

Intercomparison of Precipitation Sensors Based on Optical, Radar, and Gauge Technologies Across Diverse Climates and Operating Environments

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Abstract:

Accurate precipitation measurements are essential in meteorology, hydrology, climate monitoring, and for operational warning systems. Sensors of different technologies (such as optical, radar and weighing) often respond differently to variations in precipitation intensity, hydrometeor sizes and types. Mechanisms of wind induced, and other environment related uncertainties vary for different sensing principles and implementations. Evaluations are complicated by the interplay between site characteristics (orography, shields, environmental exposure, seasonal aspects) and sensor specific characteristics (design features and actions of maintenance).

Assessments of general suitability of a measurement (a sensor) for a particular application can be pursued, by applying a common metric, such as WMO Measurement Quality Classifications for Surface Observing Stations on Land, to a set of deployments which realistically represent the variability of sites, of weather and of operating conditions. This study presents an inter-comparison of precipitation measurement technologies deployed across multiple sites operated through multiple seasons representing different climatic and environmental conditions. The objective is to improve understanding of technology-dependent measurement behavior across varied climatic and environmental conditions, and to contribute to best practices for selecting suitable instruments for specific climates and deployment environments.

The analysis considers time series of data from an ensemble of vertically pointing Doppler sensors, of optical sensors, and of gauges, deployed as multiple units to sites with double fence shielding or pit mounts, representing climatologies of equatorial rainforest (Köppen Af), of low altitude humid continental (Dfb), of elevated altitude semi-arid/humid continental (Bsk/Cfa), and of temperate maritime climate (Cfb). Event-based and long-term performances are considered of precipitation intensity, accumulation, detection skills, temporal responses, and robustness in varied weather conditions.

1. Introduction

Accurate precipitation measurements are essential in meteorology, hydrology, climate monitoring, for a wide range of applications, including meteorology, hydrology, climate monitoring, and operational warning systems. Evaluations of individual sensors and sensor technologies are complicated by the interplay between site characteristics (orography, shields, environmental exposure, seasonal aspects and sensor specific characteristics. To capture a comprehensive view on sensor performances, the evaluated

sensors need to be exposed to the full variability of weather representing the climatological and site conditions in their intended use cases.

This study is an intercomparison of sensor ensembles of PRECIPAP technology, of optical precipitation sensors and of wind shielded gauges, deployed to four sites representing substantial climatological variability, globally. PRECIPAP is a recent realization of a high resolution vertically pointing Doppler radar. The sensors have been operated through multiple seasons capturing varied events and conditions of liquid and frozen phases of precipitation, whenever applicable to the site climate.

The precipitation data are considered as seasonal accumulations of rain (or liquid water equivalent of frozen hydrometeors), or projected as classes of varied rain intensity, and of wind conditions. Data of cool seasons and from hail prone locations allow assessments of precipitation type estimation skills of the technologies with the skill (PRECIPAP and optical sensors). Through deployment of several sensor units of each technology, their unit-to-unit variations can be calculated.

General suitability to meteorological measurements in views of applications and user needs is assessed by utilizing a common qualitative metric of the WMO Measurement Quality Classifications for Surface Observing Stations on Land "OSCAR, see WMO, 2024). The OSCAR scheme allows quantifying measurements' qualities obtained at actual sites, i.e. characterizing the performances in ambient variable weather thus including the factors of instrument coupling, of broader environmental effects, and of maintenance and field verification. The intent of WMO metrics is to assist industry to deliver solutions to meet user needs,

This report is structured as follows. Section "Sites, their climate features and the instrumentation" introduces the sites, their climatology and the common aspects of site infrastructure, sensor deployments, as well as site specific features. Section "common data analysis methods" describes the data sets utilized in the analyses of cases and seasonal statistics. The common and site-specific quality selection criteria of valid data sets are depicted. The analysis specific method of defining common local synthetic estimates of precipitation amounts (local 'truths') are described. Section "Statistical analyses of rain measurements" first compiles the outcomes of the seasonal statistical analyses, site-by-site. Section "Specific weather cases" presents complementary studies of weather cases exploring features not evident in the coarse statistical approach. Section "Conclusions" represents a synthesis of findings in the preceding material. Section "Summary" recaps the main outcomes of the work.

2. Sites, their climates and the instrumentation

For precipitation sensor technology intercomparisons, Vaisala instrumented three test sites in the same layout at different continents. Multiple precipitation sensor units were deployed representing three different sensing technologies, supported by auxiliary co-located measurements of wind and temperature.

The sites are in Boulder Colorado, United States, in Vantaa, Finland and in Selangor Malaysia, see the map in Figure 1. Additionally in co-operation with The Irish Meteorological Service (Met Éireann), Vaisala has operated individual sensors in Valentia, Ireland, co-located with Valentia Observatory sensors with long term records of consistent surface observations of precipitation, wind and temperature. Operations of these four sites for several years have accumulated time series of observations of

precipitation amounts, intensity and precipitation type in varied weather cases in multiple seasons thus representing variabilities of precipitation, globally.

Time series of precipitation data are acquired by the sensor technology of PRECIPCAP™ which is recently introduced high resolution vertical Doppler radar, of an optical sensor and of a rain gauge. Multiple sensor units of each technology were deployed, to allow capturing unit-to-unit variations which may arise due to statistics in precipitation samples or may be characteristic of each sensor.

SITES CHARACTERISTICS

Vaisala has operated an in-situ surface precipitation test site at the office location in Boulder (Colorado, USA) for several years - with the sensor composition in the wind fence of this campaign since begin of 2023. The location is at the altitude of 1660 m (MSL) representing a semi-arid/humid continental climate (Köppen class Bsk/Cfa), with distinct mild summer and cool winter seasons. Events of hail (varied sizes) may occur in summertime. Intense snowstorms may occur in winter. The mean annual precipitation amount is 490 mm. In subsequent analyses, the time series of this site are labelled as "elevated altitude continental (Boulder)".

Similarly, Vaisala has operated an in-situ surface precipitation test site at the headquarters in Vantaa (Finland) for decades - with the sensor composition in the wind fence of this campaign since 2021. The location is close to sea level at the altitude of 50 m (MSL) representing a climate of a cold hemi boreal humid continental climate, moderated by the influence of the Baltic Sea and the North Atlantic Current. Intensities of rain vary in summertime, while events of drizzle, of mixed phase and of frozen precipitation recur in the cool season. The mean annual precipitation amount is 650 mm. In subsequent analyses, the time series of this site are labelled as "low-altitude humid boreal (Vantaa)".

Vaisala has operated an in-situ surface precipitation test site in the county of Selangor in Malaysia, with the sensor composition in the wind fence of this campaign since May of 2023. The location is at the altitude of 100 m (MSL) representing an equatorial tropical rainforest climate (Köppen class "Af"). The annual rain amount is 2000 mm, distributed throughout the year with a maximum monthly rain amount exceeding 280 mm in November and the minima in February and in June approaching 120 mm. In subsequent analyses, the time series of this site are labelled as "tropical rainforest (Selangor)".

Additionally in co-operation with Met Éireann /Valentia Observatory, a subset of the precipitation sensors has been operated since October 2024, co-located with the Valentia Observatory sensors (see Figure 1) which have long records of surface observations of precipitation, wind and temperature, representing the climate of "temperate maritime" climate (Köppen class "Cfb"). The design of the test site follows the principle of open fields (no wind shields, see Figure 3) allowing ambient winds unhindered over the weather sensors. The functionality and performance of the gauges used for the local rain composite is based on their mounts on ground, each in a circular turf wall. The location at the coast of Atlantic Ocean and its open non-obscured layout are complementary to other test sites of this campaign which are equipped with wind fences and shields dedicated to maintaining the performance of weighing gauges in windy weather. This test site resembles the Class-2 criteria of the Siting Classifications for Surface Observing Stations on Land, Annex 1.D of WMO (2024).

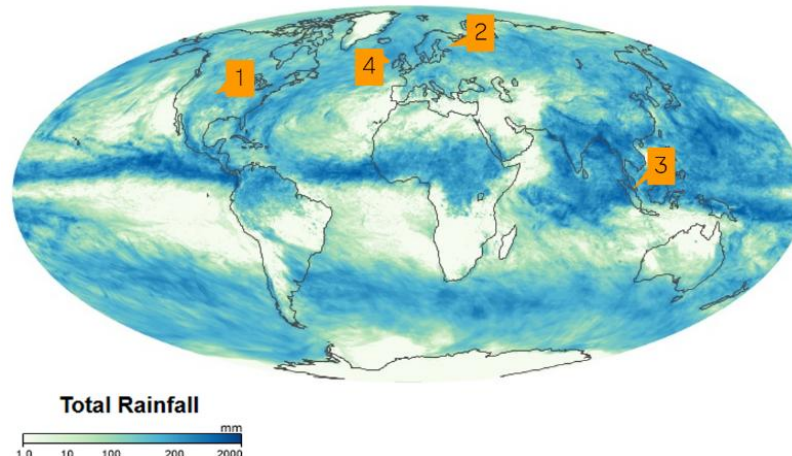


Figure 1. The test site locations instrumented for the intercomparison campaign – 1) the site of elevated altitude semi-arid/humid continental (Bsk/Cfa) in Boulder, CO/USA, 2) the site of low-altitude humid boreal in Vantaa, Finland, 3) the site of tropical rainforest in Selangor, Malaysia, and 4) the site of temperate maritime in Valentia, Ireland. The global map background illustrates the global reconstruction of monthly rainfall for August 2024, source NASA (2024).

COMMON INFRASTRUCTURE

Three precipitation test sites in the USA, Finland and Malaysia were constructed in the same layout of sensor mount points/masts within a wind shield constructed of wooden fences. See Figure 2 for the installations and a drawing with dimensions. The wooden fences extended to the height of 1.7 m serve for the purpose of the outer wind shield for the pair of weighing gauges, each equipped with an Altera shield operated in the middle within the fences. From viewpoint of weighing gauges, the test sites meet the Class-1 criteria of the Siting Classifications for Surface Observing Stations on Land, Annex 1.D of WMO (2024).

The layout of the fencing sets priority to the requirements for weighing gauges measurement quality while a key campaign objective was to evaluate robustness of PRECIPAP and optical sensor technologies in varied and potentially sub-optimal site conditions. The sensor units representing PRECIPAP and optical sensors were mounted on masts extending slightly above the outer wind fence. Consequently, the air flows at their sensitive measurement volumes and areas may get affected by the outer wind shield thus exposing them to the challenges of turbulence, characteristic of diverse deployment sites. In combination with the open field layout (no fences) of the site of temperate maritime (Valentia), the campaign thus served as a deliberate test of robustness of these technologies, in view of potential operations in diverse deployment environments.

Local operators were instructed not take any actions of maintenance on the sensors representing PRECIPAP, to validate the objective of evaluating maintenance free functionality.

The site infrastructures in the USA, Finland, and Valentia were robust in regards mechanical integrity, supplies of electricity and telecommunications. Maintenance actions could be taken promptly in rare events of infrastructure failures, resulting to a very high data availability. Operating the remote site at Selangor, Malaysia turned out challenging due to repeated instabilities in local electric power network and other weather-related issues which persisted with introduction of uninterrupted power supplies. Gauges

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required maintenance. This posed challenges in carrying out statistical analyses of the data time series, limiting the analysis to selected time spans and weather cases in which the impacts of infrastructure instability could be separated from sensor technology performances. Unusual drought persisted at Selangor site during the strong El-Nino phase in 2026.

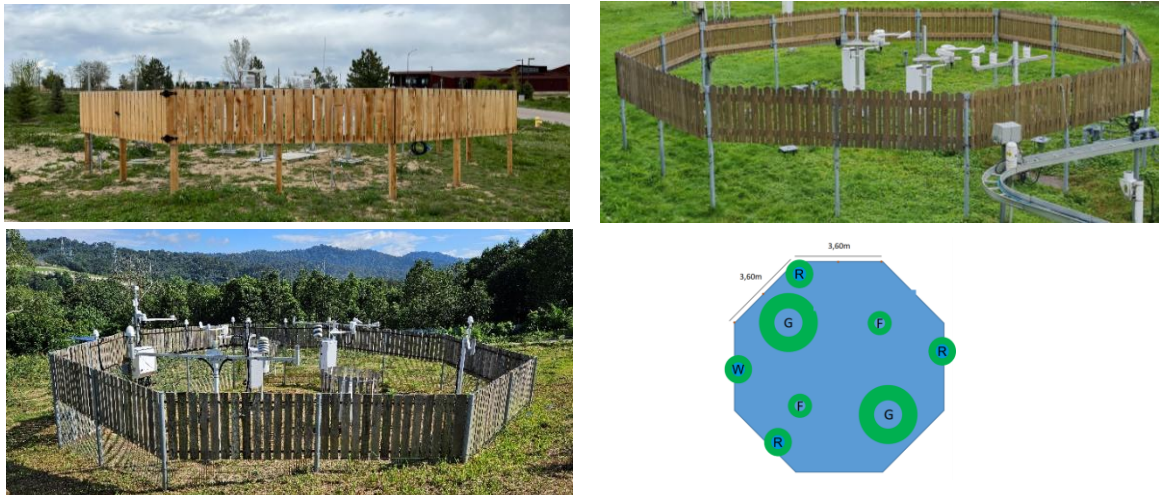


Figure 2 Common layout of the precipitation test sites, instrumented by Vaisala. Top left and right: snapshot at an early construction at the US and Finland site, bottom left: the realization at the Malaysia site, bottom right: the top view of the layout with dimensions. The height of the outer fence is 1.7 m. Symbols "G" refer to weighing gauge, equipped with Alter shield, "F" refer to the mast mount points of FD70 sensors, "W" to the mount point of the wind sensor, and "R" to the typical locations of the RM60 sensors, all mounted above the outer fence upper edge. The intend of the outer fence is to serve as a wind shield to weighing gauges, while FD70 and RM60 sensors operated in air flows above the wind shield.



Figure 3. (left) The mount point of the FD70 sensor and of the RM60 sensor at Valentia Observatory. (right) the satellite map view of the test site, where the red symbol locates the mount point of the FD70 and the RM60 sensor, the orange arrow indicates the view of direction in the photo on the left. The blue rectangle indicates the area of pit mounted rain gauges of Valentia Observatory.

PRECIPITATION SENSORS

Representing recently introduced PRECIPAP high resolution vertically pointing Doppler radar sensor technology, several units (typically three) of Vaisala RM60 sensors, see Vaisala RM60 (2026), were deployed to each Vaisala test site of "elevated altitude

semi-arid/humid continental" (Boulder), of "low-altitude humid boreal" (Vantaa) and of "tropical rainforest" (Selangor), while one RM60 sensor was deployed at the site of "temperate maritime" (Valentia).

Two units of optical sensors, represented by Vaisala Forward Scatter Sensor FD70, see Vaisala FD70 (2026), were deployed to each Vaisala test site, while one unit was deployed at the site of "temperate maritime" (Valentia).

Two units of weighing gauges, represented by OTT HydroMet Pluvio 400 (see OTT Pluvio (2026)), equipped with Alter shields were deployed to each Vaisala test site. The gauges were maintained according to the product guides, operated with the default settings, taking values of Near-Real-Time (NRT) estimates as the most accurate measurements of rain amounts – with trade-offs discussed in Section "Analysis methods and data selection".

Data time series are available at the temporal resolution of one minute, or better.

Site specific rain estimates

At the site of "temperate maritime" (Valentia), the public hourly reports by Met Éireann, see Met Éireann (2026), of rain amounts were taken as the local gauge composite estimates of rain amounts. The local gauge composite is based on readings of two Tipping Bucket Rain (TBR) gauges mounted on ground in turf walls. Their rain estimates agree with a co-located UKMO Mk 2 gauge (12.5 cm orifice) with a catch ratio of 0.97, see O'Leary et al. (2024). Gauges are known to be vulnerable to under-catchment in windy conditions. O'Leary et al. (2024) report under-catches of four percent from a Pluvio2 weighing gauge reports with or without a Tretyakov type windshield, with respect to the turf mounted UKMO gauge at this site.

AUXILIARY SENSORS

Each Vaisala precipitation test site was equipped with a 3D wind sensor, see Metek3D (2026), for providing co-located estimates of wind speed, wind direction, vertical air flow, horizontal and vertical turbulence. The public reports of wind speed and direction, recorded at the site of "temperate maritime" (Valentia) by Met Éireann, see Met Éireann (2026), were used as measures of windy conditions.

For detecting the occurrences of hail at the site of "elevated altitude continental climate" (Boulder), camera views on a tilted metal plate were recorded at the temporal resolution of 10 frames per second.

