



Information gain from different processing steps and additional variables for rainfall retrieval from commercial microwave links

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Abstract. Commercial microwave links (CMLs) are opportunistic rainfall sensors that provide indirect rainfall estimates from attenuation data. This is achieved by separating the raindrop path attenuation from the observed total loss and converting it to rainfall intensity using the $k - R$ formula. Various methods have been proposed for CML rainfall retrieval using either attenuation data alone or additional external variables. However, the majority of studies evaluate CML rainfall estimates deterministically and do not reveal how individual processing steps and variables affect the rainfall estimation uncertainty. This study proposes to evaluate CML processing using an information-theoretic framework and demonstrates this probabilistic concept on two particular problems. The first analysis reveals the reduction of the uncertainty in CML rainfall estimates by measuring the information content of individual variables and their combinations. Both quantitative and qualitative predictors are used, including internal variables such as CML signal attenuation, and external variables such as temperature, or synoptic types. The rainfall intensity derived from $k - R$ formula and synoptic type is an informative combination of internal and external variable for the uncertainty reduction about the reference rainfall intensity. The second analysis demonstrates the application of information theory for classifying wet and dry periods in signal attenuation data and other external variables. A classification model is developed using various predictors, including CML signal attenuation data and external predictors towards a target represented by manually defined wet and dry periods. The model application outperforms the well-established wet-dry classification approach developed for CML data in terms of true positives while maintaining a low level of false positives. The proposed information theory framework enables the identification of informative internal and external variables, the evaluation of the effects of different processing steps on the estimated rainfall intensity, or the development of a wet-dry classification model calibrated in a probabilistic manner, and ultimately facilitates the improvement of CML rainfall estimates.

25 1 Introduction

Opportunistic rainfall observations can leverage existing precipitation monitoring networks. One of the most prominent sources of opportunistic rainfall data are commercial microwave links (CMLs), point-to-point radio connections operating as a backhaul of telecommunication networks. CMLs provide indirect rainfall observations with a dense monitoring network situated a few metres above ground (Uijlenhoet et al., 2018). In addition to the opportunistic nature of the observation, the



30 data are accessible via standard communication protocols in near-real time (Chwala et al., 2016). Over the past decade, CMLs have successfully been employed in hydrology and hydrometeorology, particularly for rainfall monitoring (Messer et al., 2006; Rios Gaona et al., 2017; Graf et al., 2020), water vapour estimation (David et al., 2009), drop size distribution estimation (van Leth et al., 2020), weather radar adjustment (Graf et al., 2024), nowcasting (Imhoff et al., 2020), hydrological modelling in natural and urbanised catchments (Cazzaniga et al., 2022; Pastorek et al., 2023). The field of
35 hydrometeorology can exploit dense near-ground CML networks providing reliable quantitative precipitation estimates (QPE). However, there are several challenges related to rainfall retrieval using CMLs.

As with weather radar, CML rainfall retrieval has to deal with significant uncertainties and bias when estimating rain-induced specific attenuation and, consequently, rainfall intensity using a power law. The transformation of observed total loss (TL) on individual CMLs to rainfall intensity R requires several processing steps. The first step eliminates background
40 attenuation levels, the so-called baseline separation or identification of dry weather attenuation (Ostrometzky and Messer, 2018; Polz et al., 2020; Schleiss and Berne, 2010). The second step involves removing residual attenuation originating from the wetting of radio antenna radomes in the form of additional, multiplicative, or time-dependent bias (Leijnse et al., 2008; Overeem et al., 2011; Pastorek et al., 2022; Schleiss et al., 2013). Lastly, CML path-specific attenuation k is transformed to rainfall intensity using a power law and its empirical parameters depending on CML frequency, microwave polarization, and
45 precipitation drop size distribution, frequently adopted from ITU recommendations (ITU-R, 2005).

CML rainfall retrieval is susceptible to multiple factors of varying origin, all of whose roles must be accounted for and considered, including radio hardware, antenna shielding, CML installation, CML length, microwave propagation near ground (vegetation, surfaces wetness), as well as atmospheric conditions such as rainfall drop size distribution, the terminal velocity of drops, wind speed, humidity, temperature or sunlight. A review of different sources of errors in CML rainfall
50 retrieval can be found in Leijnse et al. (2010), Chwala and Kunstman (2019) or Špačková et al. (2023).

Furthermore, compared to the quantitative precipitation estimation (QPE) provided by the weather radar product, the CML rainfall composite is derived from the observations of hundreds or thousands of individual sensors with spatially variable densities, sensor characteristics, sensor sensitivities to rainfall, errors and uncertainties.

In summary, despite significant progress in the retrieval of CML QPE over the past decade, the interpretation of the CML
55 data using deterministic models is difficult. CML empirical relations are designed to reduce bias by utilising variables that can be obtained from the opportunistic sensors. However, systematic errors may be explained by external variables. Standard approaches do not reveal different data inputs with respect to the uncertainty of the estimation. Furthermore, the interpretation of CML rainfall data is also questioned by uncertainty and the bias of reference rainfall products, e.g., commonly used gauge-adjusted weather radar which is prone to significant uncertainties (Schleiss et al., 2020).

60 In this context, we apply an information-theoretic framework (Shannon, 1948) which enables the evaluation of the strength of the relations between data using derived discrete probability distributions instead of standard optimization processes in formulated deterministic or empirical models. The approach is objective, minimises model parameters and directly measures the information value of data (and strength of their relations), together with the estimation of uncertainty.



Furthermore, the framework allows the favourable integration of both quantitative and qualitative data. The discretization employed in the application of the information theory framework allows wider binning for more intense rainfalls, thus partly mitigating the increasing uncertainty of observations of high rainfall intensities.

This paper presents two analyses. The first examines information value and uncertainty contribution of individual CML processing steps, CML characteristics and the external atmospheric variables to the resulting QPEs. The second experiment is focused on wet-dry classification and a comparison of the information-theory-based non-parametric model with established wet-dry classification and baseline separation approaches.

For the first analysis, 117 sublink CMLs from the Prague region are utilised. Firstly, the contribution of the rainfall-attenuation relation, the WAA and the dependence of rainfall retrieval on CML characteristics are evaluated by measuring the strength of their relations towards reference rainfall. Secondly, the information value and relevance of external variables, namely temperature, seasonality and synoptic type, for CML rainfall retrieval is explored. Thirdly, the effect of data sample size, with respect to different predictive models and the number of predictors, is investigated. In this study, the gauge-adjusted weather radar product is used as the reference.

The second analysis assesses the information value of internal CML data and external variables towards wet-dry classification on a single CML across three non-winter seasons. The investigation of different combinations of variables is followed by the application of the model and its comparison with established CML wet-dry classification and baseline separation approaches.

This study proposes data-driven models for CML rainfall estimation and wet-dry classification using the information theory approach which emphasises the key variables driving the two objectives integral to CML data processing.

