Operational adoption of new probabilistic point rainfall forecasts: the crucial role of a “user-oriented” approach

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# ABSTRACT

A new post-processing technique (ecPoint) was developed to produce more reliable/skilful probabilistic forecasts (e.g. for rainfall and temperature) at points. However, ecPoint adds layers of complexity to traditional probabilistic forecasts. Therefore, are the current guidelines helping users to use ecPoint-derived products correctly? A collaborative pilot study with the national hydro-meteorological services of Costa Rica and Hungary helped to understand whether the guidelines for ecPoint-Rainfall forecasts might need to change, and if so, how. Operational forecasters examined ecPoint-Rainfall forecasts over one year and discussed their perceived usefulness with ecPoint experts. The study showed that if ecPoint developers adopt a "user-oriented" approach to build ecPoint-Rainfall guidelines that fit better users' experience with probabilistic forecasts, there would be a more extensive operational adoption of the new product, also in those environments with a predominant deterministic background like Costa Rica. It was found that different type of users would benefit from diverse type of guidelines. For example, users with less experience would benefit from a closer engagement with ecPoint experts, e.g. via forums or one-to-one contact. In general, users would also benefit from publishing user cases about forecasting situations that forecasters face frequently. The knowledge gained in this study might not be generalizable to all types of users but helped to start improving the documentation already existing in the ECMWF Forecaster User Guide and promoted the inclusion of ecPoint-Rainfall in the ECMWF Forecaster User Forum. It also promoted the pursue of similar studies to continue tailoring the ecPoint-Rainfall guidelines for diverse users (e.g. hydrologists).

# Introduction

Worldwide, extreme-rainfall-related hazards (e.g. storms, tropical cyclones, floods, flash-floods, landslides) have cost millions of lives and billions of dollars in economic losses between 2000-2019 (UNDRR 2020). In future, such hazards are expected to become more frequent and damaging due to global warming (Hoegh-Guldberg et al. 2019) and increasing exposure/vulnerability of people and assets (Ward et al. 2020).

The Sendai Framework for Disaster Risk Reduction 2015-2030 (UNDRR 2015) advocates the crucial role of forecasts-based early warning systems (EWSs) in reducing the risk from hazards for which other protections are unavailable or unaffordable. EWSs are being built at regional/national (Arnal et al. 2020; Demuth et al. 2020; Flack et al. 2019; Acosta-Coll et al. 2018) and international scale (Emerton et al. 2020; Zsótér et al. 2019; WMO 2017; Coughlan De Perez et al. 2015; Alfieri et al. 2012, 2013). The experience gained by the developers of such systems suggests that efficient EWSs not only must provide cutting-edge, high-quality hazard forecasts to end-users (i.e. forecasters, decision-makers, emergency responders, or the public), but they must also show end-users that they provide added value to decision-making processes. Otherwise, end-users will naturally opt to inspect outputs from sources they are better acquainted with their strengths and weaknesses (Herman and Schumacher 2016), which might ultimately slow down or stop the adoption of new developments (Taylor et al. 2018).

To deliver forecasts that end-users need and can understand, several studies (Golding et al. 2019; Zhang et al. 2019) encourage the adoption of a “user-oriented” approach. Through a two-way interdisciplinary communication system between developers and end-users, this approach connects forecast production systems to end-user’ decision-making processes. On the one hand, the “user-oriented” approach helps developers to convey to end-users the social, economic, and environmental value of the EWS’s forecasts (Fundel et al. 2019; LeClerc and Joslyn 2015; Joslyn and LeClerc 2013; Morss et al. 2008). On the other hand, it helps developers to identify research targets to satisfy end-users’ needs (Demuth et al. 2020; Wilson et al. 2019; Losee and Joslyn 2018; Morss et al. 2016; Demeritt et al. 2013).