3. Analysis methods and data selection

COMMON DATA ANALYSIS METHODS

The statistical parts of this work considered distinguished warm and cool seasons, except at the climate of tropical rain forest (Selangor) where all data are liquid rain. This division allows considering measurements of rain intensity and amount and related uncertainties in conditions of liquid rain separately from conditions of mixed water phases. As known, measurements of liquid water equivalent of frozen and mixed water phases and related uncertainties differ substantially from those of liquid rain, and they are best evaluated as distinct data subsets. At the site of temperate maritime, mixed water phases are rare while it continues to make sense to split the data in seasons of more stormy winter seasons and of milder summer. Contributions of independently

observed cases of hail were excluded in the warm season analysis. As complementary approach, specific weather case analyses evaluated the sensor performances in varied weather conditions of warm and cool seasons, at the high temporal resolution of one minute.

Daily estimates were considered in statistical analyses. The need for this arises as the time response functions vary for different technologies or sensor models, evident in their characteristics in responding to stepwise changes in rain intensity. PRECIPAP technology and optical sensors report variations in precipitation promptly (at the scales of once or a few times per minute) while the weighing gauge model used in this campaign and the reporting mode of 'near-real-time' (NRT) tends to report rain amounts with varied latency. See examples in Figures 29 and 30, Section "Specific weather cases". Some applications are interested in accurate measures of rain amount at a coarse temporal scale, such as from start to end of the precipitation ('event') or daily or seasonal totals. High temporal fidelity such as prompt detection of start of precipitation is of critical value in other use cases. The skills of temporal resolution (rain intensity) and of accurate rain amount are thus better to be separated. In this analysis, rain intensities were taken as one minute running averages, reported by the sensors.

The statistical analysis considered the cumulative rain amounts through the seasons as well as the presenting daily correlations (scattergrams) accompanied by linear regression analysis. Sensor units were first compared against each other, whereby the observed unit-to-unit variations can be viewed as measures of precision in the metrology context, see (Bureau International des Poids et Mesures, 2026). In analyses of precipitation amounts in varied conditions of wind speed and direction and in classes of (persistent) rain intensities, data were considered at the temporal resolution of one minute.

Weather sensor intercomparisons face conceptual and practical challenges in defining a measurement reference (a proxy of the true measurement value) in field conditions. In this work, a proxy of the true measurement values is needed in carrying out OSCAR classifications, see WMO (2024). The proxy is useful in other assessments and in visualizations, too. For liquid rain measurement, a gauge installed in well-drained pit could be taken as a reference, see WMO (2024), while that mount method was considered unfit at sites instrumented by Vaisala, in this campaign covering frozen precipitation and facing the maintenance challenges. In this analysis, the method described in the WMO field intercomparison of rainfall intensity of gauges, see Vuerich et al. (2009), was reapplied to sensor sets representing three technologies of PRECIPAP, optical sensors and weighing gauges. Common local synthetic estimates (CSE) of precipitation amounts, serving as a proxy of the true values, were constructed as weighted averages of the recorded measurements. Weights reflected strengths of the varied sensor technologies while mitigating their vulnerabilities in specific conditions - known a priori or evident in the data. Preference was on simplicity.

Formally, Vuerich et al. (2009) defined a weighted average of sensors i

$$RI_{ref} = \frac{\sum_i \mu_i RI_i}{\sum_i \mu_i}$$

where the weights (μ_i) compiled in the sensor specific persistent uncertainty (σ_i constant in time) and the time (event) dependent quality factors (F_i)

$$\mu_i = \frac{\sigma_i^{-1} F_i}{\sum_j \sigma_j^{-1} F_j}$$

The CSE of rain amount were derived, analogously. Performances of catchment type precipitation measurements have been evaluated in prior studies, including the gauge model utilized in this campaign (Vuerich et al., 2009). Weighing gauges have the advantage of the longest records of historical data. Standardized procedure defines their calibration with water flowmeters in controlled conditions. The Vaisala sites of this campaign were equipped by double wind fences optimized for gauges, and the NRT reports were selected as the best estimates of rain amounts of the gauge model. As outcome, unit-to-unit variations in rain amounts of weighing gauges appeared generally low in this campaign. Even if not a proof of high accuracy per se, this consistency, in combination with prior research, justifies weighing up the NRT readings as the dominant term in the CSE. Exceptions are the repeated events of precipitation in which the gauges missed the precipitation completely i.e. null rain amounts were reported, while the independent sensor technologies reported unambiguously non-vanishing precipitation, see Section "Specific weather cases". These special instances were treated through activation of data quality flags (F_i). To avoid over weighing a measurement technology due to more numerous sensor deployments, the weighing was applied by first computing technology specific averages.

CSE of rain amount RA_{CSE} thus is:

$$RA_{CSE} = \frac{\sum_t \mu_t (\sum_{i_t} RA_{i_t} / N_t)}{\sum_t \mu_t}$$

where t is an index summing through three independent sensor technologies of PRECICAP, optical sensor and weighing gauge and i_t is an index of sensor units (N_t : number of units deployed) representing technology t . Based on the general considerations in the previous paragraph, supported by the outcomes of the unit-to-unit variations in the varied site and weather conditions, the technology specific weights μ_t and data quality selectors (F_i) were derived as follows

$$\begin{aligned} \mu_{PRECICAP} &= \mu_{optical\ disdrometer} = (\sigma_{non-catchment}^{-1} F_{non-catchment}) / \sum_t \sigma_t^{-1} F_t ; \\ \mu_{gauge} &= (\sigma_{gauge}^{-1} F_{gauge}) / \sum_t \sigma_t^{-1} F_t \end{aligned}$$

where the weights σ_{gauge}^{-1} of gauge data were chosen to dominate over those of non-catchment technologies $\sigma_{gauge}^{-1} \gg \sigma_{non-catchment}^{-1}$. In regards quality flags, $F_{non-catchment} = 1$ while $F_{gauges} = 1$ when the average gauge rain amount exceeded 0.01 mm, else $F_{gauges} = 0$. The common local estimate of rain amounts reduced to the simple computation of

if $RA_{average\ of\ gauges} > 0.01\ mm$

$RA_{CSE} = RA_{average\ of\ gauges}$

else

$RA_{CSE} = (average(RA_{average\ of\ PRECICAP}) + average(RA_{average\ of\ optical\ sensor}))/2.$

This computational rule was applied to sites of elevated altitude continental (Boulder), of low-altitude humid boreal (Vantaa), of tropical rainforest (Selangor) where the numbers of sensors allowed the computations. The choice of CSE prevails over perception for potential bias towards too optimistic assessments of measurements by PRECIPAP and by optical sensor – they are referring to a proxy truth composed of themselves, partially. Firstly, the rain amounts recovered by the non-catchment type of sensors are a small fraction of the total rain amounts. Significant persistent rain intensities are gauge based – rendering CSE ineffective as a reference for gauges. In the relatively rare instances where gauge data are in apparent error, there is no perception for true value. Given this lack of prior knowledge, a simple average of all valid data with equal weights is a logically and statistically valid proxy. Both measurements of PRECIPAP and optical sensors have their intrinsic uncertainties which can be taken independent given the substantially different functional principle. Practically, the choice of CSE likely yielded the most realistic outcomes as proxy for true values, in statistical assessments. Given lack of assessments of potentially site-specific uncertainty in gauge measurements, no adjustments were applied to NRT readings – hence the potential biases remain as an uncertainty in CSE in this study.

At the site of temperate maritime (Valentia), the public rain amounts of Met Éireann at Valentia, see Met Éireann (2026), were taken as input to the CSE rain amounts, with an added merit of independence of Vaisala instrumentation. Based on prior evaluations of uncertainty through intercomparisons of co-located turf mounted manual gauge, see O'Leary et al. (2024), the inputs were adjusted upwards by a factor of 1.03. This small adjustment is to be viewed with typical differences in measurements by varied gauge models and mount points, at the level of three percent in annual rain amounts at other sites of similar climate, see Quinlan (2022). Monthly deviations beyond fifteen percent have been observed, including statistical uncertainty.

It is useful to recognize that less than seven percent of the total precipitation amounts were from precipitation recovered by the non-catchment type of measurements (PRECIPAP and optical sensor) in time intervals where weighing gauges reported null, considering all seasons and intensities – the latter branch of the conditional CSE calculation. In classes of modest, heavy and violent rain, the recovered rain amounts contributed to a couple of percent of the warm season CSE rain amounts. It is necessary to account for them in statistical analyses at resolution of this study. The precipitation amount fractions recovered in short-lived modest rain and in drizzle were larger while analyses of those events focused on detection at high temporal resolution rather than on quantities of precipitation.

The Measurement Quality Classification Scheme (OSCAR, Measurement Quality Classifications for Surface Observing Stations on Land, WMO (2024) was applied as a prescribed metric to assess overall quality of the data streams at varied conditions and environments. Table 1 is summary of performance criteria for OSCAR classes from "A" (ideal) and "B" (break-through) combined into "A&B" (break-through, or better), "C" (threshold) and "D" (less than threshold or unknown). The classes A and B were merged for the intent of seeing significant differentiation in state-of-the-art, as a stepwise approach to ideal. The counts of sensor classifications in the OSCAR scheme were normalized to the number of precipitating days, defined by days where the common local composite reference (see above) estimates exceed 0.01 mm.

In more detailed looks, the data of warm and cool seasons were re-grouped in classes of rain intensity (1 minute running average) at one minute temporal resolution of the CSE. Five classes of rain intensity were Drizzle (0.05-0.2 mm/h), Light (0.2-2.5 mm/h), Moderate (2.5-10 mm/h) Heavy (10-50 mm/h) and Violent (> 50 mm/h). Quality criteria were applied to durations of and gaps between the events to a few minutes in the Light, Heavy and Violent classes to avoid unjustified breaks of continuity.

Table 1. Criteria for precipitation quality classification (OSCAR). Accuracies are taken as deviations of the sensor readings with respect to the common local composite reference

Class	Measurement quality	Criteria on daily rain accuracy
A&B	Breakthrough or better	Greater of 3 mm or 5%
C	Threshold	Greater of 5 mm or 10%
D	Less than threshold	-

As complementary information, selected weather cases were analysed in detail for evaluations of rain amounts and liquid water equivalents in cool season events)

- rain amounts in heavy and violent rain,
- temporal resolution in light and short-lived rain,
- detectability of drizzle and of snowfall, and
- rain amounts in windy weather.

The case studies allowed evaluating the skills in temporal resolution of rain intensities. These results are informative while subject to larger uncertainty due to mismatches in reported momentary readings.

DATA SELECTIONS

Intervals of hourly data were selected in which sensors were logging and representing the three technologies of PRECICAP, optical sensors and gauges. The technologies of optical sensor and weighing gauges are well established and these sensor units were operated with fixed settings. PRECICAP is recent technology and the sensor units deployed in the campaign were product development prototypes of the sellable product item, version V1. While the prototyped sensor units generally represent PRECICAP hardware and methodology features, the methodology of PRECICAP was subject to modest updates during the campaign. For the sake of objectivity, the time periods of a stable PRECICAP version were selected for blind statistical analyses, whereas the case studies utilized the full campaign era in collecting representative weather cases.

Elevated altitude continental (Boulder)

Continuous data sets of the common sensor composition were logged from January 15th, 2025, extending to August 31st, 2026, valid for case studies. The period with stable PRECICAP methodology was selected for the statistical analysis, from June 1st, 2025, to August 31st, 2026, 457 calendar days consisting of valid 10679 hours (445-day equivalents) with all data streams available (97% data availability). Due to distinct warm

and cool seasons at the site of “elevated altitude continental”, the data set was further divided in the periods of the ‘cool’ season, in which varied phases of precipitation were present, and of the ‘warm’ seasons in which events of liquid rain were selected only. A few events with hail were removed, based on observations at ground by PRECICAP, optical sensors and an independent camera setup. There were 121 rainy days in the warm season and 59 days of precipitating weather in the cool season, defined as the CSE precipitation amount larger than 0.01 mm.

As technical check of data integrity, temporal synchronization between each PRECICAP sensors and the other sensor were tested in two ways: (i) a lag cross-correlation of the hourly RI series over lags of ± 3 hours, and (ii) a diurnal (hour-of-day) mean-intensity check focused on the midnight boundary, where a common data-logger error introduces a one-hour offset. All three units peak at lag 0 h and no one-hour offsets nor midnight discontinuities were found, hence the sensor logged time stamps are correctly time-synchronized.

Table 2. Summary of data selected for statistical analyses at the elevated altitude continental site (Boulder).

Period	Dates	Assigned season
P1	June 1 st – October 31 st 2025	Warm (liquid rain)
P2	November 1 st 2025 – May 31 st 2026	Cool (any water phase)
P3	June 1 st – August 31 st 2026	Warm (liquid rain)

Low-altitude humid boreal (Vantaa)

Data streams from varied precipitation sensor compositions have been logged at the site of low elevation humid boreal climate (Vantaa) for decades. The period from July 15th, 2026, extending to September 19th, 2026, was valid for case studies with varied versions and units representing PRECICAP technology. The period from June 1st, 2025, to July 9th, 2026, was selected for statistical analysis of two sensor units representing a stable version of PRECICAP technology.

The data set selected from June 1st, 2025, to July 9th, 2026, for the statistical analysis 404 calendar days consisted of 8754 valid hours (365 day-equivalents) with all data streams available (90% data availability). Due to distinct warm and cool seasons at the climate of low altitude humid boreal, the data set was further divided in the periods of the ‘cool’ season, in which varied phases of precipitation were present, and of the ‘warm’ seasons in which events of liquid rain were selected only. There were 118 rainy days in the warm season and 137 days of precipitating weather in the cool season, defined as the CSE precipitation amount larger than 0.01 mm.

The data set to September 19th, of the warm season 2026, with six sensor units representing PRECICAP technology, consisted of 818 valid data hours (34 day-equivalents) with all data streams available (51% data availability). The data availability was limited by occasional updates in site infrastructure.

As technical check of data integrity, temporal synchronization between each PRECICAP sensors and the other sensor were tested in two ways: (i) a lag cross-correlation of the hourly RI series over lags of ± 3 hours, and (ii) a diurnal (hour-of-day) mean-intensity check focused on the midnight boundary, where a common data-logger error introduces a one-hour offset. Both units peak at lag 0 h and no one-hour offsets nor midnight discontinuities were found, hence the sensor logged time stamps are correctly time-synchronized.

Table 3. Summary of data selected for statistical analyses at the low-altitude humid boreal site (Vantaa).

Period	Dates	Assigned season
P1	1 Jun – 31 Oct 2025	Warm (liquid rain)
P2	1 Nov 2025 – 31 May 2026	Cool (any water phase)
P3	1 – 9 July 2026	Warm (liquid rain)
P4(6 units)	15 July – 19 September 2026	Warm (liquid) rain

Tropical rainforest (Selangor)

Continuous data sets of the common sensor composition were logged from August 22nd, 2023, extending to August 31st, 2026, valid for case studies. The period with stable PRECICAP methodology was selected for the statistical analysis, from August 1st, 2025, to August 6th, 2026, 371 calendar days consisting of valid 6988 hours (291 day-equivalents) with all data streams available (78% data availability). As an equatorial site all precipitation was liquid, and the record was treated as a single period. There were 265 rainy days, defined as the CSE precipitation amount larger than 0.01 mm. Maintenance of gauges, interruptions in electric power and in communications correlating with rainy conditions posed a challenge in statistical analysis, and the data sets are best suited for case studies.

Temperate maritime (Valentia)

Continuous data sets of the site-specific sensor composition were available from October 2024. One sensor unit with a fixed version of PRECICAP methodology was running unattended since June 1st, 2025, extending to August 31st, 2026. The data were compared with the Met Éireann public hourly reports of rain amounts which served as the local common synthetic estimate (CSE). These independent data streams were checked for time synchronization through correlating the time series of hourly time intensities. Daily totals require valid data available in 22 hours, at least. 407 days were qualified out of 457 days in total, with a data availability of 89%.

Precipitation is liquid rain at this temperate maritime site. The data records were divided into the wetter, windier half (November–May, the Atlantic-storm season) and the milder half (June–October), see Table 4. The milder half consisted of 213 days of which 172 days were rainy (the CSE rain amounts larger than 0.01 mm). The wet and windier half consisted of 194 days of which 171 were rainy, 343 days of precipitation in total.

Table 4. Summary of data selected for statistical analyses at the temperate maritime site (Valentia).