The paper is structured as follows: Section 2 elaborates on an overview of information theory methodology and introduces the terminology of the information and uncertainty in the context of information theory, in addition to the measures applied in this approach. The section then assimilates questions to be answered by the information theory approach.

Section 3 summarises the methodology steps in the context of this study. The two tasks, rainfall estimation and wet-dry classification, are elaborated upon separately.

Section 4 presents the available target and predictor data including its preprocessing.

Section 5 presents the results. Firstly, the results of the rainfall estimation analysis which highlight the significance of the variables of rainfall estimation and an evaluation of the models built from the sample showing the data demand. Secondly, the results show the influential variables for wet-dry classification. The information-theory model application is then compared to established wet-dry classification approaches.

The discussion follows with conclusions being drawn in the last section.



95 2 Information theory

This section outlines the fundamental principles of the information theory approach, including the most relevant measures and their application within the context of this paper.

The idea of entropy as a measure of uncertainty comes from a mathematical theory of communication (Shannon, 1948). For a method overview we refer the reader to these textbooks (Cover and Thomas, 2006; Singh, 2013) and papers (Timme and Lapish, 2018; Neuper and Ehret, 2019). Owing to its generality, the approach found its application in e.g., biology (Uda, 2020), design monitoring networks (Foroozand and Weijs, 2021), neuroscience (Timme and Lapish, 2018), the social sciences (Šlerka and Šisler, 2018) or bioinformatics (Steuer et al., 2002). In the field of hydrology, relevant studies include the analysis of the linkage between the hydrological system and topography (Loritz et al., 2018), precipitation variability (Mishra et al., 2009), precipitation estimation (Neuper and Ehret, 2019), model performance evaluation (Liu et al., 2016), or rainfall-runoff event identification (Thiesen et al., 2019).

Information theory benefits from its multivariate analysis setup, in which interactions between variables (in principle, a large number) are examined. It describes uncertainty and dependency between variables and their reciprocal influence (Cover and Thomas, 2006). It both highlights and distinguishes between the variables that determine the system. Even nonlinear interactions of the system variables are successfully detected (e.g., Fig. 5 in Timme and Lapish, 2018). It poses minimum assumptions about the system structure and data interactions. No a priori parameters nor their optimization are required, the data are incorporated directly into the information theory framework. Favourably, data can be of any type (continuous and/or discrete) and can be pre-processed.

However, the information theory approach also has weaknesses. It does not provide a description of the system mechanism and how the system works but highlights the strength of association between variables. It only sets the boundaries of possible models, in the sense of constraining relations between physical quantities. It assumes that the system produces outcomes within a certain range. Even though the continuous form of information theory framework is possible (Cover and Thomas, 2006), it works more instinctually with discrete data which implies that the data needs to be discretized into bins depending on the user's choice. As multivariate data distribution is possible, it can lead to a distribution with inadequate population (Darscheid et al., 2018) when dataset size is insufficient. Nonstationary data may complicate the interpretation of results, thus system stationarity is often assumed (Timme et al., 2018). Moreover, the temporal order of data is lost with the transformation to probability distribution.

The model is, in the context of this study, a multivariate probability distribution of target, the variable we want to predict, and predictors which are variables that potentially reduce uncertainty about the target or carry information about the target. Thus, the model consists of a target and predictor variable(s). The model dimension is the number of predictors plus one (which is the target).

The key quantity in the context of information theory is information ($I(x)$, Eq. (1)) which is a negative logarithm of probability p of outcome x :



$$I(x) = -\log_2 p(x) \quad (1)$$

With a base 2 logarithm, information has units of bits. Information is additive which is an intuitive characteristic. The data in the time series have an information value that is based on occurrence probability p in the dataset. Thus, information value is derived for a specific dataset.

Data carry information and information reduces uncertainty. Having a large enough dataset, the true probability distribution of a variable is known. Different sources of uncertainty can be formulated and quantified: uncertainty due to data variability, uncertainty that can be limited by the knowledge of other variables, and uncertainty by the limited knowledge of data distribution. The measures to comprehend those are provided in the following paragraphs.

Entropy ($H(X)$, Eq. (2)) is a non-negative measure of information content, or measure of uncertainty, and it is unit invariant:

$$H(X) = -\sum_{x \in X} p(x) \log_2 p(x) \quad (2)$$

It measures the spread of the distribution, but in contrast to variance, it is not as influenced by data at large distances from the mean. On the contrary, it is mainly influenced by higher probability outcomes. Consequently, the distribution of qualitative variables can be incorporated in the models. Compared to variance it has an upper boundary (see the next subsection).

Conditional entropy ($H(X | Y)$, Eq. (3)) measures the power of information that we have, in advance, to reduce uncertainty:

$$H(X | Y) = \sum_{y \in Y} p(y) H(X | Y = y) \quad (3)$$

Prior knowledge of other variables will never increase the level of uncertainty compared to the state without the other variable. In the worst-case scenario, prior knowledge of other variables will not be helpful, and uncertainty will remain the same. It describes functional behaviour and does not anticipate performance, such as RMSE.

The model uses the predictor(s) to condition the target and evaluates the information gain when an observation of another variable is used to predict the target. The more informative the predictor, the lower the uncertainty. Thus, different predictors can be evaluated for the significance of their information relating to the target.

In conclusion, the entropy of the target variable distribution scales the uncertainty level at which our models, conditioned by predictors, always perform better. Conditional entropy is always equal or smaller than the entropy of the target (Cover and Thomas, 2006). In this study, the scale is set by the entropy of the distribution of reference rainfall intensity and, for the other analysis, the entropy of the target distribution of reference wet-dry timesteps.

Kullback–Leibler distance (D , Eq. (4), Kullback–Leibler, 1951) is a model-based component of uncertainty:

$$D(p \parallel q) = H_{pq}(p \parallel q) - H(p) = \sum_{x \in X} p(x) \log_2 \frac{p(x)}{q(x)} \quad (4)$$



It is the statistical distance between true p and approximate q distribution (Cover and Thomas, 2006). It serves as a measure of representativeness of the sample to the target.

160 Cross entropy (H_{pq} , Eq. (5)) combines the uncertainty of data (conditional uncertainty) and of the model (Kullback–Leibler distance):

$$H_{pq}(p \parallel q) = -\sum_{x \in X} p(x) \log_2 q(x) \quad (5)$$

Thus, it allows the evaluation of the magnitude and origin of the uncertainty: If the true probability distribution of the system differs from the model, cross entropy increases, as it equals the sum of the Kullback–Leibler distance and entropy.

165 It may happen that some bins in the distribution become empty, thus representing zero probability and leading into an infinite Kullback–Leibler distance. To prevent this, Darscheid et al. (2018) suggested replacing zero probability by small, nonzero values.

3 Methods

The application utilises opportunistic rainfall observations from commercial microwave links. Further, it employs the external, ordinarily collected environmental observations and assesses the potential of their incorporation in CML rainfall estimation models.

