. Statistical parameters of the complete dataset and the precipitation data of station No.5705

Data	**HDWS data**	**P-HDWS data**
Number of data	524841	30686
Mean (m/s)	3.19	4.01
Median (m/s)	2.60	3.40
SD	2.15	2.57

The results show that the statistics of the HDWS and P-HDWS data are different, so the conditional probability of the investigated 10-minute data is not identical to that of the HDWS data. The statistics of the HDWS data cannot be used directly to correct the wind-caused error.

The result of the investigation for the other stations is similar, with some spreading of course. There was only one station, where the P-HDWS's mean was lower than the HDWS's (No.1550). This station is situated in a relatively deep valley in the Bayern Alps.

The means of P-HDWS data are presented in *Fig. 4*. The spatial distribution of the means resembles the earlier investigations of wind speed distribution surveyed and modeled for wind energy production (*Blankenhorn* and *Resch,* 2014).

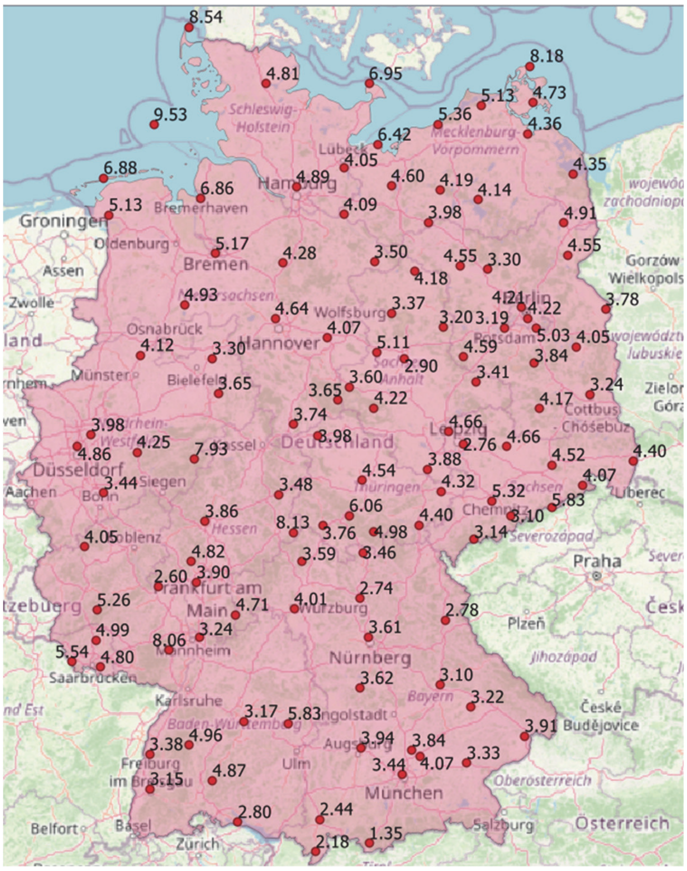

Fig. 4. Means of P-HDWS statistics of the investigated stations.