Period	Dates	Assigned season
P1	1 st Nov 2025 – 31 st May 2026	Wetter / windier (Atlantic-storm season)
P2	1 st June – 31 st Oct 2025 & 1 st Jun - 31 st August 2026	Milder season

4. Results of seasonal statistical analysis

ELEVATED ALTITUDE CONTINENTAL CLIMATE (BOULDER)

Seasonal performances

Cumulative rain amounts of the sensor ensemble representing three measurement technologies of PRECICAP, of optical sensors and of weighing gauges are summarized in Table 5, in the warm and cool seasons at the elevated continental site (Boulder). Without presumed mean (two degrees of freedom), the standard deviations (relative) of three PRECICAP sensors are 3.6 percent in the warm season and 2.7 per cent in the cool season, respectively. These estimates are indicative of long-term unit-to-unit variability of PRECICAP technology measurements in the data sample. The corresponding measures for the optical sensors are 3.5 percent and 3.9 percent, and 0.2 percent and 0.6 percent for the gauges, respectively. Figure 4 displays the temporal evolutions of the cumulative rain amounts in the warm season and the liquid water equivalents in the cool season, by three sensor units representing PRECICAP technology together with the CSE.

Figure 5 displays the cumulative rain amounts averaged from three sensors of the PRECICAP technology together with the same of two gauges mean and the CSE. The mean catch ratio of PRECICAP technology sensors with respect to the CSE is found to be 1.03 and 1.06 for the warm and the cool seasons, respectively. The corresponding catch ratios for the gauges means are 0.92 and 0.93, respectively – reflecting the events where two other independent technologies observe non-negligible precipitation while the gauges report null. The catch ratios of the optical sensors' average are 0.82 and 0.68 for the warm and cool seasons, respectively.

The correlograms of daily estimates of rain amount (warm season) and of liquid water equivalent (cool season) averaged from three sensors of PRECICAP technology versus the CSE are displayed in Figure 6. Tables 6 and 7 summarize the parameters of the regression analysis of the correlogram data from the warm season and from the cool season. Generally, data sets correlate at the level of 98 percent in the warm season, 89 percent in the cool season and the linearity of the measurements is good. Variability is higher in the cool season, reflecting the challenges all technologies face in measuring frozen precipitation, accurately. Catch ratios differentiated to each sensor unit confirm the general agreement at a level well below 10 percent.

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Table 5. Summary of the rain amounts in the warm seasons and of the liquid water equivalents in the cool season reported by sensors representing technologies of PRECIPCAP, of optical sensors and of weighing gauges, at the elevated altitude continental site (Boulder). Averages of each measurement technology and the CSE are reported. Catch ratios are with respect to the CSE.

Measurement/estimate	Warm (mm)	Cool (mm)	Total (mm)	Catch ratio
PRECIPCAP-1	216.6	126.2	343.0	1.06
PRECIPCAP-2	205.9	119.7	325.6	1.01
PRECIPCAP-3	220.9	121.5	342.3	1.06
PRECIPCAP average	214.5	122.5	337.0	1.04
Optical-1	174.8	81.6	256.4	0.79
Optical-2	166.4	77.3	243.7	0.75
Optical average	170.6	79.4	250.0	0.77
Gauge-1	191.3	107.3	298.6	0.92
Gauge-2	191.9	108.2	300.1	0.93
Gauge average	191.6	107.8	299.4	0.93
CSE	207.6	116.0	323.6	

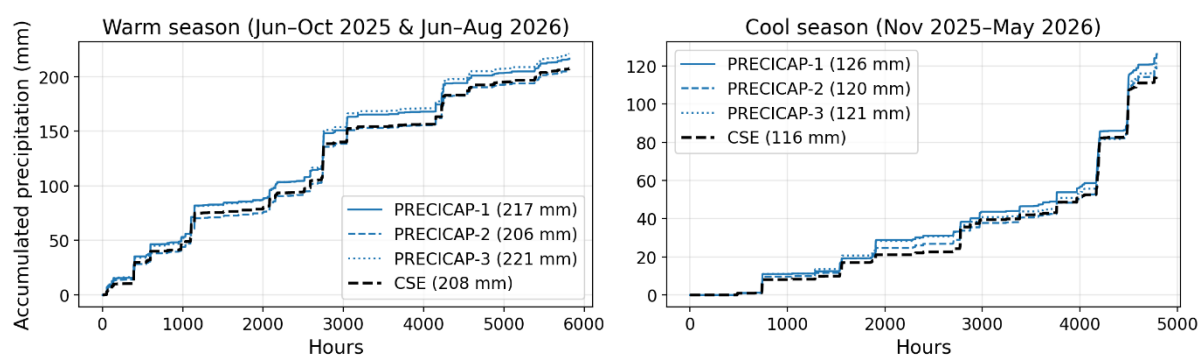


Figure 4. Cumulative amounts of liquid water equivalents (left, cool season) and of rain amounts (right, warm season) measured by three sensors representing PRECIPCAP technology, and of the CSE estimate, at the elevated altitude continental site (Boulder).

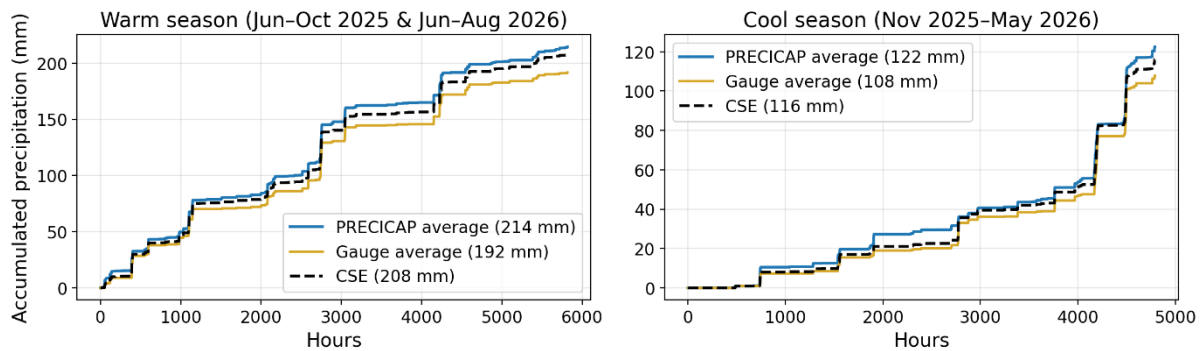


Figure 5. Cumulative amounts of liquid water equivalents (left, cool season) and of rain amounts (right, warm season) of measurements averaged over three sensor units representing PRECIPCAP technology, of measurements averaged over two gauges, and the CSE, at the elevated altitude continental site (Boulder).

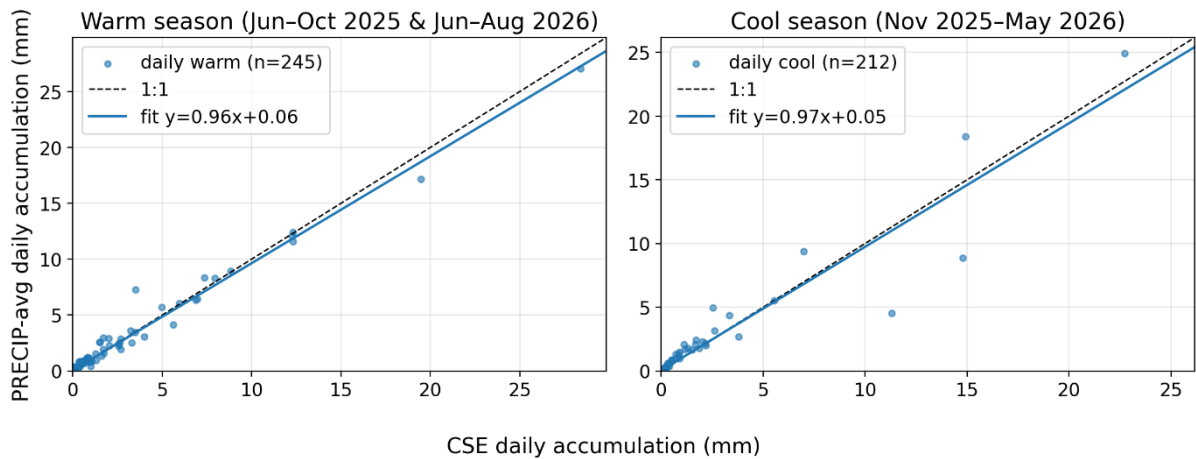


Figure 6. Correlograms of daily rain amounts (left, warm season) and of liquid water equivalents (right, cool season) averaged from three sensors of PRECIPCAP technology versus the CSE, at the elevated altitude continental site (Boulder). The blue line depicts a linear fit; the black dash line is diagonal.

Table 6. Linear regression analysis of daily rain amounts from estimates of three sensor units of PRECIPCAP and of their daily averages against the CSE in the warm season (121 rainy days) at the elevated altitude continental site (Boulder). All data columns are in units of mm, except Slope and Catch Ratio.

Measurement / estimate	Slope	Intercept	R ²	Bias	RMSE	Catch ratio
PRECIPCAP-1	0.977	0.057	0.982	0.037	0.379	1.043
PRECIPCAP-2	0.912	0.067	0.976	-0.007	0.479	0.992
PRECIPCAP-3	0.983	0.068	0.980	0.054	0.407	1.064
PRECIPCAP average	0.957	0.064	0.983	0.028	0.382	1.033

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Table 7. Linear regression analysis of daily rain amounts from estimates of three sensor units of PRECICAP and of their daily averages against the CSE in the cool season (59 precipitation days) at the elevated altitude continental site (Boulder). All data columns are in units of mm, except Slope and Catch Ratio.

Measurement / estimate	Slope	Intercept	R ²	Bias	RMSE	Catch ratio
PRECICAP-1	0.988	0.056	0.904	0.048	0.762	1.089
PRECICAP-2	0.962	0.038	0.927	0.017	0.642	1.032
PRECICAP-3	0.960	0.048	0.875	0.026	0.860	1.047
PRECICAP average	0.970	0.047	0.906	0.031	0.741	1.056

Performances by Rain Intensity Classes

The data of warm seasons were rearranged in five event classes of Drizzle, Light, Moderate, Heavy and Violent, see methodology in Section “Common Data Analysis Methods”. 14 events of drizzle, 84 events of light rain, 39 events of moderate rain, 20 events of heavy rain and 3 violent rain events were reconstructed, of 160 events in total. For the sake of sufficient statistics, they were re-grouped in two sets a) drizzle and light precipitation and b) moderate, heavy and violent precipitation, displayed in Figure 7 for the warm seasons.

The estimated rain amounts selected from events of drizzle and modest rain, see Figure 7 (left) and Table 8, of PRECICAP, of optical sensors and of gauges are modest at 10 mm level, in absolute terms. However, their relative differences are substantial, a factor of two approximately. These findings are to be reflected on expectations of larger uncertainties in detection and measurements of drizzle and short-lived light rain events, characteristic of the site. The case studies also illustrate that the weighing gauges repeatedly missed reporting rain amounts in drizzle and in short-lived light rain events while the other two independent technologies unambiguously detect and report rain amounts.

In contrast, the rain measurements of three independent technologies of PRECICAP,

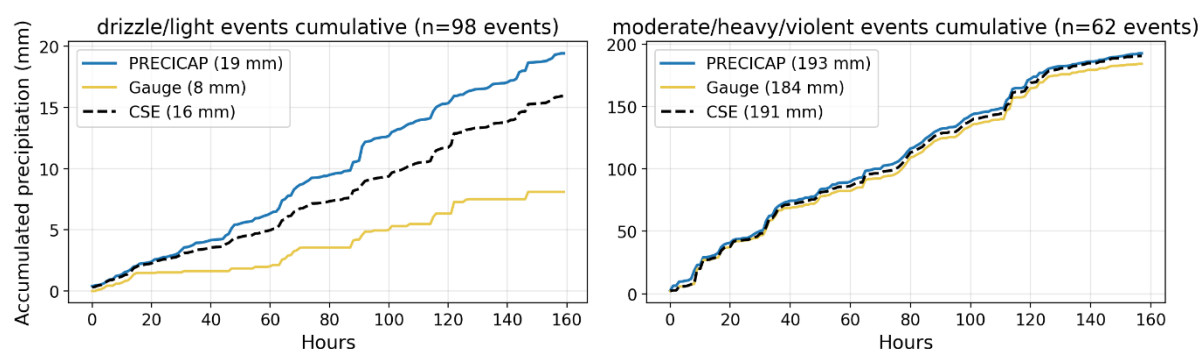


Figure 7. Chronologically cumulative rain amounts of averaged over three sensor units representing PRECICAP technology, of measurements averaged from two gauges and of the CSE, in the warm season at the elevated altitude continental site (Boulder). Left: subset selected from the events of drizzle and light rain. Right: subset selected from the events of moderate to violent rain.

of optical sensors and of weighing gauges display remarkable agreement both in absolute and in relative views, see Figure 7 and Table 8, when warm season rain events

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of higher intensity are considered. In these higher-intensity events, PRECIPAP and the gauges agree with the CSE to within about 5 percent, whereas the optical-sensor average is about 18 percent lower.

Table 8. Rain amounts in the subsets of Drizzle/Light rain intensities and of Moderate/Heavy/Violent rain intensities in warm season measured by sensors representing technologies of PRECIPAP, of optical sensors and of weighing gauges, at the elevated altitude continental site (Boulder). Averages of each measurement technology and the CSE are included.

Measurement / estimate	Drizzle/Light (mm)	Moderate/Heavy/Violent (mm)
PRECIPAP-1	19	197
PRECIPAP-2	18	187
PRECIPAP-3	19	202
PRECIPAP average	19	195
Optical-1	14	161
Optical-2	13	153
Optical average	14	157
Gauge-1	9	183
Gauge-2	9	183
Gauge average	9	183
CSE	16	192

Dependencies on ambient wind

According to the measurements by a co-located 3D wind sensor, ambient winds are modest at the Boulder site (elevated altitude continental). Occurrences of events where winds exceed 5 m/s are too few to conduct statistical analysis.

Assessments in the Measurement Quality Classification Scheme (OSCAR)

Figure 8 and Table 9 present the outcomes of assessing the measurement quality of daily rain amounts in the WMO OSCAR scheme. The differences of daily rain amounts (warm season) and of liquid water equivalents (cool season) of three sensors representing PRECIPAP technology were computed with respect to CSE. The outcomes can thus be interpreted as an assessment of joint measurement quality of PRECIPAP technology and the other two independent technologies of optical sensors and weighing gauges contributing to the CSE, at the elevated altitude continental climate (Boulder) in conditions of warm and cool seasons, combined for maximal statistics. There are 121 rainy days in the warm season and 59 days of precipitation in the cool season, 180 days in total.

In more than 97 percent of precipitation days, the daily rain amount (or liquid water equivalent) measurements of PRECIPAP technology agree with those of the CSE at the class level A or B ("breakthrough" or better). In more than 98 percent of the precipitating days, the agreements meet the level of Class C ("threshold") or better. On

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one percent of the rainy days, the measurements deviated more than Class C threshold requirement. The three sensor units performed equally, in this regard.

Table 9. Assessments of overall quality of the daily rain amounts measured by three sensors representing PRECICAP technology with respect to the CSE in the WMO OSCAR scheme, at the climate of elevated altitude continental (Boulder). Relative occurrences of quality classifications are reported, warm and cool seasons combined. The sample consists of 180 days of precipitating weather.

Measurement	Class A&B (%)	Class C (%)	Class D (%)
PRECICAP-1	97.2	1.7	1.1
PRECICAP-2	97.8	1.1	1.1
PRECICAP-3	97.8	1.1	1.1

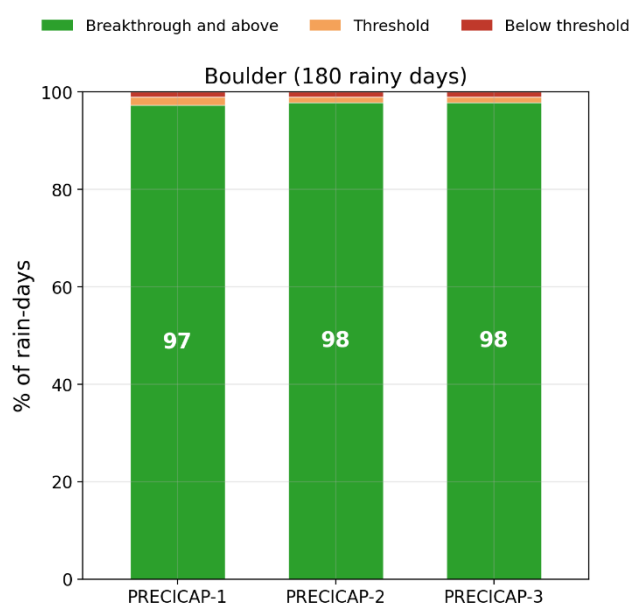


Figure 8. Assessments of overall quality of the daily rain amounts measured by three sensors representing PRECICAP technology with respect to the CSE in the WMO OSCAR scheme, at the climate of elevated altitude continental (Boulder). Relative occurrences of quality classifications are displayed. The warm season and the cool season data are combined. The sample consists of 180 days of precipitating weather.