The two analyses, each focusing on distinct targets, are conducted using selected predictors. The first analysis is directed towards estimating reference rainfall intensity as observed by independently adjusted weather radar. The second analysis focuses on the classification of wet-dry timesteps in the CML signal attenuation time series.

175 3.1 Rainfall intensity estimation

The targets for the first analysis are reference rainfall intensities retrieved from the intersect of the CML path with the gauge-adjusted weather radar pixels. It is assumed that the reference observation reflects the truth, however, rainfall is an environmental process variable (both in space and time), complex, large in scale and inaccessible meaning the uncertainty of the target observation to the truth is hardly estimated. As in other studies comparing CML and adjusted radar observations (Overeem et al., 2013; Graf et al., 2020), we accept the reference as truth and a target to aim for.

The predictors, listed in Table 1, are variables that potentially reduce our uncertainty about the target. Data are aggregated into 15 min resolutions. Data with longer sampling (seasonality, synoptic type, temperature) are considered as constant for the unsampled timesteps.

To prevent skewness, caused by a large number of dry timesteps, the dataset is subset by exceedance over a threshold of 185 0.5 mm h⁻¹ rainfall intensity of the adjusted radar at the corresponding CML path.



Table 1: Data used in the rainfall estimation analysis. Binning is identified by the edges of the bins.

Target/Predictor	Variable	Unit	Binning
Target	Gauge adjusted radar rainfall intensity	mm h ⁻¹	0.5; 1; 2; 4; 6; 8; 10; 15; 20; 25; 30; 40; 50; 160
Predictor	CML rainfall intensity	mm h ⁻¹	0; 0.5; 1; 2; 4; 6; 8; 10; 15; 20; 25; 30; 40; 50; 602
Predictor	CML specific attenuation	dB km ⁻¹	0; 0.12; 0.23; 0.45; 0.85; 1.24; 1.62; 1.99; 2.91; 3.80;
Predictor	CML specific attenuation without WAA	dB km ⁻¹	4.68; 5.54; 7.24; 8.91; 92.30
Predictor	CML WAA	dB	0; 0.5; 1.0; ...; 6.0; 6.5; 7.0
Predictor	CML frequency	GHz	19.1; 21.2; 24.5; 31.8; 37.0; 39.2
Predictor	CML length	m	45; 295; 545; ...; 6295; 6545; 6795
Predictor	CML polarization	-	^a
Predictor	Temperature	°C	5.5; 8.0; 10.5; ...; 33.0; 35.5; 38
Predictor	Month of the year	-	4; 5; ...; 9; 10
Predictor	Week of the year	-	17; 18; 19; ...; 40; 41; 42
Predictor	Synoptic type	-	^b
Predictor	Rain gauge rainfall intensity	mm h ⁻¹	0; 0.5; 1; 2; 4; 6; 8; 10; 15; 20; 25; 30; 40; 50; 95

For qualitative predictors: ^a horizontal or vertical; ^b 15 synoptic types

The last column of Table 1 shows binning of the data. The binning with uniform width is applied when possible. However, to keep the data distribution skewness, some variables have uneven binning width (e.g., rainfall intensity). Binning is subjective, based on user requirements and should reflect data size, distribution, and precision (Thiesen et al., 2019).

The information theory measures (entropy and conditional entropy) are calculated for single- and multi-predictor models. The power of the predictor combinations to reduce uncertainty is ranked. (500, 750, 1000, 1500, 2000, 5000, 10000, 30000, and the full dataset 52738). A randomly drawn subset for each sample size is repeated 500 times.

3.2 Wet-dry classification

The targets for the second analysis are reference timesteps manually identified as wet or dry in CML total loss (TL) data. The predictors are variables that potentially reduce our uncertainty about the target and are listed in Table 2.

CML data are aggregated into a 1 min resolution. Data with longer sampling (seasonality, synoptic type, temperature) are considered as constant for the unsampled timesteps.

Data are discretized into bins (Table 2). Binning with uniform width is applied when possible. However, to keep the data distribution skewness, some variables have uneven binning width (e.g., attenuation).

Entropy and conditional entropy are calculated for single- and multi-predictor models and the power of the predictor combinations to reduce uncertainty is ranked. The most informative predictor combination is used for the application of the wet-dry classification model.

**Table 2: Data used in the wet-dry classification analysis. Binning is identified by the edges of the bins.**

Target/Predictor	Variable	Unit	Binning
Target	Wet-dry timesteps	-	^a
Predictor	TL, TL (± 1 min), TL (± 2 min)	dB	49.0; 49.5; 50.0; ...; 56.0; 56.5; 57.0; 100.0
Predictor	TL relative magnitude	-	0; 0.1; 0.2; ...; 0.8; 0.9; 1.0
Predictor	TL gradient (prior) TL gradient (following)	dB min ⁻¹	-21; -10; -9; -8; -7; ...; 7; 8; 9; 10; 22
Predictor	TL standard deviation in 15 or 30 min window	dB	0; 0.1; 0.2; ...; 1.8; 1.9; 2.0; 13.4
Predictor	Rain gauge rainfall intensity	mm h ⁻¹	0; 1; 2; ...; 28; 29; 30; 168
Predictor	Temperature deviation from 14 day average	°C	-15; -14; -13; ...; 16; 17; 18
Predictor	Synoptic type	-	^b

205 For qualitative predictors: ^a dry or wet; ^b 28 synoptic types

3.2.1 Application and evaluation of wet-dry classification model

210 The binary nature of the target in the wet-dry classification analysis allows the conversion of the model into binary wet-dry flagged timesteps in the original data time series. The objective is to convert a multivariate probability distribution into binary output as in Thiesen et al. (2019). The dataset is split into a training subset for calibrating detection threshold and a testing subset used for validation. Different training sample sizes are drawn as a subset of 10000, 50000 and 90000 timesteps. The detection threshold is determined as follows:

- 1) Each combination of predictors has a probability for wet and dry timesteps. If a time step has a wet probability greater than the threshold, it is labelled as wet.
- 2) The match rate with the target is checked using receiver operating characteristics (ROC) that reflect the ratio of true positives and the ratio of false positives.
- 3) The optimal threshold is found by minimising the distance to the ideal scenario:

$$\min(\sqrt{(1 - RTP)^2 + (0 - RFP)^2}) \quad (6)$$

where RTP is a true positive ratio and RFP is a false positive ratio defined as:

$$RTP = \frac{\text{true positives}}{\text{all positives}} \quad (7)$$

$$220 \quad RFP = \frac{\text{false positives}}{\text{all negatives}} \quad (8)$$

Validation of the optimal threshold is performed on the test data by the ROC. The ROC is a statistical tool for the evaluation and visual representation of binary classifier performance. It is defined by mapping RFP on the horizontal axis and RTP on the vertical axis, thus the top-left corner of the plot represents a perfect model.



The results of the proposed information theory model are then compared to alternative wet-dry classification approaches that are widely used in CML data processing.