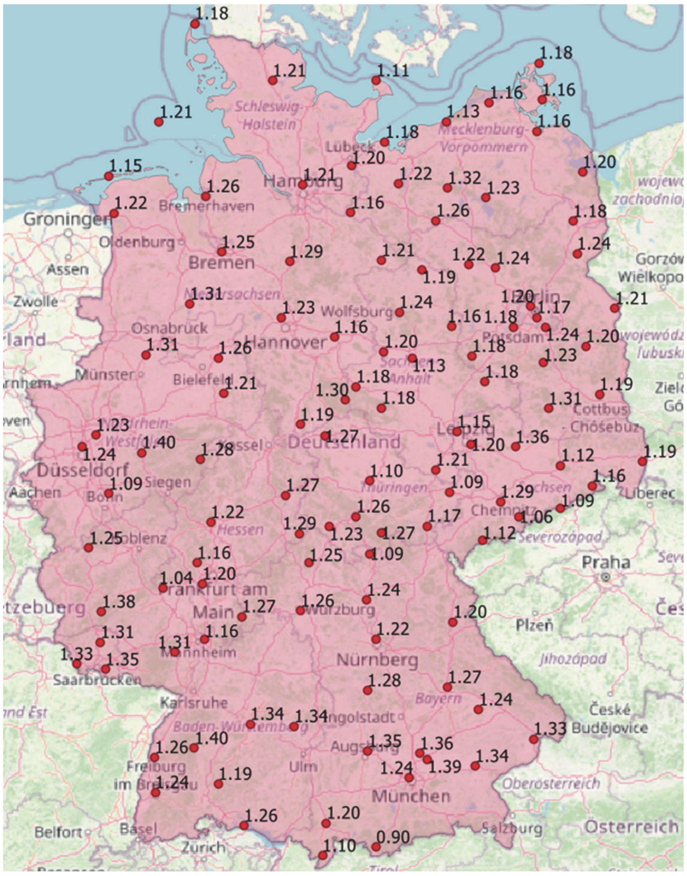

Fig. 5. Rate of means of P-HDWS and HDWS data.

Fig. 5 shows the spatial distribution of the rates of P-HDWS and HDWS values. The values do not depend significantly on the station's latitude, longitude, or geodetic height data. The most frequent values are around 1.20–1.25, with some low and high-value spots in this average field. Interestingly, nearby the river Danube in Bavaria, a consequent 1.30–1.35 value can be observed.

The further step of the investigation was a searching for a statistical relation between the HDWS and P-HDWS data. In this phase, regression has been looked for. On the plot of the data, strong linear regression can be seen in the case of the means (*Fig. 6*). A similar result can be found for the medians (*Fig. 7*) and SD values (*Fig. 8*). The regression lines have a convincing correlation for the three parameters in the 94–96% range.

The linear regression equations for the means, medians, and SDs are

$$MEAN_{P-HDWS} = 1.1952 \cdot MEAN_{HDWS} + 0.0915 \,, \tag{4}$$

$$MEDIAN_{P-HDWS} = 1.2106 \cdot MEDIAN_{HDWS} + 0.1551 \,, \tag{5}$$

$$SD_{P-HDWS} = 1.1590 \cdot SD_{HDWS} - 0.0799 \,. \tag{6}$$

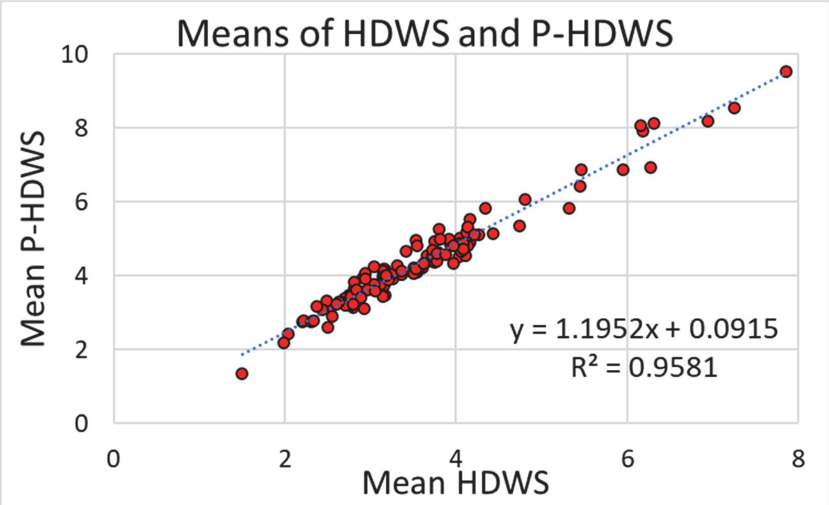

Fig. 6. Comparison of coupled Means of HDWS and P-HDWS data.

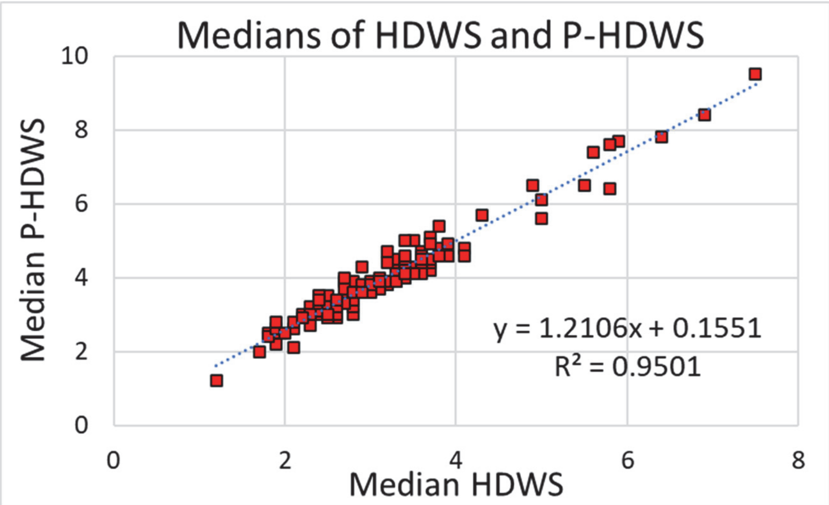

Fig. 7. Comparison of coupled Medians of the HDWS and P-HDWS data.