LOW-ALTITUDE HUMID BOREAL (VANTAA)

Cumulative rain amounts of the sensor ensemble representing three measurement technologies of PRECICAP and of weighing gauges are summarized in Table 10, in the warm and cool seasons at the low altitude humid boreal site (Vantaa). The PRECICAP measurement values agree unit-to-unit within 1.2 percent (relative) in the warm season and within 4.8 percent in the cool season, respectively. Figure 9 displays the temporal evolutions of the cumulative rain amounts in the warm season and the liquid water equivalents in the cool season, measured by two sensor units representing PRECICAP technology together with the CSE.

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Table 10. Summary of the rain amounts in the warm seasons and of the liquid water equivalents in the cool season reported by sensors representing technologies of PRECIPAP, of optical sensors and of weighing gauges, at the low altitude humid boreal site (Vantaa). Averages of each measurement technology and the CSE are reported. Catch ratios are with respect to the CSE.

Measurement/estimate	Warm (mm)	Cool (mm)	All (mm)	Catch ratio
PRECIPAP-1	398.5	192.8	591.3	0.94
PRECIPAP-2	391.7	206.5	598.2	0.95
PRECIPAP average	395.1	199.7	594.8	0.95
Gauge-1	397.4	198.3	595.7	0.95
Gauge-2	410.3	204.6	615.0	0.98
Gauge average	403.9	201.5	605.3	0.96
CSE	411.9	216.6	628.6	

Figure 10 displays the cumulative rain amounts averaged from two sensors of the PRECIPAP technology together with the same of two gauges mean and the CSE. The mean catch ratio of PRECIPAP technology sensors with respect to the CSE is found to be 0.96 for the warm seasons and 0.92 for the cool season. The corresponding catch ratios for the gauges means are 0.98 and 0.93, respectively – reflecting the events where two other independent technologies observe non-negligible precipitation while the gauges report null. The average catch ratios of the optical sensors are 0.97 and 1.11 for the warm and cool season, respectively. In the cool season, the liquid water equivalent (LWE) estimates from the optical sensors exceed those from PRECIPAP and the CSE by about 10%.

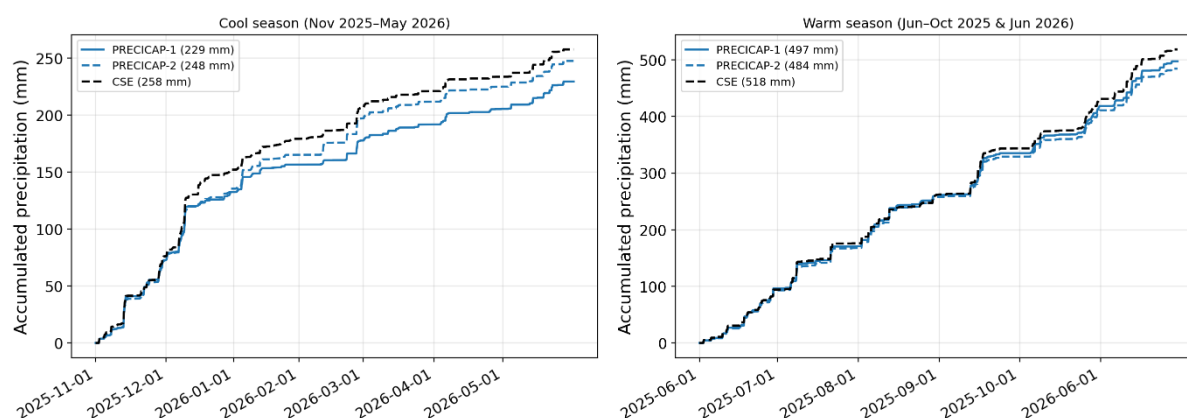


Figure 9. Cumulative amounts of liquid water equivalents (left, cool season) and of rain amounts (right, warm season) measured by two sensors representing PRECIPAP technology, and the CSE, at the low altitude humid boreal site (Vantaa).

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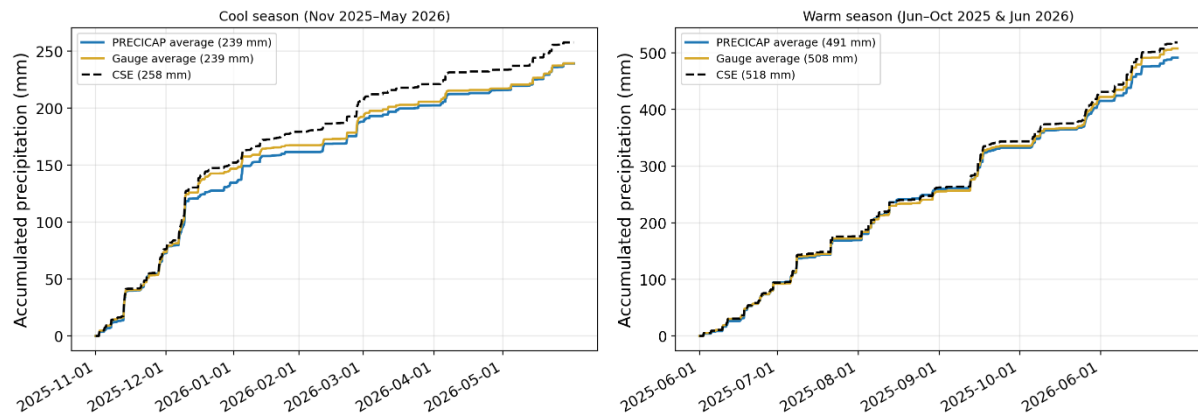


Figure 10. Cumulative amounts of liquid water equivalents (left, cool season) and of rain amounts (right, warm season) as measurements averaged over two sensor units representing PRECICAP technology, as measurements averaged from two gauges, and the CSE, at the low altitude humid boreal site (Vantaa).

Independently, a set of six sensors representing PRECICAP technology were operated from July 15th to September 19th, 2026, in the warm season. Figure 11 (left) displays the temporal evolutions of the cumulative rain amounts, measured by the six sensor units together with the CSE. The rain amount of this period consists mostly of convective rain showers reoccurring in the warm season with violent intensities reaching up to 80 mm/h. The PRECICAP measurement values agree unit-to-unit within 2.3 percent (STD, relative). These estimates are indicative of seasonal unit-to-unit variability of PRECICAP technology measurements in the data sample. Figure 11 (right) displays the cumulative rain amounts averaged from six sensors of PRECICAP technology together with the same of two gauges mean and the CSE. The mean catch ratio of PRECICAP technology measurements with respect to the CSE was 0.95.

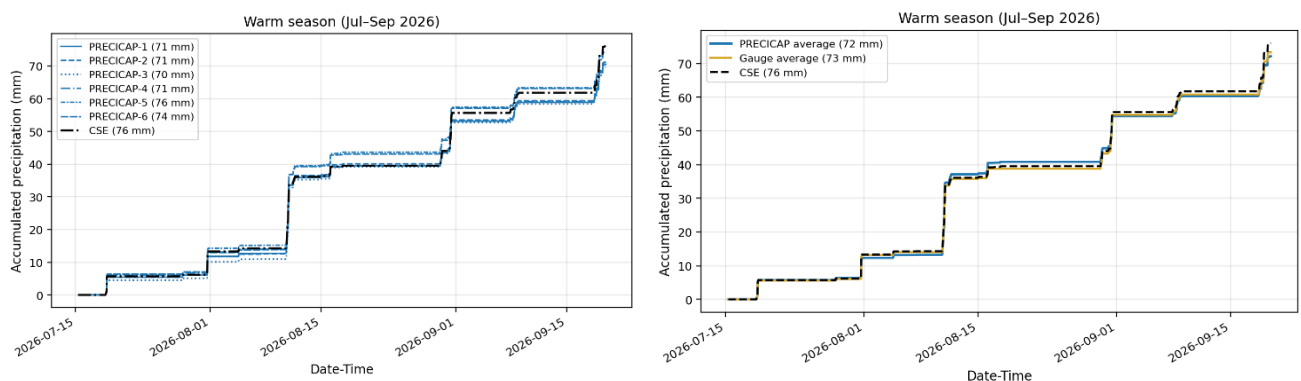


Figure 11. left: Cumulative amounts of rain amounts measured by six sensors representing PRECICAP technology and the CSE. Right: Cumulative amounts of rain amounts averaged from six sensors representing PRECICAP technology, using the extended sensor configuration at the low altitude humid boreal site (Vantaa).

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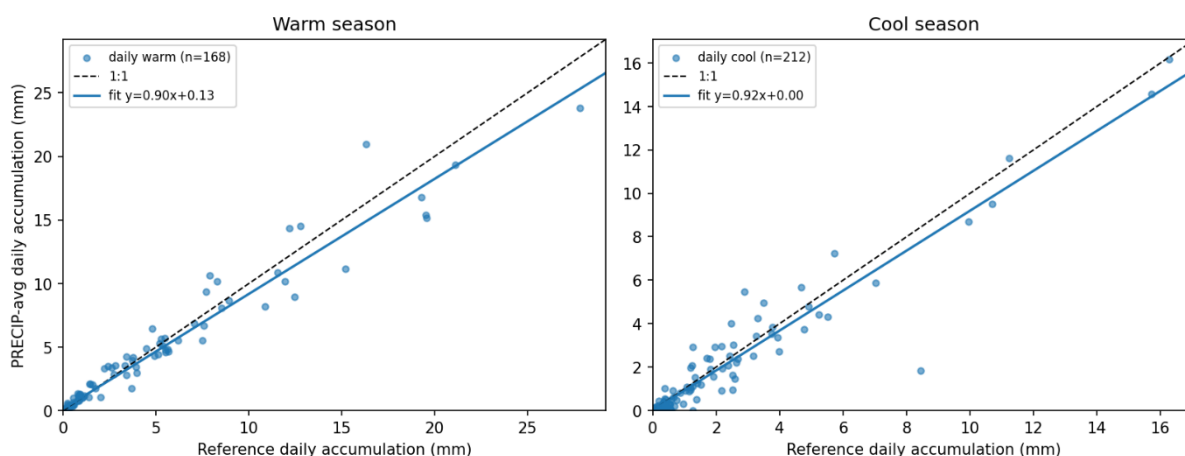


Figure 12. Correlograms of daily rain amounts (left, warm season) and of liquid water equivalents (right, cool season) averaged from two sensors of PRECICAP technology versus the CSE, at the low-altitude humid boreal site (Vantaa). The blue line depicts a linear fit; the black dash line is diagonal.

The correlograms of daily estimates of rain amount (warm season) and of liquid water equivalent (cool season) averaged from two sensors of PRECICAP technology versus the CSE are displayed in Figure 12. Tables 11 and 12 summarize the parameters of the regression analysis of the correlogram data from the warm season and from the cool season. Generally, data sets correlate at levels better than 90 percent. Variability is higher in the cool season, reflecting the challenges all technologies face in measuring frozen precipitation, accurately. In the warm season, the catch ratios calculated for each sensor unit confirm good overall agreement: PRECICAP and the gauges agree to within ~5%, whereas the optical-sensor average is ~18% lower.

Table 11. Linear regression analysis of daily rain amounts from estimates of two sensor units of PRECICAP and of their daily averages against the CSE in the warm season (118 rainy days) at the low-altitude humid boreal site (Vantaa). All data columns are in units of mm, except Slope and Catch Ratio.

Measurement / estimate	Slope	Intercept	R ²	Bias	RMSE	Catch
PRECICAP-1	0.908	0.145	0.959	-0.080	0.985	0.967
PRECICAP-2	0.902	0.121	0.954	-0.121	1.051	0.951
PRECICAP average	0.905	0.133	0.958	-0.100	1.008	0.959

Table 12. Linear regression analysis of daily amounts of liquid water equivalents from estimates of two sensor units of PRECICAP and of their daily averages against the CSE in the cool season (137 precipitation days) at the low-altitude humid boreal site (Vantaa). All data columns are in units of mm, except Slope and Catch Ratio.

Measurement / estimate	Slope	Intercept	R ²	Bias	RMSE	Catch
PRECICAP-1	0.915	-0.026	0.918	-0.112	0.674	0.890
PRECICAP-2	0.924	0.030	0.910	-0.048	0.699	0.953
PRECICAP average	0.920	0.002	0.923	-0.080	0.650	0.922

Performances by Rain Intensity Classes

The data of warm seasons were rearranged in five event classes of Drizzle, Light, Moderate, Heavy and Violent, see methodology in Section "Common Data Analysis Methods". 24 events of drizzle, 98 events of light rain, 74 events of moderate rain, 25 events of heavy rain and 7 violent rain events were reconstructed, of 228 events in total in warm season. As with the site of Boulder, they were re-grouped in two sets a) drizzle and light precipitation and b) moderate, heavy and violent precipitation, displayed in Figures 13 and 14 for the warm seasons.

Considering the rain amounts selected from events of drizzle and modest rain, see Figure 13, the estimates of PRECIPAP technology and gauges agree within 3 mm, in absolute terms. The relative differences with respect to the CSE of 41 mm are at a level less than 10 percent. Large uncertainties are expected in detection and measurements of drizzle and while measurements of sustained light rain events are known to be more accurate, characteristic of the site.

In the warm season events of higher intensities (modest, heavy, violent), three independent technologies of PRECIPAP and of weighing gauges display good agreement both in absolute and in relative views, see Figure 14. The seasonal estimates of the three independent technologies agree at a level of 5 percent.

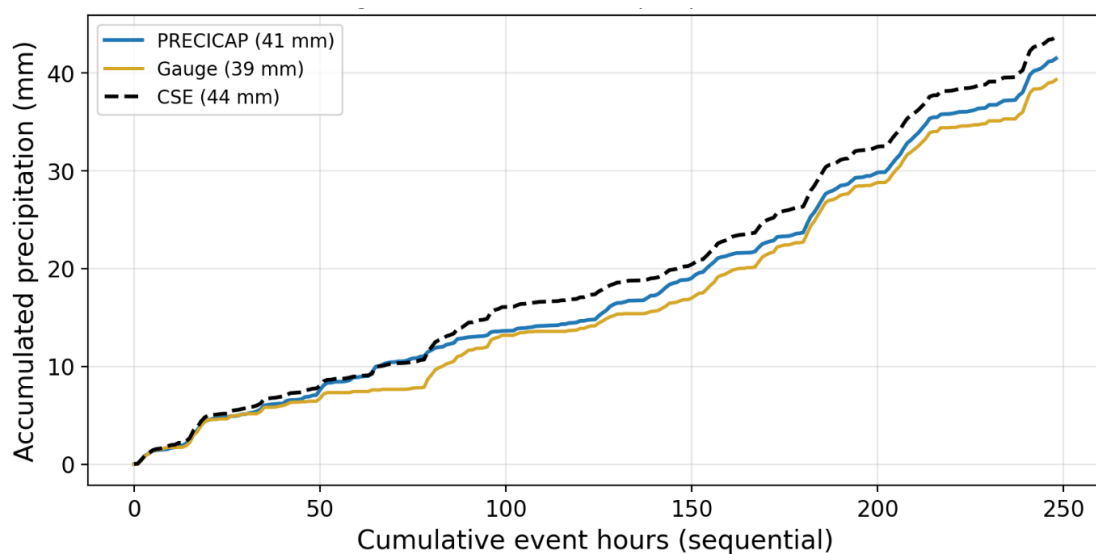


Figure 13. Chronologically cumulative rain amounts of averaged over two sensor units representing PRECIPAP technology, of measurements averaged from two gauges and of the CSE, selected from the events of drizzle and light rain in the warm season at the low altitude humid boreal site (Vantaa).