3.2.2 Alternative wet-dry classification approach

Common wet-dry classification approaches are used in this study in comparison with the information theory approach. The most prominent and established approaches are the following:

a) *Baseline separation approach*

It first estimates the baseline on a data-driven basis as a 1 % quantile of total loss baseline, a 7 day baseline of 15 min averages, a constant median baseline, or as 7 day moving quantile window baseline.

The time series is then binarized based on the level of total loss that is larger (wet) or smaller (dry) than the baseline.

b) *Wet-dry classification by Schleiss and Berne (2010)*

It is commonly used in CML research and often considered represents the state-of-the-art. It sets a threshold for a rolling 15 min window standard deviation of total loss. Its detection ability is limited by the window and level of fluctuation within the window.

4 Data

The study presents available CML data available from the non-winter seasons between 2014 and 2016 in the Prague area (35x35 km). In addition to CML data, gauge-adjusted radar data, rain gauge data and other easily accessible environmental data are used. The data resolution for rainfall estimation analysis is 15 min and for wet-dry classification analysis it is 1 min. Lists of all variables for the rainfall estimation analysis and the wet-dry classification analysis can be found in Tables 1 and 2, respectively.

Binning has equal width as often as is reasonably possible, or, is adjusted to keep the distribution shape. Binning for CML frequency data follows the ITU Recommendation for frequency bands (ITU-R, 2001). To avoid empty bins, the absent frequency bands and missing intervals between the ranges of frequency bands are merged with lower frequency bands. Binning for the specific attenuation data is set by the reverse transformation of rainfall intensity binning edges to specific attenuation binning edges by ITU coefficients for 30 GHz CML.

The qualitative data of synoptic type and CML polarization are labelled by integer and binned.

4.1 Target data

Target data (the first lines in Tables 1 and 2) in this study are:

- For the rainfall intensity analysis: rainfall intensities from gauge-adjusted weather radar averaged along a CML path.



- For the wet-dry classification analysis: a manually flagged time series of total loss classifying for one CML wet and dry time steps.

4.1.1 Adjusted radar data – rainfall intensity analysis

Raw radar images are composites of two dual-polarized weather radars from the CZRAD network operated by the Czech Hydrometeorological institute. Reflectivity from 2 km above sea level (CAPPI 2 km) is in a resolution of 1 km x 1 km and 5 min. From the raw rainfall images an area of 35 km x 35 km over Prague is selected.

The raw data are aggregated into a 15 min resolution and multiplicative bias correction is applied by the wradlib package (Heistermann et al., 2013) using 23 municipal rain gauge stations. Further information about rain gauges used for the adjustment is found in Sect. 4.2.3 Rain gauge data.

4.1.2 Manual detection of wet and dry timesteps – wet-dry classification analysis

The target wet and dry timesteps are separated manually by visually inspecting the total loss attenuation data. The attenuation data are collected from a selected CML (25.56 GHz, 2480 m long) from the Prague CML network. In total, 97 % of the timesteps are dry and 3 % of the timesteps are wet.

A wet event is a consistent timespan of higher total loss compared to the total loss level before and after the event, or, compared to the available dataset. Manual detection allows the use of alternative wet-dry classification approaches while comparing their results with the information theory approach.

4.2 Predictor data

Predictor data (other than the first lines in Tables 1 and 2) consist of various sources, either derived from CML data, collected from other sensors, or are synthetic as seasonality or of the synoptic type.

4.2.1 CML data

The CML data comes from the telecommunication network of T-Mobile Czech Republic a.s., which uses Ericsson MINILINK devices. The majority of CMLs consist of two sublinks separated by approximately 1 GHz. Each of two sublinks within one CML in this study is considered as an independent sensor and will, hereafter, be called CML.

The data of the transmitted and received power levels are collected by custom-made data acquisition software and sampled every 10 s.

Only CMLs with a stationary baseline level are considered. Stability is checked by visual inspection and only those CMLs with no visual shift are accepted, thus making 117 CMLs available. The frequency of the CMLs is between 19.16 GHz and 39.16 GHz. Length of the CMLs range from 48 m to 6791 m (Fig. 1). Quantization of transmitted power is 1 dB and received power is 1/3 dB.

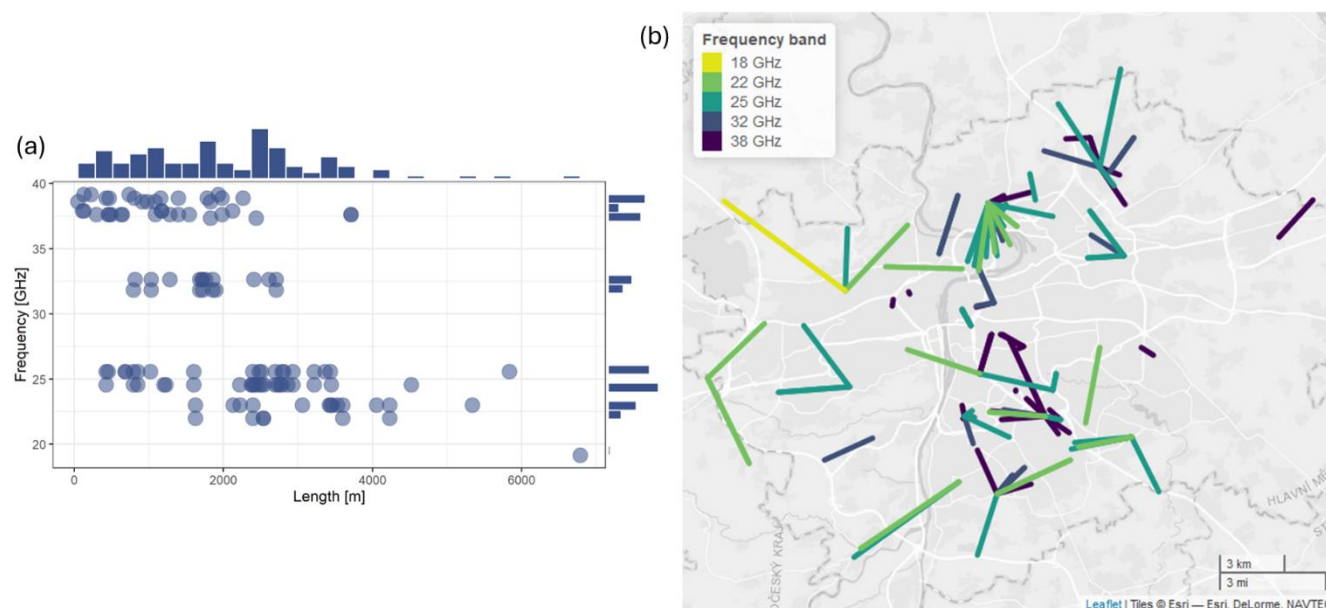


Figure 1: a) Scatterplot of CML length and frequency. b) Map of the distribution CMLs over the Prague area. ©OpenStreetMap contributors 2024. Distributed under a Creative Commons BY-SA licence.