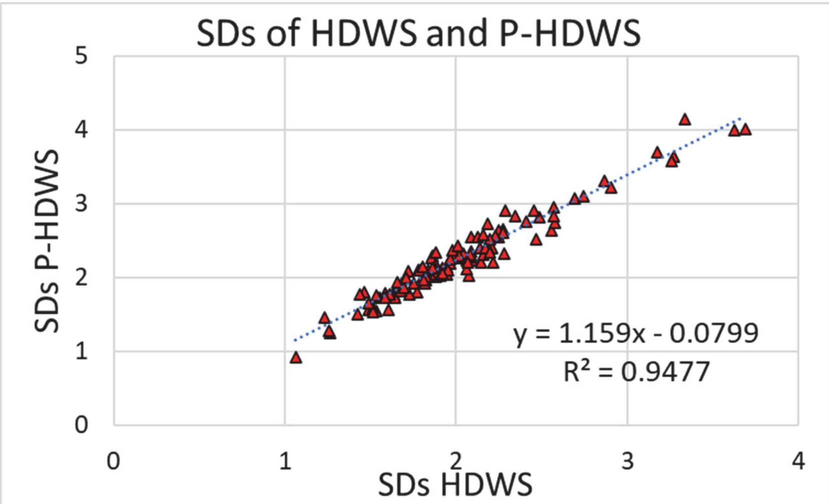

Fig. 8. Comparison of coupled Standard Deviations of the HDWS and P-HDWS data.

Another question was the stability of the statistics. In order to get information about it, the relation between means and medians of the unique station's P-HDWS data were investigated. The data showed pretty strong linearity with 0.9922 steepness and a 99% correlation, so the rate between the means and medians was quasi-stationary in the range of the investigated data. The difference between the means and medians is -0.29 m/s (*Fig. 9*).

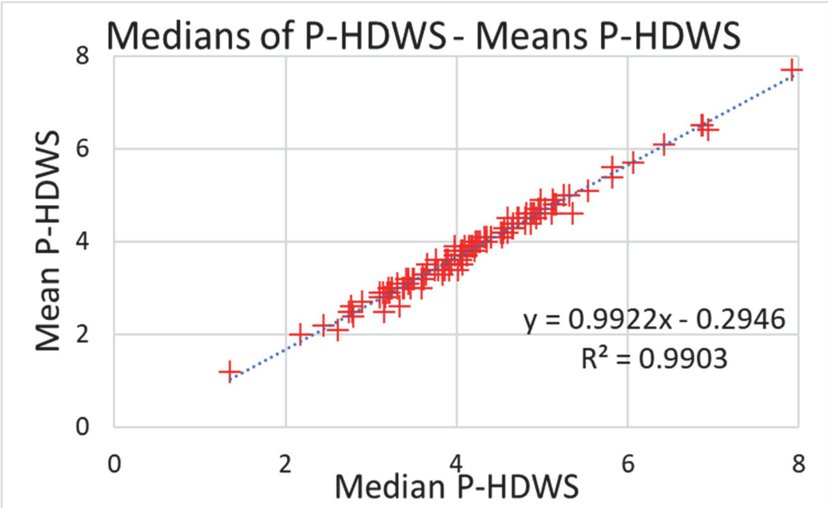

Fig. 9. Regression between the medians and means of P-HDWS data.

Geographical relation with latitude, longitude, and height above sea level with the means of P-HDWS values and rate of P-HDWS and HDWS means was not found. It means that other local factors influence the variability of the means and the rate of means.

Based on the investigations, a strong linear correlation can be constated between the HDWS and P-HDWS data. The linearity of the relationship between means and medians (with the linearity of the SD) gives hope that a fitted CDF of the parameters show the same relationship.