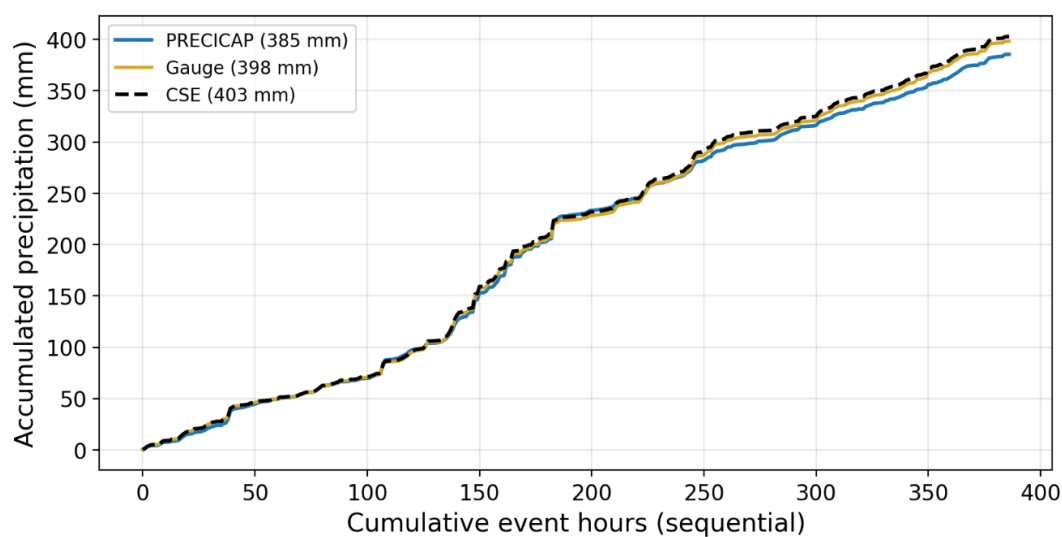


Figure 14. Chronologically cumulative rain amounts of averaged over two sensor units representing PRECICAP technology, of measurements averaged from two gauges and of the CSE, selected from the events of modest, heavy and violent rain in the warm season at the low altitude humid boreal site (Vantaa).

Dependencies on ambient wind

According to the measurements by a co-located 3D wind sensor, ambient winds are modest, hardly ever exceeding 5 m/s at the site of low-altitude humid boreal (Vantaa). Occurrences of events where winds exceed 5 m/s are too few to conduct statistical analysis.

Assessments of Measurement Quality in the OSCAR Classification Scheme

Figure 15 and Table 13 presents the outcomes of assessing the measurement quality of daily rain amounts in the WMO OSCAR scheme. The differences of daily rain amounts (warm season) and of liquid water equivalents (cool season) of two sensors representing PRECICAP technology were computed with respect to the CSE. The outcomes can thus be interpreted as an assessment of joint measurement quality of PRECICAP technology and the other two independent technologies of optical sensors and weighing gauges contributing to the CSE, at the low-altitude humid boreal climate (Vantaa) in conditions of warm and cool seasons, combined for maximal statistics. There are 118 rainy days in the warm periods and 137 days of precipitation in the cool season.

In more than 96 percent of precipitation days, the daily rain amount (or liquid water equivalent) measurements of PRECICAP technology agree with those of the CSE estimator at the class level A or B ("breakthrough" or better). In about one percent of the precipitating days, the measurements deviated from the CSE at a level not meeting the Class C. The two sensor units performed equally within statistical uncertainty, in this regard.

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Table 13 Assessments of overall quality of the daily rain amounts measured by two sensors representing PRECICAP technology with respect to the CSE in the WMO OSCAR scheme, at the low altitude humid boreal site (Vantaa). Relative occurrences of quality classifications are reported, warm and cool seasons combined. The sample consists of 255 days of precipitating weather.

Measurement	Class A&B (%)	Class C (%)	Class D (%)
PRECICAP-1	96.8	2.4	0.8
PRECICAP-2	96.5	2.4	1.2

Breakthrough and above Threshold Below threshold

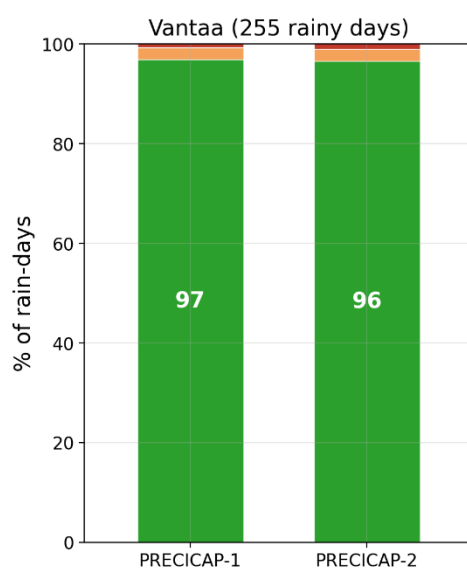


Figure 15. Assessments of overall quality of the daily rain amounts measured by two sensors representing PRECICAP technology with respect to the CSE in the WMO OSCAR scheme, at the climate of low altitude humid boreal (Vantaa). Relative occurrences of quality classifications are displayed. The warm season and the cool season data are combined. The sample consists of 255 days of precipitating weather.

TROPICAL RAINFOREST (SELANGOR)

Seasonal performances

Currently available data set from the site of Selangor is statistically too limited to represent the climatology of tropical rainforest (complete series of rain events of varied intensities) and to represent the productized PRECICAP functionalities with concurrent valid data from sensors of independent technologies which require regular maintenance.

TEMPERATE MARITIME SITE (VALENTIA)

Seasonal performances

Cumulative rain amounts of the sensor representing PRECICAP technology, and of the CSE (Met Éireann public reports) are displayed in Figure 16, in the milder and in the wetter windier seasons at the temperate maritime site (Valentia). The seasonal and total rain amounts are summarized in Table 14. In the mild season consisting of 213 days (172 rainy days), the PRECICAP sensor unit logged the rain amount of 981 mm with a catch ratio of 1.006 with respect to the local reference rain amount of 975 mm. In the wet and windier season consisting of 194 days (171 rainy days), the sensor unit representing PRECICAP technology logged the rain amount of 1326 mm with a catch ratio of 1.19 with respect to the local reference rain amount of 1111 mm. The average

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catch ratio is 1.1. The significance of windy conditions is assessed in Subsection "Dependencies on ambient winds". At the unshielded, unattended temperate maritime site, the optical sensor's performance, like catchment gauges, depend on appropriate siting and routine maintenance to perform to specification.

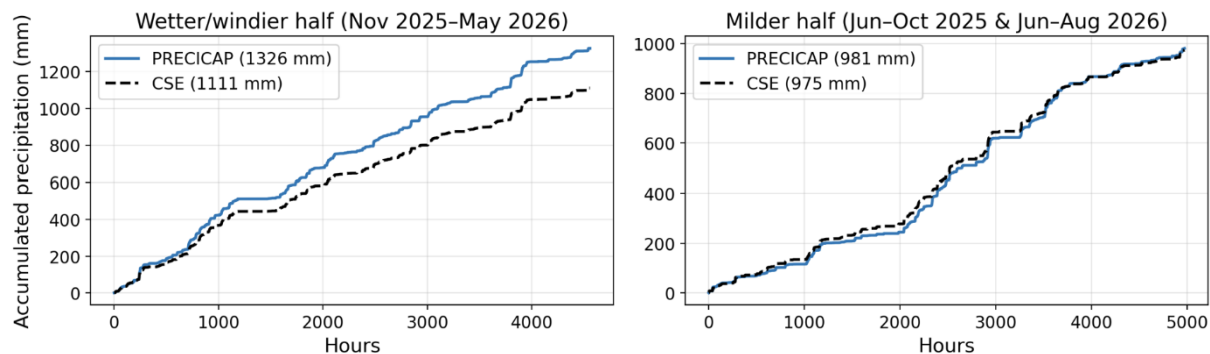


Figure 16. Cumulative rain amounts in the wet windier season (left) and in the mild season (right) measured by one sensor of PRECICAP technology at the temperate maritime site (Valentia). The public reports by Met Éireann are taken as the CSE.

Table 14. Summary of the rain amounts in the mild season and in the wet windier season as measured by one sensor of PRECICAP technology, and as reported by Met Éireann, at the temperate maritime site (Valentia). Catch ratio is with respect to the CSE.

Measurement/estimate	Mild (mm)	Wet,windy (mm)	All (mm)	Catch ratio
PRECICAP	981	1326	2307	1.11
CSE	975	1111	2086	

The correlograms of daily estimates of rain amount from the sensor of PRECICAP technology versus the CSE in the mild season and in the wet windier season are displayed in Figure 17. Tables 15 summarizes the parameters of the regression analysis of the correlogram data from the mild season and from the wet windier season. Generally, data sets correlate at levels better than 95 percent and the linearity is good. The slope parameter deviates upwards in the data set of the wet and windier season, to be analysed closer in Subsection Dependencies on ambient winds.

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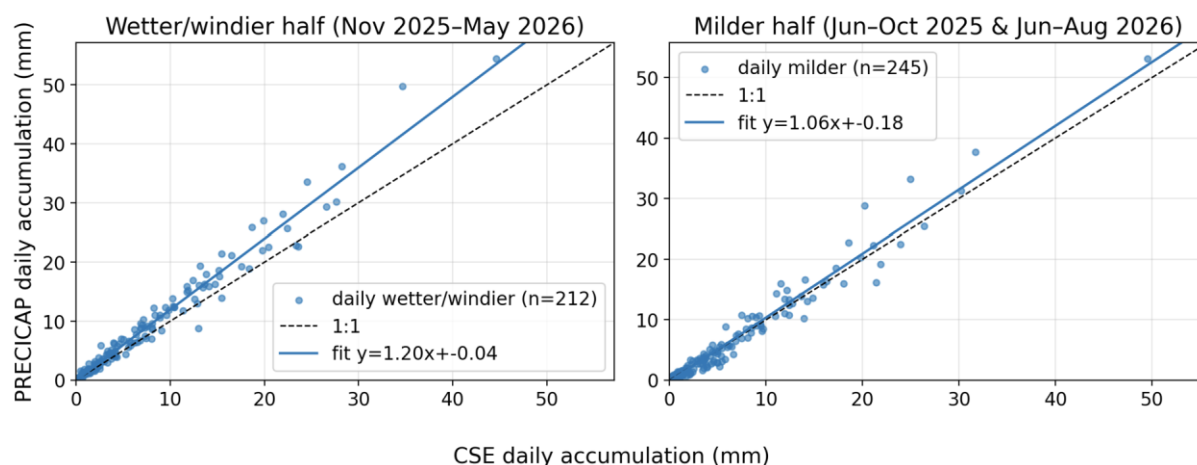


Figure 87. Correlograms of daily rain amounts in the wet windier season (left,) and mild season (right) from the sensors of PRECICAP technology versus the CSE (Met Éireann), at the temperate maritime site (Valentia). The blue line depicts a linear fit; the black dash line is diagonal.

Table 15. Linear regression analysis of daily rain amounts from estimates of a sensor unit of PRECICAP and of its daily averages against the CSE in the wetter, windier season (171 rainy days) and of the milder season (172 rainy days) at the site of temperate maritime climate (Valentia). All data columns are in units of mm, except Slope and Catch Ratio.

Period	Slope	Intercept	R ²	Bias	RMSE	Catch
Wetter / windier	1.200	-0.040	0.975	1.013	2.242	1.193
Milder	1.055	-0.185	0.967	0.037	1.334	1.006

Rain intensity performance

Typical rain intensities at site of temperate maritime climate (Valentia) range from Drizzle to Modest. Occurrences of rain events of high intensities are too rare to conduct statistical analysis, while other characteristics of the weather, such as wind speed and direction may dominate the performance features.

Dependencies on ambient winds

The site of temperate maritime climate (Valentia) is located at an open field at the coast of Atlantic Ocean, see Figure 3. The site is well suited for evaluating precipitation sensor performances in windy weather conditions. Statistically, hourly wind mean is 4.9 m/s, while gusts to 30.8 m/s were recorded during the campaign and major part of rain falls under significant winds, exceeding 5 m/s, see figure 18.

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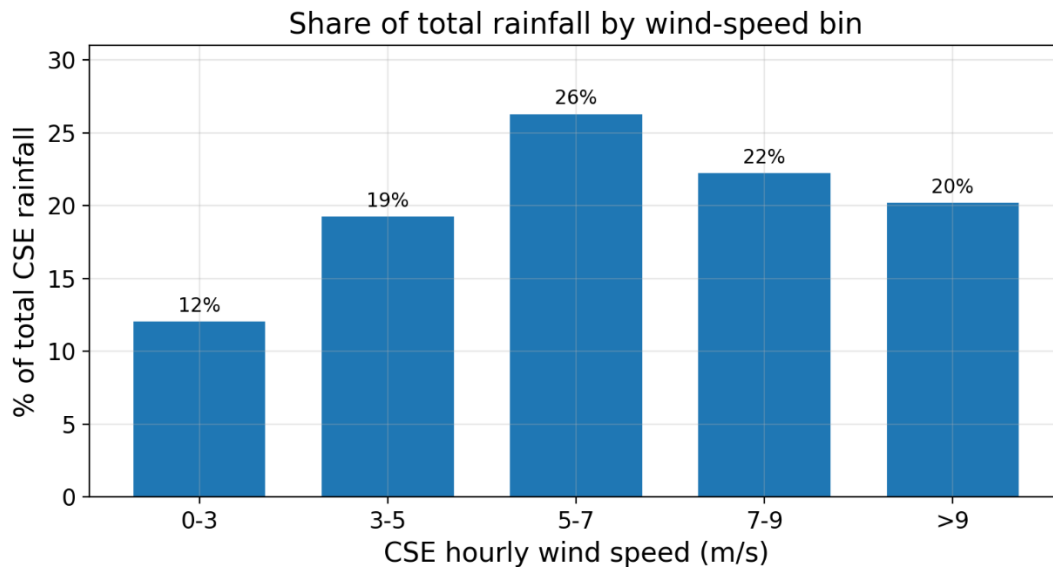


Figure 18. Share of hourly rain amounts of the rain amount CSE in classes of hourly wind speeds, both from Met Éireann public reports.

Figure 19 presents the median catch ratios of rain amounts as measured by the sensor of PRECICAP technology, with respect to the CSE (Met Éireann public reports), for five statistically significant classes of hourly winds speeds, spanning from zero to the class of wind speeds more than 9 m/s. Similarly, catch ratios are displayed for four classes of wind gusts from zero to the class of gusts exceeding 20 m/s. In calmest event classes of hourly winds less than 3 m/s and wind gusts less than 10 m/s, the catch ratios are unity within a couple of percent. The catch ratios grow monotonously towards higher winds and wind gusts, reaching values of 1.19 and 1.41, respectively.

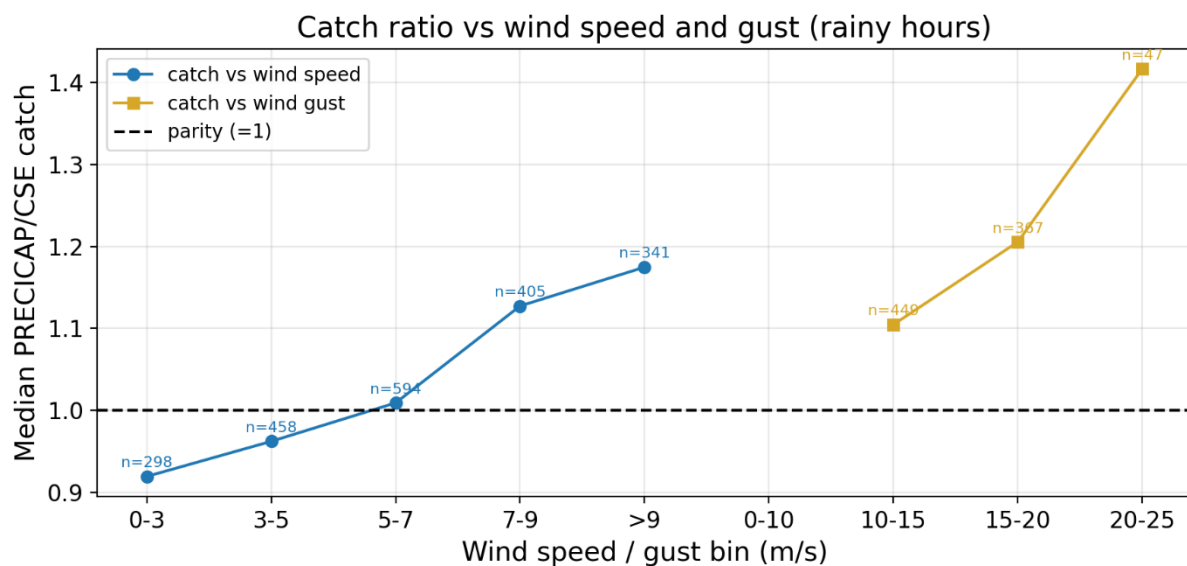


Figure 19. Catch ratios of rain amounts measured by the sensor of PRECICAP technology, with respect to the CSE (Met Éireann public reports), in classes of hourly wind speeds (left, blue graph) and of wind gust speeds (right, yellow graph). The dashed line indicates parity (unit catch ratio).