Each CML operates at a different power level across the network. To ensure comparability, the transmitted and received power levels are subtracted and aggregated to a 1 min resolution. For the transformation of attenuation to rainfall intensity, the baseline (10 day moving average) needs to be subtracted to eliminate the dry weather attenuation. Then the WAA can be considered by using the approach of Pastorek et al. (2022) that explicitly derives WAA from rainfall intensity estimated from observed attenuation. Specific attenuation, the total loss divided by link length, can be transformed to rainfall intensity using the $k - R$ relation (Olsen et al., 1978) with empirical parameters (ITU-R, 2005).

4.2.2 Further data derived from CML observation

To evaluate the amount of information preserved, the raw and converted data are used as predictors.

The total loss and its values from 1 min and 2 min prior and after the timestep of interest i ($TL(i - 2)$; $TL(i - 1)$; $TL(i)$; $TL(i + 1)$; $TL(i + 2)$), standard deviation of the signal within a 30 min ($sd(i - 15, \dots, i + 15)$) and a 15 min centred moving window ($sd(i - 7, \dots, i + 7)$) are tested. The gradient expressed, with respect to the timestep before or after the timestep of interest and the relative magnitude of total loss within a 209 min window are considered (the window with the largest information value is estimated by the approach presented in Thiesen et al., 2019).

4.2.3 Rain gauge data

In the Prague permanent municipal rain gauge network (maintained and operated by Pražské vodovody a kanalizace, a.s.), there are 23 tipping bucket rain gauges. The sampling is 500 cm² and the resolution is 0.1 mm (MR3, METEOSERVIS



v.o.s.). To relate the CML and rain gauge time series, the minimum distance between the centre point of the CML and all rain gauge stations is found, and the corresponding rain gauge data are aligned. The calibrated tip records are transformed to a rainfall intensity time series of resolution 15 min for the rainfall estimation analysis or 1 min for the wet-dry classification analysis.

4.2.4 Other available datasets

Other easily available environmental data are utilised in the analyses. The first set of data includes temperature-related quantities: the current temperature and its deviation from a 14 day moving average, which can indicate a temperature drop associated with rainfall events. Temperature data are collected from five municipal stations in Prague with the closest station to the CML being used in the data tuples.

Additionally, seasonality is represented by both month and week of the year.

Lastly, the synoptic type is determined based on the expertise of the Czech Hydrometeorological Institute (CHMI, 2024).

5 Results

In the following section, we investigate the opportunistic rainfall observations from the CMLs and external environmental observations for rainfall estimation models. First, we analyse the predictors towards the reference rainfall intensity observed by independently adjusted weather radar. Second, we analyse the predictors for the classification of wet-dry timesteps in the CML signal attenuation time series. Finally, we show a comparison of the wet-dry classification approach to the established models used in CML data processing.

5.1 Rainfall estimation

The value of predictors for rainfall intensity estimates is quantified by conditional entropy. The evaluation of selected variables and their combinations is presented in Fig. 2.

The solid vertical line in Fig. 2 scales the other results, with respect to the entropy of the reference distribution that is caused by the variability of the rainfall intensity of the reference. Target uncertainty is thus expressed as the entropy of the reference distribution. The upper boundary of uncertainty (dashed line in Fig. 2) is expressed as the entropy of the uniform probability distribution with the bin range as its target.

Incorporating predictors reduces uncertainty in the target variable (bars in Fig. 2, note that only selected results are shown) which allows a comparative evaluation of the influence of the predictors via conditional entropy.

Specific attenuation as a predictor gains less information for estimating the target compared to CML rainfall intensity alone, a 3 % difference that represents the effect of the data transformation from specific attenuation to rainfall intensity using parameters that reflect the frequency and polarization of CMLs. The combination of specific attenuation and CML frequency (double-predictor model) approximates CML rainfall intensity well (single-predictor model), confirming that



frequency-related effects in the data are present. Specific attenuation without WAA leads to a 6 % increase in uncertainty which indicates that the largest space for method development lies in the WAA estimation.

The 4 % decrease in relative conditional entropy for the combination of CML rainfall intensity and CML length, compared to stand-alone CML rainfall intensity, suggests that the effects of CML length should be further incorporated into rainfall retrieval models.

The combination of CML frequency and length, along with CML rainfall intensity, yields results that are 1.5 % better than the combination of CML frequency, length and CML specific attenuation.

The external predictors of seasonality and synoptic type are valuable predictors for further uncertainty suppression. Uncertainty decreases by 10 % when combined with CML rainfall intensity and by 5 % when combined with the synoptic type only. The potential to improve and leverage CML data processing methods with those easily obtainable variables is within reach.

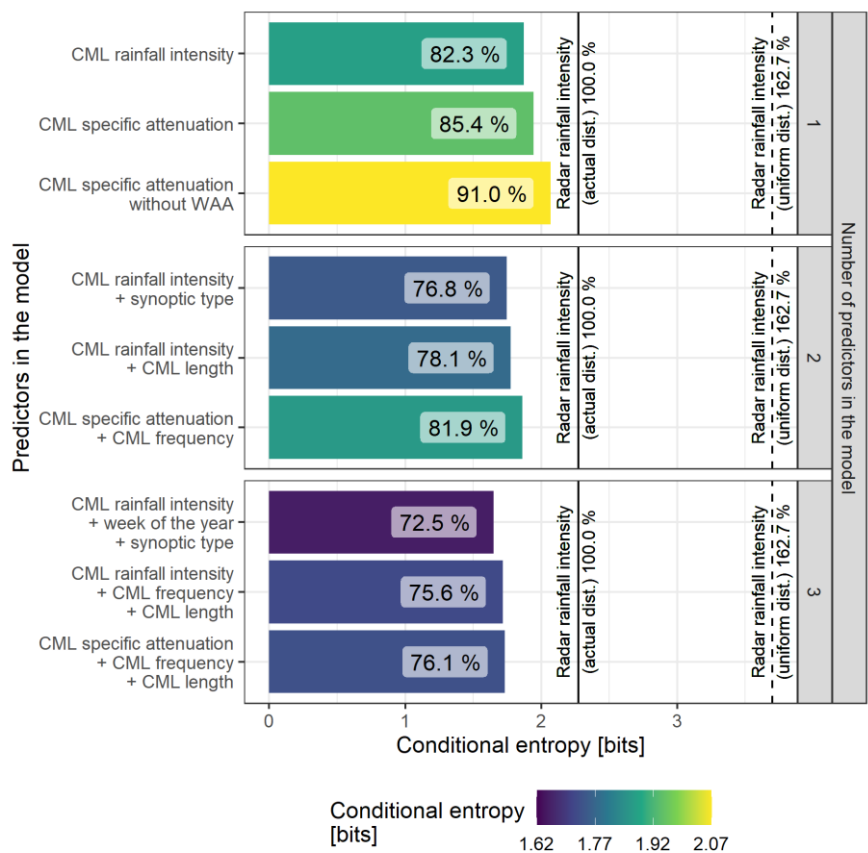


Figure 2: Conditional entropy of models built using one to three predictors. Relative entropy is indicated in percentage with respect to the entropy of the target. The entropy of the target is indicated by the solid line. The entropy of the uniform distribution is the dashed line.