Supposing that the wind speed data is stationary for extended periods, Eq.(4) can be used to determine the mean of wind speeds for the correction of the wind-caused error of 10-minute sampled historical precipitation data, possessing the adequate correction factor function (e.g., Eq.(1)).

The possibility of correction is also valid for those precipitation data in which measurement records can be reshaped to 10-minute sampled data format. For different sampling periods, the investigation must be repeated to determine a relation of means of HDWS and P-HDWS data, of course.

3.3. *The effect of time delay between wind and precipitation data*

As it was shown in metadata, the precipitation data were detected in a 5-minute time delay, so the theoretical coincidence of the measurements was not correctly fulfilled. It was necessary to analyze the effect of this time delay, demonstrating how it influences the statistical parameters.

Shifting data by 5 minutes was impossible, since the dataset contains 10-minute data only. The possible least shift of data can be 10 minutes. For the first, the -10 and +10 minutes shifted datasets were produced. The three dataset's statistical parameters were calculated, and these are shown in *Table 2* for the station No.5705.

Table 2. Statistical parameters of P-HDWS data with Dt minutes time shift of wind speed data, station No.5705

Parameters	**Dt = -10 min**	**Dt = 0 min**	**Dt = 10 min**
Number of data	30686	30686	30686
Mean	3.91	4.01	3.95
Median	3.30	3.40	3.30
SD	2.54	2.57	2.53

As the statistical parameters show, the parameters of the shifted datasets have decreased for both shifted datasets. For the case of some minutes shift, the similarity of wind data can be assumed; the wind characteristics may have been similar to the P-HDWS data, independently of the backward or forward direction of shifting. The frequencies of maximum wind speeds increased as the time was shifted (*Fig. 10*).

When the time shift has been chosen to be more extended (1440 and 2880 minutes, so one and two days) than the characteristic precipitations, the frequencies are getting closer to the statistics of HDWS data (*Fig. 11*). The cause of this effect can be that the wind data coincided with the non-precipitation periods in most cases.

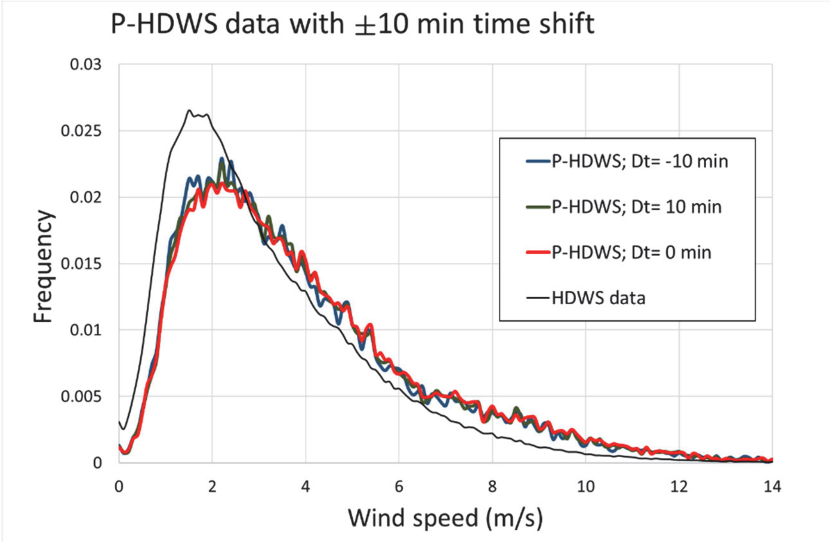

Fig. 10. PHDWS data with ±10 min time shift, station No.5705.