Assessments in the Measurement Quality Classification Scheme (OSCAR)

Figure 20 presents the outcomes of assessing the measurement quality of daily rain amounts of the sensor representing PRECICAP technology in the WMO OSCAR scheme. The daily rain amount differences are computed with respect to the CSE. The outcomes can thus be interpreted as an assessment of joint measurement quality of PRECICAP technology and the CSE, at the temperate maritime climate in conditions of mild and wet windier seasons, combined.

In 91 percent of rainy days, the daily rain amount measurements of PRECICAP technology agree with those of the CSE at the class level A or B ("breakthrough" or better). In less than four percent of the rainy days, the measurements deviated at a level not meeting the Class C. For simplicity, the data sets of milder and windier seasons were combined.

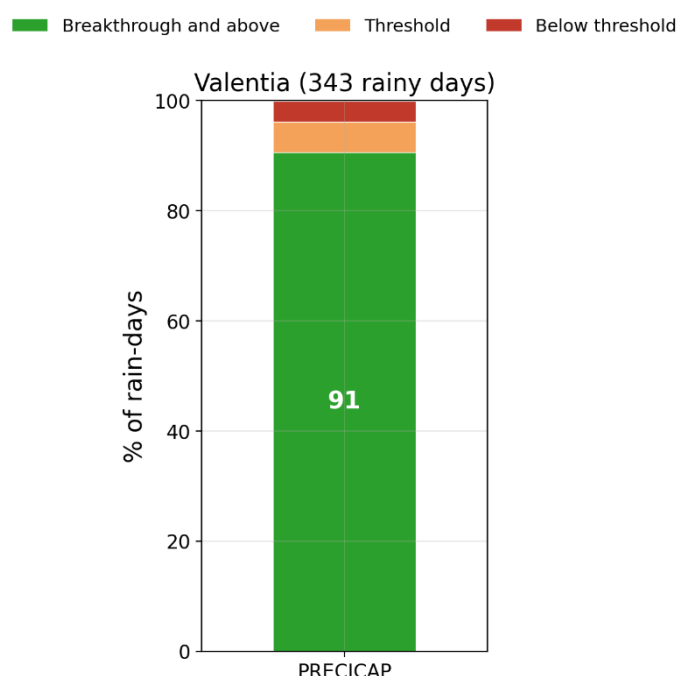


Figure 90. Assessments of overall quality of the daily rain amounts measured by a sensor representing PRECICAP technology with respect to the CSE in the WMO OSCAR scheme, at the climate of temperate maritime (Valentia). Relative occurrences of quality classifications are displayed. The warm season and the cool season data are combined. The sample consists of 343 days of precipitating weather.

5. Specific weather cases

RAIN MEASUREMENTS IN WINDY WEATHER

Windy weather is a known challenge in precipitation measurements, and it may induce substantial biases, typically under-catchment, see World Meteorological Organization (2022). Statistical analyses (see Results of seasonal statistical analysis section) indicate that responses of various sensor technologies tend to differ in windy weather. It is of interest to explore performances in the extreme events available in the data. High winds are common in rain events at the temperate maritime test site

(Valentia), due to Atlantic frontal weather systems passing the relatively open landscape at the coast of Atlantic Ocean. Gauges are mounted in turf pits while the sensors representing PRECICAP and optical sensor technologies are on masts, unshielded.

Three storm events occurred during the campaign at Valentia site with significant sustained winds throughout the rainy hours with gusts exceeding 20 m/s. Data were logged for detailed examination. Two events occurred within the data periods selected in statistical analysis window, on September 14th to 15th, 2025 and on December 5th to 6th, 2025. The named Met Éireann storm event “Storm Bert” developed from November 22nd to 26th in 2024, logged by a PRECICAP development version albeit valid for the case study. Thanks to successful site operations in all these three cases, rain amounts of PRECICAP could be compared against Met Éireann’s over the event windows.

Storm Bert (22–26 November 2024)

Storm Bert formed in November 2024 and moved into the mid-Atlantic on Thursday, November 21st, 2024. By Saturday, it reached peak intensity northwest of Ireland, weakening eventually by Tuesday November 26th. See Met Éireann (2024) for detailed event description.

Figure 21 depicts the evolution of the event in terms of Met Éireann accumulated rain and the sustained (10-minute) winds and the wind gusts at the site of temperate maritime (Valentia). Sustained winds were recorded at the level of 10 m/s throughout the rainy event. Wind gusts exceeding 20 m/s persisted in the most intense phase of rain. In the five days interval, the RM60 sensor prototype, representing PRECICAP technology, logged the rain amount of 88.4 mm while the amount of 85.9 mm was logged by the local gauge composite. The catch ratio is 1.02. The rain amounts are close to the maximum storm Bert rain amount of 88.9 mm recorded at Gernapeka, Co. Cork in Ireland.

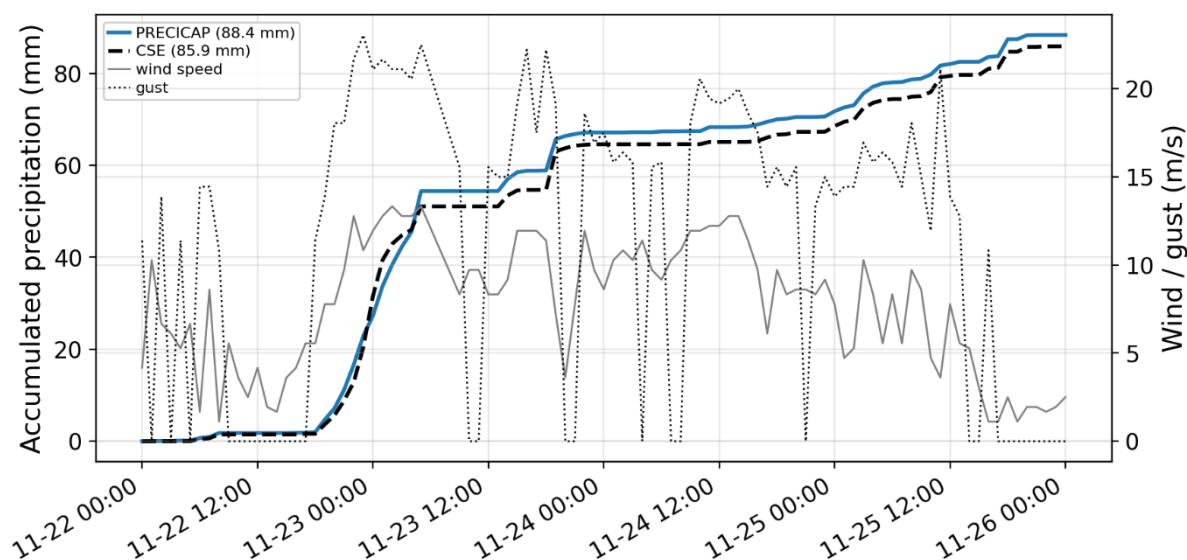


Figure 21. Time evolution of Storm Bert at the site of temperate maritime site (Valentia). Blue graphs (left scale) report the rain amounts of PRECICAP and the local gauge composite. The dashed lines (right scale) depict the mean (10 minute) wind speeds and wind speeds in gusts.

Windy weather cases (14–15 September 2025) and (5–6 December 2025)

Weather event from September 14th to 15th, 2025, is an example of rain in windy conditions with sustained winds reaching 15 m/s and wind gusts well above 20 m/s, depicted in Figure 22. Rain amounts of 26.8 mm and 27.2 mm were logged in 28 hours by the RM60 sensor representing PRECICAP technology and by the local gauge composite, respectively. The storm specific catch ratio is 0.99.

Weather event from December 5th to 6th, 2025, is another example of rain in windy conditions with sustained winds at the level of 10 m/s and wind gusts exceeding 20 m/s, depicted in Figure 23. Rain amounts of 33.7 mm and 30.1 mm were logged in 32 hours by the RM60 sensor representing PRECICAP technology and by the local gauge composite, respectively. The storm specific catch ratio is 1.12.

The combined rain amounts of PRECICAP technology (RM60 sensor) and of the local gauge composite, combined from these three significant rain events in windy weather are 148.9 mm and 143.2 mm, respectively, with a combined catch ratio of 1.04.

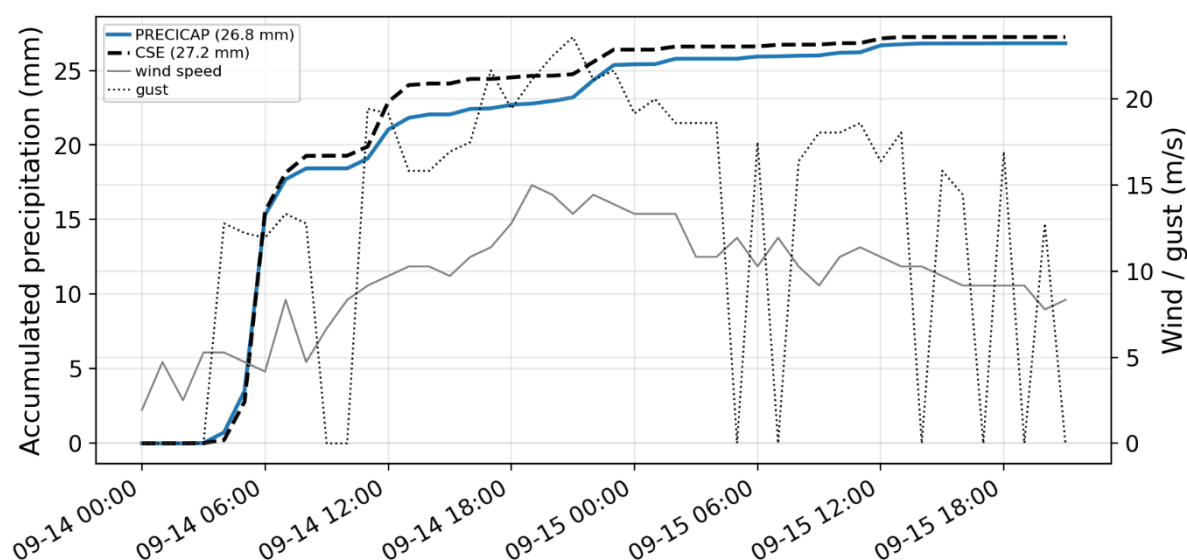


Figure 22. Time evolution of a windy rain event in September 2025 at the temperate maritime site (Valentia). Blue graphs (left scale) report the rain amounts of PRECICAP and the local gauge composite. The dashed lines (right scale) depict the mean (10 minute) wind speeds and wind speeds in gusts.

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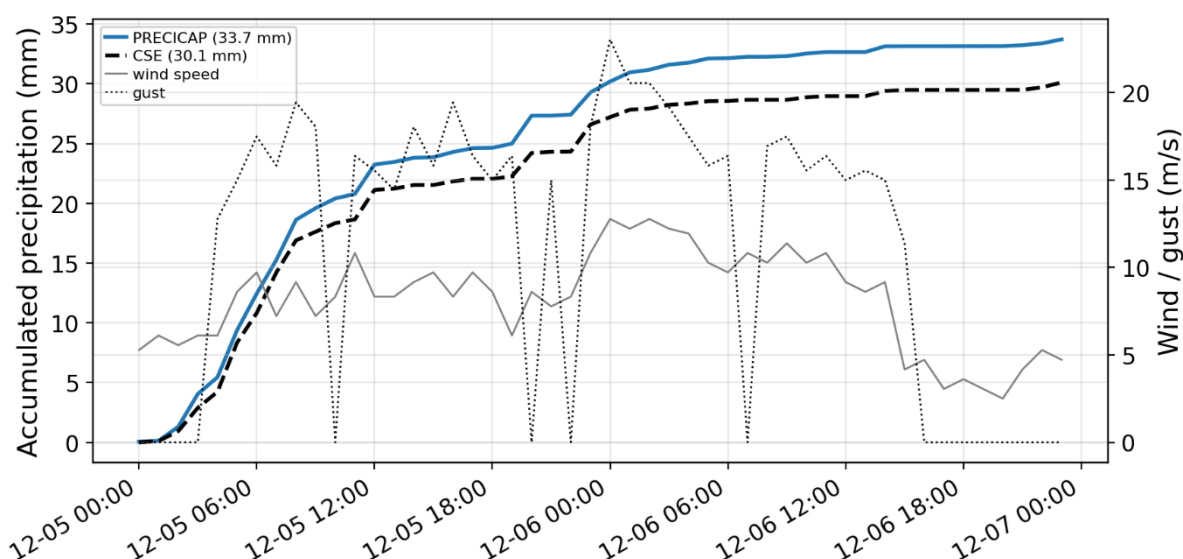


Figure 23. Time evolution of a windy rain event in December 2025 at the temperate maritime site (Valentia). Blue graphs (left scale) report the rain amounts of PRECICAP and the local gauge composite. The dashed lines (right scale) depict the mean (10 minute) wind speeds and wind speeds in gusts.

HEAVY AND VIOLENT RAIN

Moments and events of intense rain recur due to high intrinsic variability in the precipitation processes at all time and spatial scales of ambient weather. Events of intense rain generate floods which are causes of largest human, material and economical loss. Heavy and violent classes of rain intensity are common and sometimes persistent at the climate of tropical rainforest, represented by Selangor site, while they occur at other climates, too albeit in shorter time durations. Over the full campaign period in Selangor, 68 heavy-rain events and 39 violent-rain events were observed, of which a subset was fully recorded by sensors using the productized PRECICAP technology. Similarly, 22 heavy- and violent-rain events were recorded at Boulder, a high-altitude continental site, and 27 at Vantaa, a low-elevation humid boreal site. A selection of representative events is presented below.

Figures 24 to 26 present three cases of the most violent rain, recorded at the site of tropical rainforest (Selangor) in the time interval from August 2025 to July 2026. Shown are the time series of the mean rain accumulations of three sensors representing PRECICAP, two sensors representing the optical sensors and two weighing gauges, accompanied by the graphs of rain intensities (one minute running averages) which reach peak intensities up to ~80–87 mm/h.

The event on July 5th, 2026, accumulated the rain amount of 60.31 mm (average of gauge readings taken as the CSE) and it is the largest violent event rain fall in the campaign with a peak rain intensity of 87 mm/h (CSE). The sensors representing PRECICAP technology logged the average rain amount of 59.2 mm, in agreement at the level of two percent. Rain persisted five hours from start to end, while the heavy and violent phases endured less than two hours.

Two other events of violent rain intensities, exceeding 50 mm/h, at the site of tropical rain forest, see Figures 25 and 26, were shorter in durations 138 and 53 minutes. Rain amounts of 24.98 mm and 15.26 mm (CSE) were accumulated, respectively. The corresponding estimates of rain amounts reported by the sensors

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representing PRECICAP technology were 23.42 mm and 14.76 mm, respectively. They agree at levels within about 6 percent, event by event.

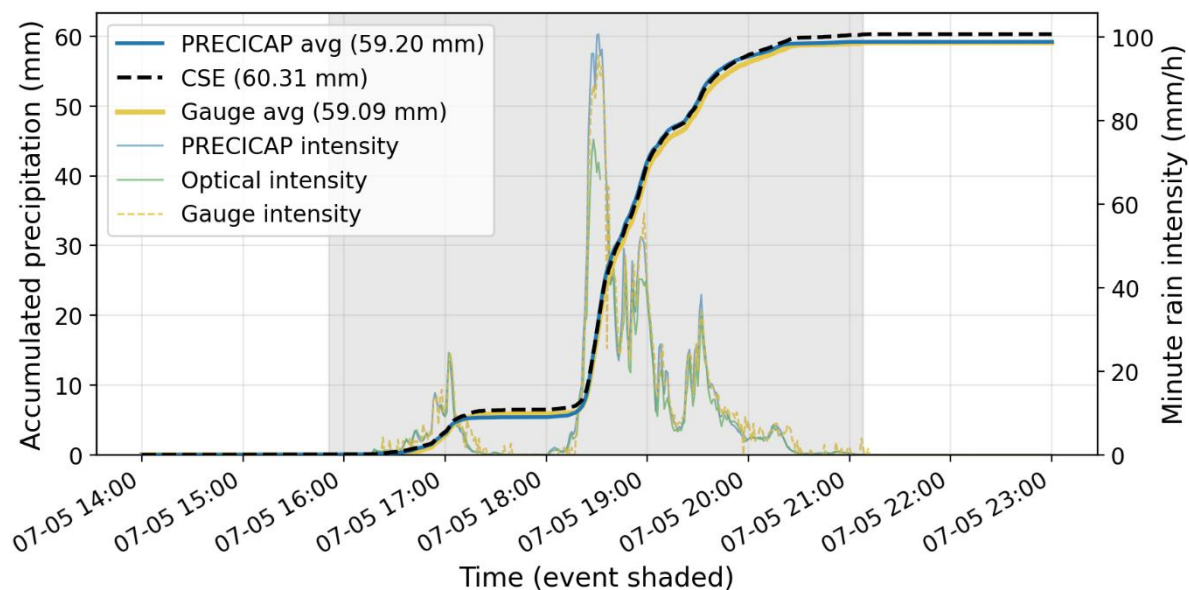


Figure 24. An event of violent rain (intensity peak 87 mm/h, duration 318 min) at the site of tropical rainforest (Selangor), on July 5th, 2026. Shown are the cumulative hourly rain amounts (left y-axis, since the dry start, shaded) as averages of three sensors representing PRECICAP technology and the CSE. On the right y-axis shown are the one-minute running averages of rain intensities of three sensors of PRECICAP technology of two sensors of optical sensors and of two weighing gauges.