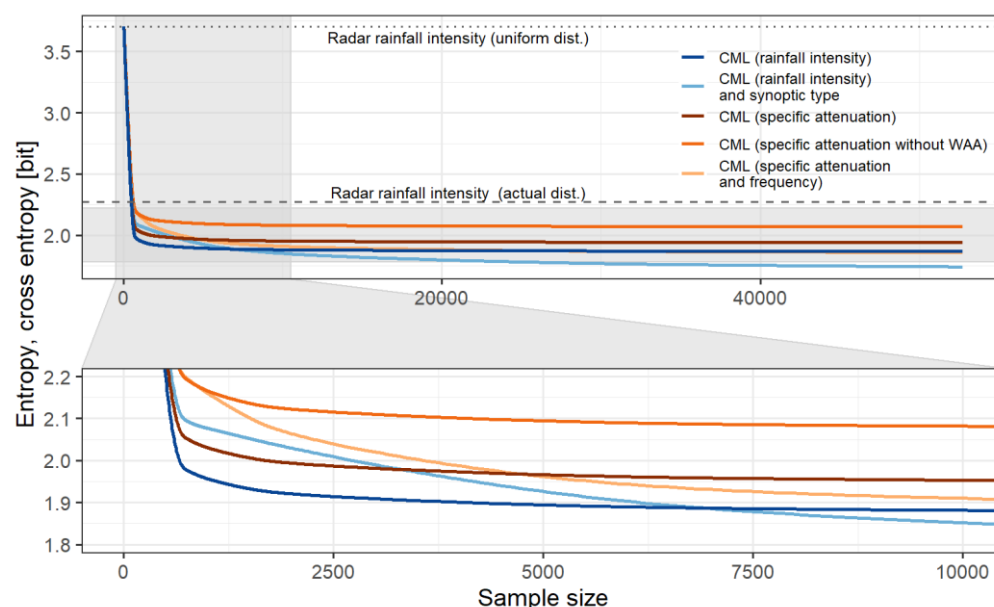
The robustness of the models is evaluated by the quantification of cross entropy for different sample sizes. Figure 3 shows how cross entropy decreases with increasing sample size. The more predictors, the larger the sample size needs to converge to the cross entropy of a full dataset. The model saturates at certain data samples (lines in Fig. 3 become close to horizontal). This is defined by a 5 % criterion for the ratio of the model-based component of uncertainty and the data-based component of uncertainty (Thiesen et al., 2019).

The small sample size model contains an extremely low amount of information and, thus, reaches the uncertainty of a uniform target distribution (dotted horizontal line in Fig. 3). With an increasing sample size, the models quickly reach the internal uncertainty of the target (dashed line in Fig. 3) that is caused by the variability of rainfall intensity of the reference. By further increasing the sample size model, the curves almost become horizontal lines, meeting the 5 % criterion. A larger dataset is not actually needed to sufficiently describe the relations between the variables in the model.

Both models, one constructed from specific attenuation with CML frequency as predictors and one from CML rainfall intensity as a predictor, exhibit similar performance for the full dataset (also measured as conditional entropy in Fig. 2) but differ in their saturation related to the sample size (cross entropy in Fig. 3). The model from specific attenuation with CML frequency as predictors saturates at a sample size of 4816 and the model from CML rainfall intensity saturates at a sample size of 904.

The incorporation of the WAA in the preprocessing of specific attenuation affects the overall level of cross entropy, but both saturate at the same sample size (sample size of 894 for specific attenuation and 903 for specific attenuation without WAA).

The CML rainfall intensity and synoptic type model achieves better uncertainty reduction for the full dataset with the improved results starting to occur at around one-fifth the size of the dataset as saturation is reached at a sample size of 10952.



370 **Figure 3: Effect of the sample size on the model expressed by cross entropy. Entropy of the target is indicated by a dashed line. Entropy of the uniform distribution is a dotted line. Cross entropies of the models as a function of sample size.**

5.2 Wet-dry classification

This study introduces an approach for wet-dry classification in signal attenuation observation based on the evaluation of information measures (conditional entropy) in the information theory approach.

375 As in the preceding section, the predictors are evaluated with the objective of estimating their effectiveness for wet-dry classification.

Figure 4 shows the conditional entropy of the models with one, two, and three predictors. The entropy of the target (solid line in Fig. 4) provides a scale for the results of conditional entropy.

Most informative predictors come from internal CML data as TL observations (from the timestep of the event and from
380 the surrounding timesteps ± 2 min) perform the best with an approximately 38 % reduction of uncertainty. There is a significant difference (9.4 %) in the uncertainty reduction for the standard deviation (sd) of a 30 min moving window and a 15 min moving window. The external predictor, a rain gauge approximately 3 km from the CML, reduces uncertainty by only 20.5 %. Information about synoptic type reduces uncertainty by 16.8 %. Finally, temperature deviation from the 14 day moving average is not so informative with almost no uncertainty being reduced. The temperature drop when a rainfall event
385 comes is unlikely to be strong enough or occurs only in a limited period in the peak of summer. Even less information is found in the local gradient of the total loss and in total loss relative magnitude (not shown in Fig. 4).

The TL, in combination with the relative magnitude of TL, is the most informative of the two-predictor models as it decreases uncertainty to 46.4 %. Both the TL and TL (+1 min) with synoptic type reaches almost 50 %. Combining the TL with the TL sd in the 30 min window decreases uncertainty by more than 10 % compared to the TL model only (and by



almost 16 % compared to the model using only the TL sd in a 30 min window). The rain gauge data from the relatively distant rain gauge does not significantly improve the results of the TL model. Similarly, the temperature data and the TL gradient are not significantly informative.

The three predictor models are all based on a combination of the TL and the relative magnitude of the TL. The most informative combination includes the synoptic type which reaches 36.8 % of relative conditional entropy. The combination with TL sd in a 30 min window (39.6 %) is about three percent worse in comparison. Temperature deviation ranks third best with 41.7 %. At this point rainfall intensity from the rain gauge does not enhance the results (1 % reduction compared to the two-predictor model). Other variables retrieved from the TL time series (TL (+1 min) and TL gradient) do not cause any significant improvement.