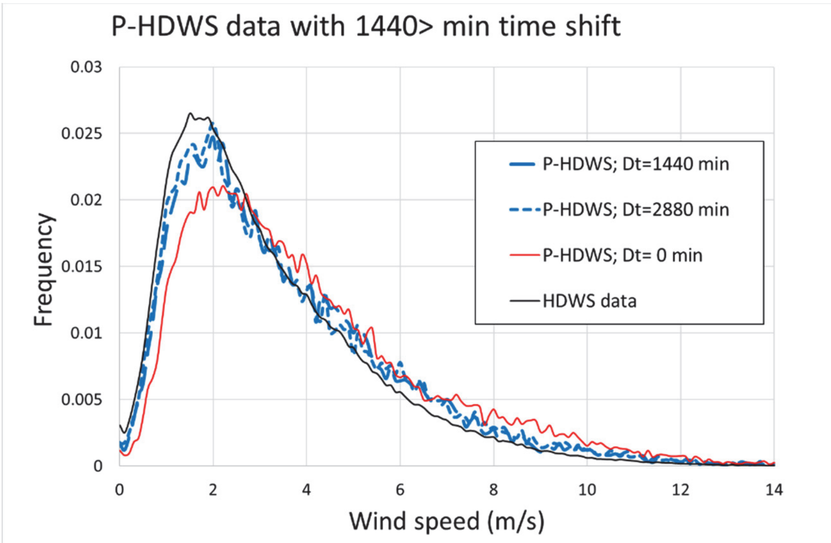

Fig. 11. P-HDWS data with 1440 and 2880 min time shift, station No.5705.

Fig. 12 presents the means of variously shifted P-HDWS data. As the investigated data show, the non-shifted data resulted in the highest mean, and for the means of shifted data by -30 to 160 minutes, lower means can be observed. This decrease of the value, however, are not cosequent, the non-shifted value seems to show an exeptional position. The result does not verify a need of time shifting in the investigation. The results show that the P-HDWS data seems to be adequate for the investigation despite the 5 minutes of data shifting between the HDWS and P-HDWS data.

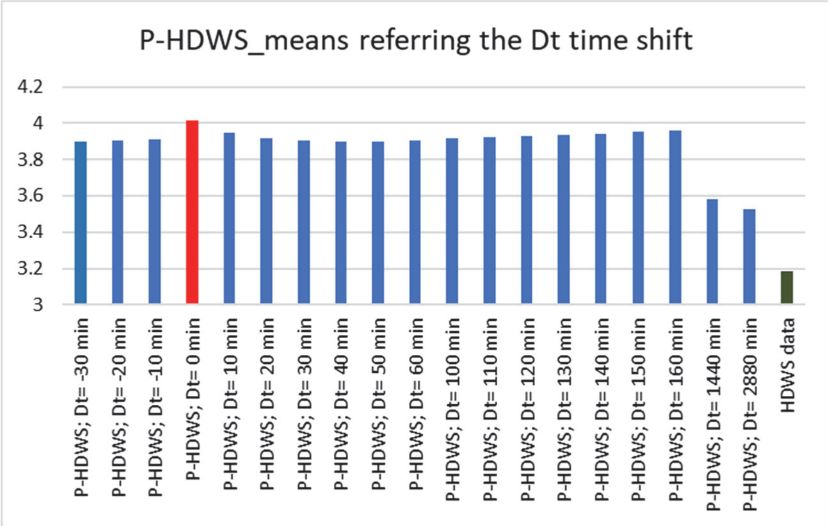

Fig. 12. Ratio of P-HDWS and Dt shifted P-HDWS means, red column: not shifted P-HDWS data; green column: HDWS data, station No.5705.

4. Consequences and further investigations

The investigation results demonstrate that the HDWS statistics cannot be used as a substitution for the P-HDWS statistics in Germany. Further study is needed to proove a generality of this result. The investigation resulted in a robust linear regression between the two statistics for the mean, the median, and the standard deviation. The correlation between the investigated parameter couples is around 95%. Since the arithmetic mean of a large sample is the unbiased estimate of the real distribution's expected value, the mean can be used directly in the ultimately developed correction formulas to adjust statistically the effect of the wind-caused bias of precipitation measurements. Despite that the proposed procedure does not supply corrected time series, the statistical parameters of the adjusted data are good estimations of them.

If there is no wind data for a certain location, the neighboring station's wind data, or a reginally accepted value can supply an acceptable arithemtic mean for the statistical correction, if the neighborhood stations's wind data are acceptabe for this approach, regarding the distance and geographic circumstances. For those stations, where the wind statistics are available, the correction can be performed easily by the poposed method.

For the correction of the historical data, the determination of the correction factors for the earlier used gauges is necessary. For this aim, model experiments or CDF modeling must be done.

Another essential point must be taken care of during the further data processing, such as the inaccuracy by the several minutes long sampling period data. This effect can result in underestimating of wind speed and precipitation data (*Rácz*, 2021b). The correction of this kind of error is not solved yet. Despite these issues, the proposed statistical correction method for the wind-caused error assists in achieving more accurate historical precipitation and rainfall intensity data.

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