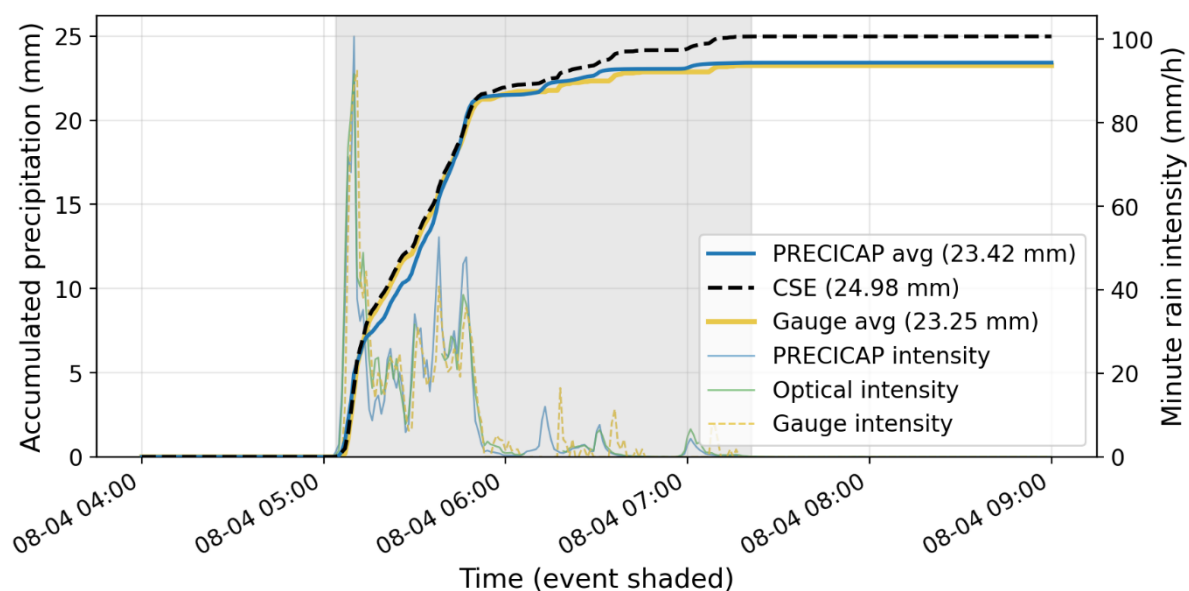


Figure 25. An event of violent rain (intensity peak 92 mm/h, duration 138 min) at the site of tropical rainforest (Selangor), on Aug 4th, 2025. Shown are the cumulative hourly rain amounts (left y-axis, since the dry start, shaded) as averages of three sensors representing PRECICAP technology and the CSE. On the right y-axis shown are the one-minute running averages of rain intensities of three sensors of PRECICAP technology of two sensors of optical sensors and of two weighing gauges.

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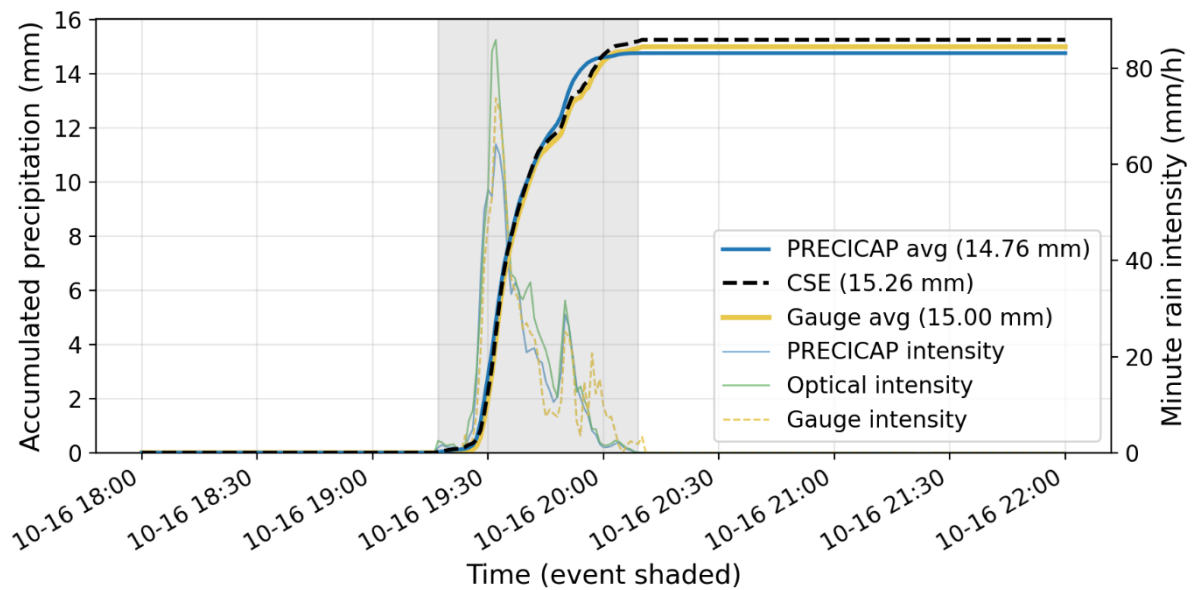


Figure 26. An event of violent rain (intensity peak 73.8 mm/h, duration 53 min) at the site of tropical rainforest (Selangor), on October 16th, 2025. Shown are the cumulative hourly rain amounts (left y-axis, since the dry start, shaded) as averages of three sensors representing PRECICAP technology and the CSE. On the right y-axis shown are the one-minute running averages of rain intensities of three sensors of PRECICAP technology of two sensors of optical sensors and of two weighing gauges.

Figure 27 presents the event of the highest rain intensity of 134.9 mm/h recorded as the mean of sensors representing PRECICAP technology in this campaign, in conditions where data are available all the three technologies of PRECICAP, of optical sensors and of weighing gauges. The event occurred on July 21st, 2025, at the site of low altitude humid boreal climate (Vantaa). Violent rain intensities occurred in an interval of 35 minutes, approximately. The common local estimate of rain amount of the event was 14.5 mm while the sensors representing PRECICAP and gauges reported rain amounts of 12.0 mm and 13.67 mm respectively, in agreement of 12%, relative.

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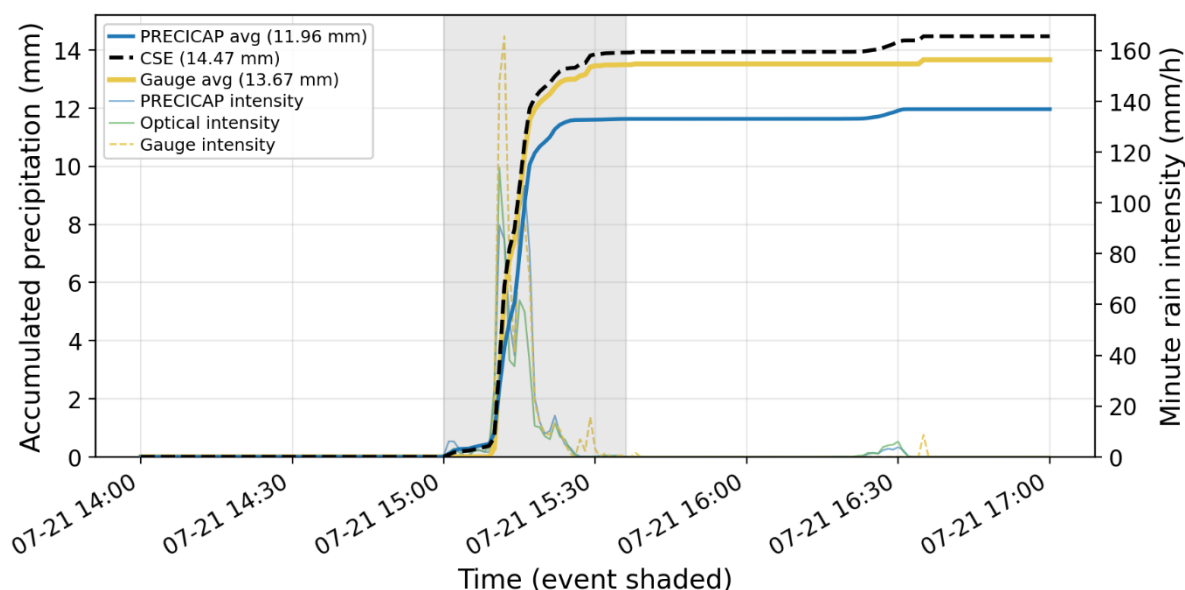


Figure 27. An event of violent rain (max PRECICAP intensity 134.9 mm/h, duration 35 min) at the site of low altitude humid boreal (Vantaa), on July 21st, 2025. Shown are the cumulative hourly rain amounts (left y-axis, since the dry start, shaded) as averages of three sensors representing PRECICAP technology and the CSE. On the right y-axis shown are the one-minute running averages of rain intensities of three sensors of PRECICAP technology, of two sensors of optical sensors and of two weighing gauges.

Figure 28 presents a case of intense rainfall that occurred on June 26, 2025, at a high-altitude continental site (Boulder). The averaged PRECICAP amount from the three sensors, 6.6 mm, corresponds to 80.4% of the CSE value (8.21 mm), while the mean gauge reading was 7.67 mm.

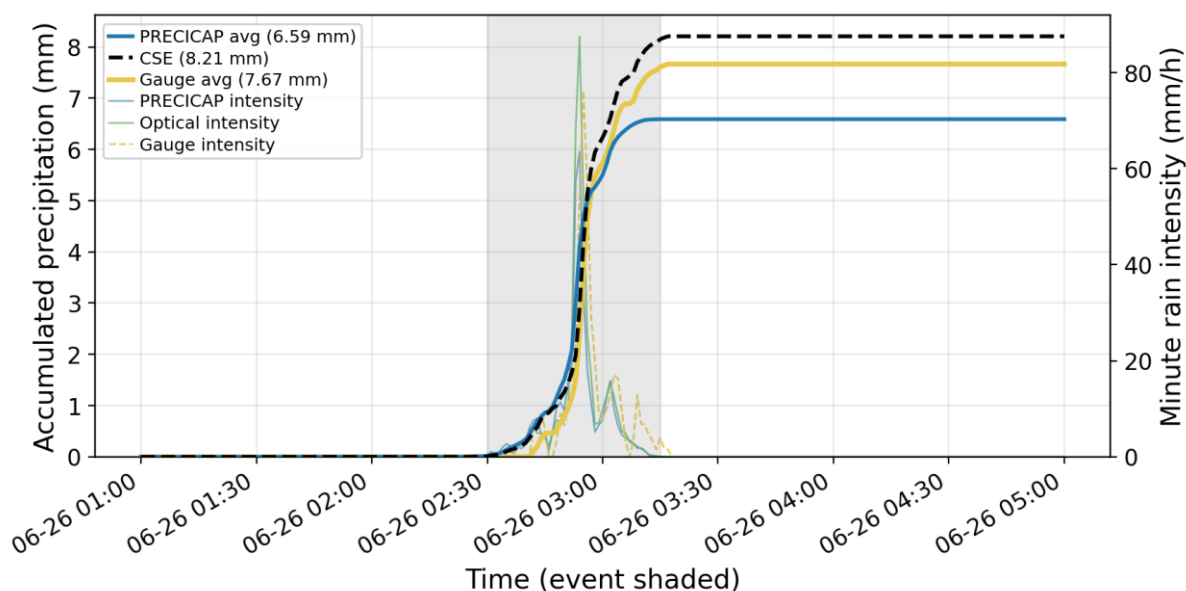


Figure 28. An event of violent rain (intensity peak 63.6 mm/h, duration 46 min) at the site of elevated altitude continental (Boulder), on June 26th, 2025. Shown are the cumulative hourly rain amounts (left y-axis, since the dry start, shaded) as averages of three sensors representing PRECICAP technology and the CSE. On the right y-axis shown are the one-minute running averages of rain intensities of three sensors of PRECICAP technology of two sensors of optical sensors and of two weighing gauges.

TEMPORAL RESOLUTION IN LIGHT AND IN SHORT-LIVED RAIN

High detection skill and high temporal resolution of precipitation estimates are of importance in applications such as aviation and road traffic. Responses of weighing gauges used in this campaign differ from those of the sensing technologies of PRECIPCAP, optical sensors, in these regards.

Figure 29 presents a light rain event, recorded on July 6th, 2026, at the site of low elevation humid boreal (Vantaa). Rain starts shortly before 03:30 (LT) and continues at varied intensity for more than 1 hour. The temporal evolution of the event is unambiguously observed by two independent technologies of PRECIPCAP and optical sensors. The gauge readings keep silent until a discrete increase, about half an hour, retarded. The pattern is repeated during the event which spans more than an hour, with rain amount at the level of 0.04 mm.

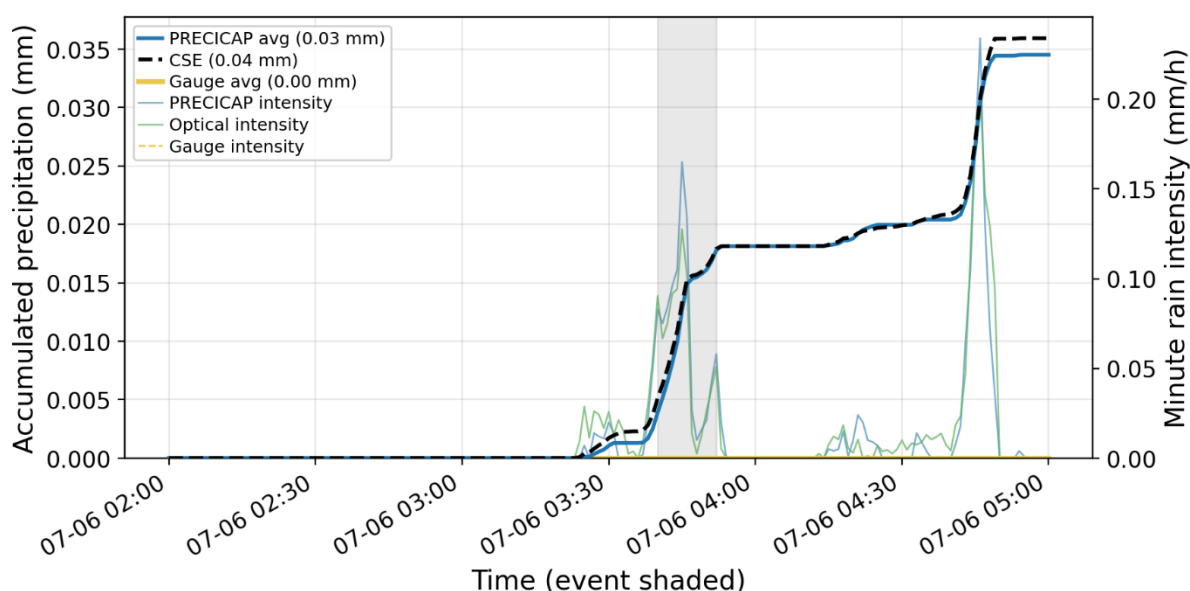


Figure 29. An event of light rain at the site of low-altitude humid boreal climate (Vantaa), on July 6th, 2026. Shown are the cumulative hourly rain amounts (left y-axis) as averages of two sensors representing PRECIPCAP technology and the CSE. On the right y-axis shown are the one-minute running averages of rain intensities of two sensors of PRECIPCAP technology, two sensors of optical sensors and two weighing gauges. Responses of weighing gauges display significantly different temporal evolution with respect to independent technologies of PRECIPCAP and optical sensors which report the apparent actual evolution of the rain event at high temporal fidelity.