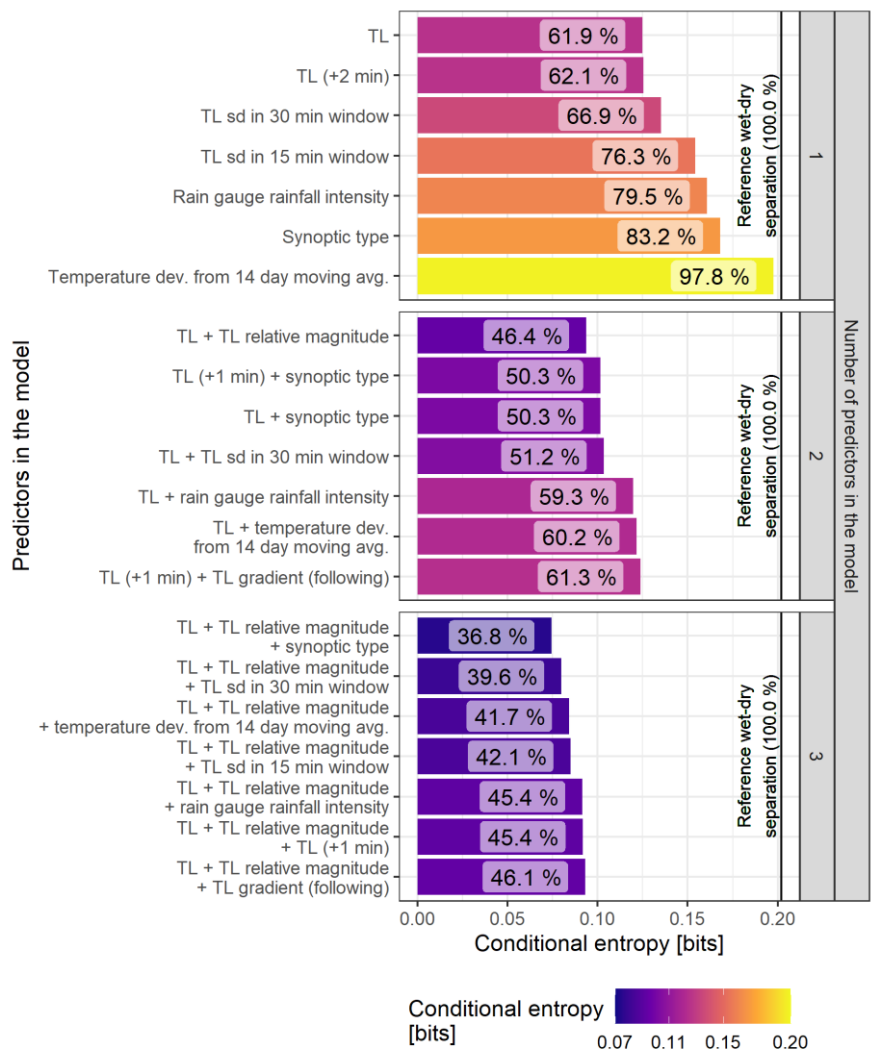


Figure 4: Conditional entropy of models built using one to three predictors. The relative entropy is indicated in percent with respect to the entropy of the target. The entropy of the target is indicated by a solid line.



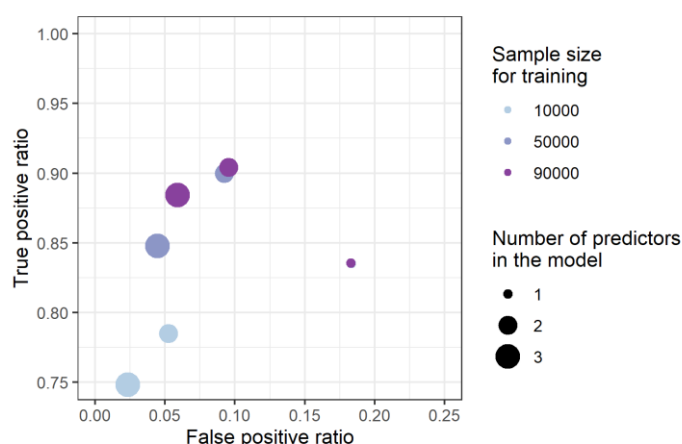
Test performing models with one (TL), two (TL and TL relative magnitude) and three (TL and TL relative magnitude and synoptic type) predictors are applied to the time series and the results are compared below with other wet-dry classification approaches.

405 The model probability distribution is first converted to binary form as described in Sect. 3.2.1. The ROC is calculated and plotted in Fig. 5. The best performance, distance to the perfect model (false positive = 0 and true positive = 1), is 0.13 for the three-predictor model with the largest sample size used for training. Generally, a small ratio of falsely positive events and a high ratio of true positive events have been found.

410 Figure 5 shows that the more predictors there are, the better the results. And the more data available for training, the better the results. The trend shows that the more data used, the greater the improvements in the true positive ratio compared to the false positive ratio, especially for the three-predictor model. For the one-predictor model, the results for the distance to the ideal model are quite similar (around 0.246). One predictor model does not require much data to learn the relations, however, their results cannot be improved by increasing the amount of data. On the other hand, the three-predictor model fails when an insufficient amount of data is available and is outperformed by the two-predictor models.

415 The results are then compared to other wet-dry classification approaches (Fig. 6). The baseline separation approaches for wet-dry identification recognise true wet timesteps very well (with RTP higher than 94 %). However, they suffer from a high ratio of falsely identified wet timesteps (mostly 48-50 %). Any random increase of the fluctuation of a signal is identified as a rainfall event.

On the other hand, the approach of Schleiss and Berne (2010) tends to have a low RFP (5 %), however, RTP is only 44 %. Longer windows for standard deviation calculations improve results. Their approach is less sensitive to smaller rainfall events, however, it works well when identifying stronger events. In contrast, the information theory approach has a similar RFP (6 %), but reaches a higher RTP (89 %).



425 **Figure 5: Receiver operating characteristics of the best one-, two- and three-predictor models trained with different sizes of the dataset. The scales of the axes are adjusted to zoom into the top-left area of the ROC plot.**

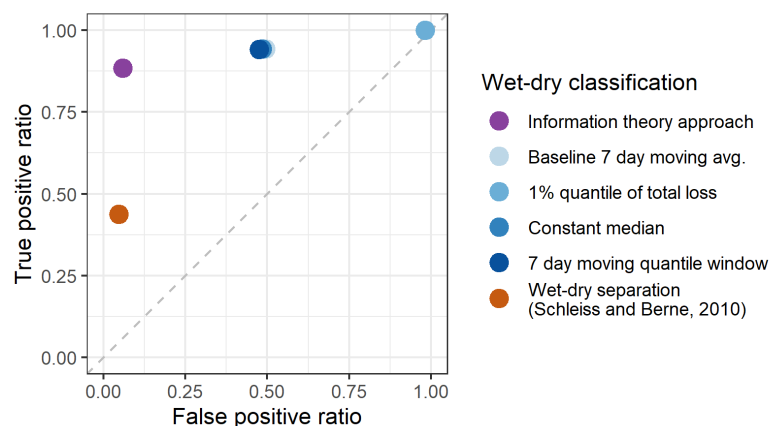


Figure 6: Receiver operating characteristics of the alternative wet-dry classification approaches.

5.3 Discussion

Interpretation of the method results When adopting an information theory approach, we exploit a long dataset of opportunistic observations and relax our assumptions about the system relations. These assumptions, traditionally formulated in data processing as empirical relations, can be reframed using information theory which focuses solely on the data-derived relations. Information theory provides a means of identifying unknown relations within a given dataset. Furthermore, it is capable of evaluating both quantitative and qualitative data in contrast to correlation or RMSE. The method, however, requires the specification of the range within which the variables occur and it is unable to extrapolate beyond the known (or estimated) range. As the position and order of the data within the time series are lost, the information theory approach considers each timestep as independent. This can be partially compensated by using the variable shifted in time, as in the second analysis in this study.

The approach does not allow the interpretation of isolated data from the context of the dataset. Conditional entropy does not provide a measure of certainty about the target variable. It does, however, estimate the relative reduction of uncertainty that comes with knowledge of other variables. The shared units of bits ensure the comparison of results across all variables.

We are aware of climate-specific constraints. The target reference rainfall distribution has been applied in central-European climatic conditions. Walraven et al. (2022) show that the relation of attenuation and rainfall needs to be adjusted for other climatic regions. This study, however, affords the opportunity to evaluate variables and characteristics that may affect the CML rainfall estimation process.

Relative reduction in uncertainty owing to CML specific attenuation is at a similar level as the uncertainty reduction. This is due to the radar reflectivity at the border of Belgium and Luxembourg that served as the predictor for target rainfall estimates of tipping bucket rain gauges for catchment in the study conducted by Neuper and Ehret (2019).



The incorporation of CML length showed an additional reduction of 4 % of uncertainty. This indicates that CML length plays a more significant role than current methods allow for. Berne and Uijlenhoet (2007) demonstrated that CML length has no influence on power-law exponents. Therefore, CML length effects arise elsewhere (e.g., WAA, which is more pronounced for shorter CMLs). It is worth noting that the work of Berne and Uijlenhoet (2007) is based on stochastic simulator data, whereas our study uses adjusted radar reference.

Accuracy of reference rainfall The accuracy of the rainfall estimates is significantly affected by the observation technique employed. In the context of CML rainfall retrieval, a common practice is to compare the results with reference weather radar gauge-adjusted rainfall intensities while utilising path-averages derived from intersected pixels. The benefits of weather radar observation, namely high spatial availability and relatively good spatial resolution, are weighted against the indirect nature of high-altitude and volume-based observation. Furthermore, the influence of wind and the 5 min sampling intervals present additional challenges in the comparison of these data to the close-to-ground CML observations which are sampled in timesteps of a few seconds. In particular, there is a lack of discussion in the CML studies regarding the extent to which they reproduce the errors and bias of the weather radar. Even though the application of rain-gauge adjustment increases accuracy and reduces the bias of the radar observations compared to the raw measurements, inaccuracies and biases to the truth remain. The longer the time aggregation, the greater the tendency to smooth out short-term fluctuations in rainfall intensity, thereby reducing discrepancies (Schleiss et al., 2020). In our study, the 15 min aggregates are used to maintain the size of the dataset while reducing errors. An independent study on the cross-validation of radar adjustment showed that RMSE decreased from 3.5 mm h⁻¹ to 2 mm h⁻¹ and correlation increased from 0.6 to 0.8 for a 15 min aggregation compared to a 5 min aggregation. However, for rainfall intensities higher than 10 mm h⁻¹, adjusted radar underestimated rain rates by 40 % at 15 min resolution. Obtaining an accurate measurement of such a highly space-time variable process as rainfall remains challenging.

Binning For models including rainfall intensity, we propose a minimal bin width of 0.5 mm h⁻¹ as the bin width should be greater than or equal to the measurement resolution. The coarsest resolution of rainfall intensity is provided by the tipping bucket rain gauges (0.1 mm h⁻¹). Thus, the bin width started with a width of 0.5 mm h⁻¹ and was then increasingly extended as uncertainty increased with higher intensities. The wider bins, for more intense rainfalls, preserve the information relating to the distribution. If the bins are too narrow, the high rainfall intensities will be fragmented leading to loss of information (Pendergrass and Hartmann, 2014). More specifically, for high rainfall intensities, which are relatively rare, the higher number of dimensions of the model can significantly defragment the occupancy of the bins. The selection of bin size and the characteristics of entropy, in contrast to e.g., variance, is more influenced by outcomes with higher probability, instead of outliers, which results in assigning a larger model impact for moderate and lower rainfall intensities.

Data set variables This study incorporated readily available variables capable of exerting an influence on CML rainfall retrieval or wet-dry classification, such as temperature, seasonality and synoptic type. It concurs with pioneering studies in the field of CML aiming to challenge the dominant approach of data processing by introducing external variables. Van het Schip et al. (2023) employed satellite products (precipitation and cloud properties) for the classification of wet and dry



conditions in the Netherlands. However, cloud properties were available only during daylight hours. Pastorek et al. (2019) employed runoff observations with the objective of enhancing the estimation of WAA in a specific context of a small, separate stormwater drainage system.

485 6 Conclusions

Analyses were performed within the framework of information theory, an approach that has vast applicability in the field of geosciences in the context of complex environmental systems which aim to synthesise data and models. Information theory quantifies information and uncertainty within any structure of data content rather than relying on descriptive relations. Information theory enables the effective handling of extensive datasets and the evaluation of data relations through
490 generalised models with minimal prior (and possibly not optimal) assumptions.

For the first time, information theory has been used on time series from opportunistic rainfall sensors, particularly CMLs, sensors requiring extensive data processing to achieve minimal bias that is likely caused by external variables that have not yet been incorporated in data processing algorithms. The information theory measures suggest that CML data processing models can be improved by incorporating external variables, from which synoptic types performed well, as the
495 combination of CML rainfall intensity and synoptic type decreased uncertainty by 5 % compared to CML rainfall intensity only. Further, adding the seasonality decreases uncertainty by an additional 5 %. Incorporation of such external variables is thus encouraged.

Accordingly, the internal variables from CMLs are evaluated for their usefulness and significance to determine the target variable which is rainfall intensity in the first analysis and wet-dry classification in the second analysis. The results confirm
500 the importance of separating wet antenna attenuation which reduced uncertainty by 6 % and reveal that CML length should be further incorporated into the rainfall retrieval models.

The presented results encourage the use of the synoptic type as a useful predictor for both rainfall estimation and wet-dry classification. The model application outperforms the well-established wet-dry classification approach in true positives while maintaining a low level of false positives. The comparative study confirmed the predictive potential of the evaluated
505 variables.

Interpreting results from an information theory approach requires recognising the limitations of the measures covered in the discussion. The presented results provide evidence that the concepts of information theory are useful tools for discovering relationships between variables and for evaluating their relevance in the context of opportunistic sensors.

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Competing interests. The authors declare that they have no conflict of interest.



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