Figure 30 presents another light rain event, recorded on November 8th, 2025, at the site of tropical rainforest (Selangor), in which the feature of retarded reporting of Near-real-time (NRT) estimates of the weigh gauge model of this campaign is explicit, too. Rain starts shortly before 19:00 (UT) and continues uninterrupted from 19:50 hrs for more than four hours. The temporal evolution of the event is unambiguously observed by two independent technologies of PRECIPCAP and optical sensors. The gauge readings keep silent until a couple of discrete increases, jointly from the pair of gauges while retarded by nearly 4 hours from the dry start. The event rain amount is about 0.17 mm.

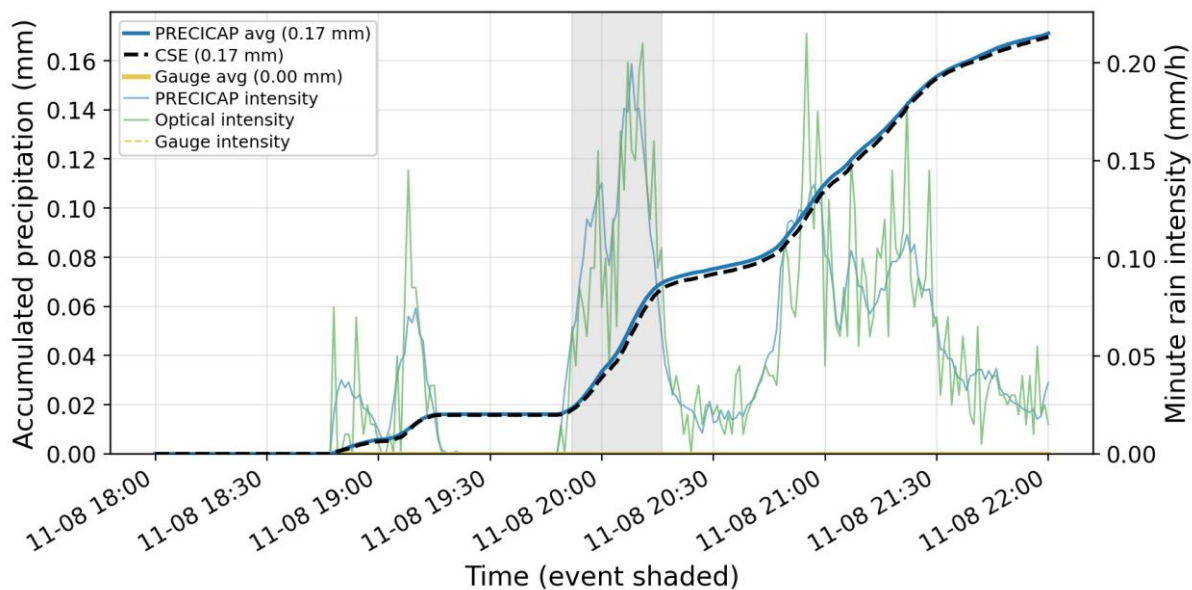


Figure 30. An event of light rain at the site of tropical rainforest (Selangor), on November 8th, 2025. Shown are the cumulative hourly rain amounts (left y-axis) as averages of three sensors representing PRECICAP technology and the CSE.

On the right y-axis shown are the one-minute running averages of rain intensities of three sensors of PRECICAP technology, two sensors of optical sensors and two weighing gauges. Responses of weighing gauges do not reflect with actual temporal evolution of the rain event, logged by the sensor representing PRECICAP and optical sensors at high temporal fidelity.

6. Discussion

The outcomes of analyses of time series of data acquired by three different precipitation sensor technologies at diverse climate, site and weather conditions depict patterns of consistent performances which appear general – that is the patterns are similar at varied climates, seasons and sites, within reasoned variability. In closer looks, there are recurring features which seem specific to a measurement technique, to a site and/or appearing conditionally in specific weather conditions. This Section compiles these findings, utilizing the site-by-site outcomes reported in preceding Section.

UNIT-TO-UNIT VARIATIONS IN LONG TIME INTERVALS

Generally, at sites where multiple sensor units were deployed, the unit-to-unit variations of the near-real-time (NRT) reports of the weighing gauges used in this campaign are small, typically at the level of one percent as soon as daily amounts or longer time integrals are considered. Even if not a proof of high accuracy per se, this consistency, in combination with prior research, justifies the use of gauge NRT readings generally as a dominant term in the CSE when the conduct needs a proxy of true values. Exceptions are the time intervals in which the independent measurement technologies of PRECICAP, and optical sensors unambiguously observe precipitation, thus defining the best proxy for true values while the gauges report null NRT readings, evidently in error.

Generally, the precipitation amounts reported by the sensor units representing PRECICAP technology and integrated over seasonal time scales agree at a level of six percent or better, in standard deviations relative. This level of consistency prevails in subsets of warm and cool seasons at varied climates represented by the three sites of elevated altitude continental (Boulder), low elevation humid boreal (Vantaa) and of

tropical rainforest (Selangor) of this campaign. In Vantaa, series of six co-located sensor units of PRECICAP integrated through a part of warm season 2026 (73 calendar days) confirm this finding at a higher statistical significance.

Generally, differences in the seasonal precipitation amounts between the pairs of sensors representing optical sensors varies from the level of few percent at site of elevated altitude continental (Boulder) to the level of ten percent at the site of low altitude humid boreal (Vantaa) and tropical rainforest (Selangor). In expert view, these variabilities may indicate the need to pay attention on the site quality of this type of technology. This type of measurement technology may require mount positions where air motion is in better control, in terms of ambient wind as well as turbulence. Optical sensors may need cleaning after exceptional weather cases.

COMPARISONS OF SEASONAL PRECIPITATION AMOUNTS WITH THE LOCAL COMMON SYNTHETIC ESTIMATES

The CSE is mostly composed of the gauge reports – hence their comparison to CSE has little meaning. Generally, less than seven percent of the total precipitation amounts are from precipitation recovered by the non-catchment type of measurements (PRECICAP and optical sensor) in time intervals where weighing gauges reported null, considering all seasons and intensities. In classes of modest, heavy and violent rain, the recovered rain amounts contribute to a couple of percent of the warm season CSE rain amounts. Their relative significance is larger, up to fifty percent in events of light rain and drizzle, and non-negligible in cool season estimates of liquid water equivalent. The CSE values, as a proxy of true values, have their intrinsic uncertainty, see WMO (2024).

Generally, the mean precipitation amounts of PRECICAP technology agree with the CSE at a level of six percent or better, taken as seasonal catch ratios across the sites. In the windy season at the climate of temperate maritime (Valentia), the seasonal rain amount of a sensor unit representing PRECICAP exceeds that of the CSE by nineteen percent. This is compatible with findings of relative deviations of various gauge models and mount points approaching twenty percent when data sets were split in smaller time intervals, see the intercomparison in similar climatic conditions by Quinlan (2022). In the milder season of the temperate maritime site, the seasonal rain amount of PRECICAP technology agreed with the CSE within four percent.

The agreement of the optical sensors with the CSE reflected their deployment conditions. At the low-altitude humid boreal site (Vantaa), where ambient winds are modest and the sensors were periodically maintained in line with the manufacturer's recommendations, the seasonal mean precipitation amounts agreed with the CSE within a few percent. Combining these outcomes with those from sites where the sensors operated above or without wind shields and without routine window cleaning (Boulder and Valentia), the results indicate that optical sensors perform to specification when sited with appropriate wind protection and maintained with periodic window cleaning.

ASSESSMENT OF GENERAL SUITABILITY TO METEOROLOGICAL MEASUREMENTS IN THE OSCAR SCHEME

The purpose of the WMO OSCAR scheme for measurement quality classifications is to allow quantifying the measurement performances from existing stations, hence assisting industries to deliver solutions to meet user needs. The scheme turned out fit for the purpose in this campaign which accumulated statistics sufficient for tentative findings.

Using the prescribed OSCAR measurement quality metric, the overall quality of the daily rain amounts (or liquid water equivalents in the cool seasons) reported by the

sensor units representing PRECICAP technology was at the levels of A ("ideal") or B "break-through", in more than 90% of the precipitating days. This level of quality was sustained at varied climates, seasons, weather and site conditions in which the statistically significant time series were available for comparison with the common local synthetic estimates serving as proxy for true values. Days with data quality "less than threshold" occurred rarely, at one percent level at the sites of elevated altitude continental (Boulder) and low elevation humid boreal (Vantaa). All sensor units performed equally, in this regard. In less than four percent of the days at windy temperate maritime climate, the measurement quality was below the threshold – subject to the unresolved uncertainty in the proxy of the true value. With the statistics available at time of the analysis, data from frozen precipitation as well from all intensity classes of rain events were combined. No differentiation was made on windy conditions. Overall, the sensor unit representing PRECICAP technology performed consistently through the milder as well as the windier seasons of temperate maritime climate, at the site of open fields (no shields) prone to windy weather of the Atlantic Ocean. At the time of compiling these results, the statistics of data valid for OSCAR metric was insufficient at the site of tropical rain forest (Selangor) while the compilation of case studies support these findings qualitatively, see Section "Specific weather cases".

These outcomes depict a different view of overall data quality of precipitation measurements, when compared with findings and conclusions in an analogous study by Spiegel-Pinzer et al (2024). Spiegel-Pinzer et al. (2024) consider ensembles of optical sensors and vertically pointing Doppler devices and weighing gauges, as in this study. Their sites are in middle/central Europe, with likely more moderated climatological variability than in this study. The sensor models are different from sensors utilized in this study, while the reports of weighing gauges are utilized as the main input to the proxy of true values, similarly to this study. Despite these similarities, they find that the data qualities of the sensor ensembles vary significantly from site-to-site, within the OSCAR classes B to D. Data quality of several sensor models tends to persistently at or below the "threshold" level. A reasoned explanation is that some sensor models are more vulnerable to varied climatic and site conditions when operating in ambient weather.

Indeed, the reasoning behind the OSCAR scheme is to acknowledge that a fixed rating of a sensor (typically the measurement accuracy inferred in controlled conditions) is not a viable metric for assessing precipitation measurements in ambient weather. In varied site and climatic conditions, the instrument coupling and broader environmental factors tend to affect the sensor performances. Robustness of the measurements gets tested when the sensor is exposed to the real variability of the weather and the sites. This became evident during this campaign, too. Some measurement techniques appear more vulnerable to weather (such as windy conditions, short-lived rain). The detrimental effects may get amplified with site features while they can be mitigated by extending the infrastructure (wind shields, optimized mount points). Emphasis on temporal fidelity of the measurements tends to expose weaknesses in methods optimized for accuracy of integrated rain amounts. Regular maintenance, repeated due extreme events, appeared to be a necessity for catchment type of devices as well as for optical sensors. PRECICAP technology differentiated remarkably positively in these regards.

TEMPORAL RESOLUTION IN LIGHT AND IN SHORT-LIVED RAIN

High sensitivity and high temporal resolution temporal resolution of precipitation estimates are of importance in some use cases, such as aviation and road traffic. The

sensing technologies of PRECICAP, optical sensors and weighing gauges perform differently in these contexts.

As a common feature in light short-lived precipitation events, the Near-Real-Time reports of the weighing gauge model deployed in this campaign tend to be retarded, sometimes up to hours, with respect to the prompt and concurrent responses of the two independent technologies of PRECICAP and optical sensors which can be jointly taken as best characterizations of the temporal evolution of precipitation events. Effectively, short-lived precipitation events appear to be missed completely in NRT time series while unambiguously detected by two independent technologies of PRECICAP and optical sensors. It remains unresolved if the later NRT reports of rain amounts include or omit these contributions of precipitation amounts. The significances of these findings, consistent with earlier studies, see Vuerich et al, (2009), are two-fold.

First in the sensor inter-comparison context, the statistical analyses are obscured when performances of various sensor technologies are explored through comparisons of rain intensities (or amounts) sampled in short time intervals. Non-negligible part of the apparent scatter appears to be due to temporal mismatches between gauge data and time series of independent technologies – not reflecting the actual deviations in the technology performances. Simplified data analyses cannot be trusted, pending consistent resolve of this persistent dilemma. As typical temporary mitigation, daily precipitation amounts can be utilized in statistical evaluations, as in this analysis. As a further complication, the temporal mismatches introduce an added uncertainty in constructing CSE serving as proxy of the true precipitation amounts and intensities.

Secondly in the broader applications' context, the near-real-time methods developed for improved accuracy in catchment type of measurements may compromise the utility and the value of the measurements in applications where prompt, high temporal resolution of precipitation measurements is needed. These skills are the characteristics of PRECICAP technology and of optical sensors.

7. Summary & Conclusion

Joint deployments of precipitation measurement technologies of PRECICAP, of optical sensors and of weighing gauges lead to improved understanding of their performances. It is imperative to deploy at multiple sites, to continue operations through multiple seasons representing different climatic and environmental conditions. Concurrent operations of different sensor technologies build up broader confidence in measurements of precipitation, given the general consistency between measurements based on substantially different principles and technical implementations. Furthermore, concurrent operation of multiple measurement technologies bring up phenomena in specific weather and site conditions, in a manner not accessible through considerations of one type of sensor, alone.

The purpose of the WMO OSCAR scheme for measurement quality classifications is to enable quantifications of the measurement quality data from actual measuring stations, hence assisting industries to deliver solutions to meet user needs. The scheme turned out fit for the purpose in this campaign. Across the diversity of climates, of weather and of site conditions explored in this campaign, the overall quality of the data reported by sensors representing PRECICAP technology is typically in the class of "break-through" or better. Days of data quality "below threshold" occurred once in hundred precipitating days, typically. At an exceptionally windy site, quality fell "below threshold" in daily

comparisons with the local synthetic estimator (subject to weather related uncertainty, as well) in less than four percent of the precipitating days.

Generally, the recently introduced PRECICAP technology

- performs consistently across all four climates over the campaign period, including significant events of stormy weather and of varied rain intensities from drizzle to violent rain at multiple sites;
- delivers accurate, repeatable precipitation measurements spanning liquid and frozen phases relative to other measurement technologies;
- is maintenance-free and operates reliably unattended;
- is suited for different use cases — aviation, road weather, hydrology, and severe-weather monitoring.

8. Acknowledgements

Vaisala acknowledges the contributions of the Met Éireann team at Valentia Observatory in operating Vaisala instrumentation at the site, and logging data at high availability.

Part of the meteorological data used in this study were obtained from Met Éireann. Copyright Met Éireann. Source: www.met.ie. This data is published under a Creative Commons Attribution 4.0 International (CC BY 4.0) licence (<https://creativecommons.org/licenses/by/4.0/>). Met Éireann does not accept any liability whatsoever for any error or omission in the data, their availability, or for any loss or damage arising from their use. This material has been modified from the original.

9. References

1. Bureau International des Poids et Mesures, (2026): Precision <https://jcgm.bipm.org/vim/en/2.15.html>
2. Met Éireann (2024): The Irish Meteorological Service: Storm Bert <https://www.met.ie/cms/assets/uploads/2025/05/Bert.pdf>
3. Met Éireann (2026): The Irish Meteorological Service: www.met.ie
4. NASA Earth Observatory (2024): Total rain fall monthly amounts 2000-2024 animation, https://earthobservatory.nasa.gov/global-maps/GPM_3IMERGM
5. O'Leary T. et al. (2024): A Comparison of Daily Rainfall Measurements at Irish Stations: Pluvio Weighing Rain Gauge versus Manual Gauge, TECO 2024.
6. OTT Pluvio (2026): Ott Pluvio L 400 Weighing Rain Gauge, <https://www.ott.com/products/pluvio4>.
7. Quinlan M. (2022): An Intercomparison of Precipitation Gauges at KNMI in De Bilt, Netherlands, TECO 2022.
8. Spiegel-Pinzer J. Korevaar M., Knauss D. Crawford A. (2024): Effects of environmental conditions on the CIMO WMO Class determination for OTT HydroMet precipitation sensors, TECO 2024.

9. Vaisala FD70 (2026): Vaisala Forward Scatter Sensor FD70,
<https://www.vaisala.com/en/products/weather-environmental-sensors/forward-scatter-fd70>
10. Vaisala RM60 (2026): Vaisala PRECIPAP™ Radar Precipitation Sensors RM60,
<https://www.vaisala.com/en/products/precipap-radar-precipitation-sensor-rm60>
11. Vuerich E., Monesi, C. , Lanza L., Stagi, L., Lanzinger, E. (2009): WMO Field Intercomparison of Rainfall Intensity Gauges. World Meteorological Organisation - Instruments and Observing Methods Rep. No. 99, WMO/TD No. 1504.
12. World Meteorological Organization (2024): Guide to Instruments and Methods of Observation; Volume I – Measurement
13. Metek3D (2026): <https://metek.de/product-group/sonic-anemometer/>