In order to engage in fruitful conversations with developers, end-users need to know first what forecasts the EWS makes available, and how to access and interpret them. To that purpose, forecast training is essential (Demuth et al. 2020; Emerton et al. 2020). It can nonetheless present a number of issues with its content and delivery. A series of studies (Demuth et al. 2020; Evans et al. 2014; Nobert et al. 2010; Novak et al. 2008) confirm what, in the authors’ experience, are the main issues with forecast training. Firstly, too often training content tends to be disproportionately heavy on the scientific developments of forecast products and to be much lighter on practical applications, e.g. on what are the strengths and limitations of a forecast product, or how and when it applies to and benefits a forecast process by adding value rather than uncertainty to operational decision making. Secondly, training usually does not mirror forecasters’ verification needs and language undermining their capability to assess and efficiently convey to the partners the confidence in the forecast. Finally, training is not always effective in informing end-users about what forecast products are available and how to access them.

With the aim to not incur into these issues when a new statistical post-processed rainfall product, called ecPoint-Rainfall, was developed at the European Centre for Medium-range Weather Forecasts (ECMWF) in 2016, a set of documentation was published (Hewson and Pillosu 2020; Pillosu and Hewson 2017) to inform end-users on the benefits of using ecPoint-Rainfall when predicting extreme (localized) rainfall: (1) better location and distribution of extreme localized rainfall totals up to day 10 compared to the ECMWF ensemble (ENS) forecasts, (2) global coverage. When ecPoint-Rainfall was operationally released in April 2019, more detailed guidelines were also published in the ECMWF Forecaster User Guide (Owens and Hewson 2018).

Yet, these efforts seemed to be not sufficient. When Peru was affected by severe flooding in 2017, the Peruvian national hydro-meteorological service (SENHAMI) was provided with temporary free access to ECMWF forecasts (Pillosu et al. 2017), and with the newly developed ecPoint-Rainfall products that, at the time, were running only internally at ECMWF in pre-operational mode. This event was the first opportunity for ecPoint developers to hear about the strengths and the weaknesses of ecPoint-Rainfall forecasts, for a specific region (i.e. Peru), and from local experts (i.e. SENHAMI forecasters). For the first time, ecPoint developers would have also hear about the perceived usefulness of ecPoint-Rainfall forecasts if SENHAMI forecasters had used the new product in the creation of forecasts/warnings for the flash flood event. From the point of view of a forecaster at a NHMS, a new rainfall product would be perceived more “useful” than other products already in use if it provides a better pointer on the location, time, and intensity of a rainfall event. The experience with SENHAMI showed that ecPoint-Rainfall guidelines were not helping forecasters to use the new product correctly. Consequently, the perceived usefulness of ecPoint-Rainfall was underrated. This condition could therefore undermine the adoption of ecPoint-Rainfall forecasts in EWSs. Collaborative pilot studies were therefore pursued to understand how guidelines might need to change to favour the correct use of ecPoint-Rainfall forecasts (Pillosu and Hewson 2018). Only forecasters at national hydro-meteorological services (NHMSs) were invited to participate to the pilot study as, currently, they are the primary costumers of ecPoint-Rainfall forecasts. The Hungarian Meteorological Service (Országos Meteorológiai Szolgálat, OMSZ) and the Costa Rican Meteorological Service (Instituto Meteorológico Nacional de Costa Rica, IMN) participated to this study.

This study collects local-expert information about:

1. The performance of ecPoint-Rainfall forecasts in the prediction of extreme localized rainfall and flash floods in diverse regions.
2. The perceived usefulness of ecPoint-Rainfall forecasts if used in the creation of forecasts and warnings. The focus is on (i) whether the available guidelines help in understanding the product, and (ii) whether prior forecasters’ familiarity with probabilistic forecasts leads to different levels of guidelines efficacy.
3. The perceived usefulness of ecPoint-Rainfall forecasts when the guidelines are subsequently modified to accommodate users’ needs.

Finally, the information gained in this study will be used to create a new set of revised users’ guidelines for ecPoint-Rainfall forecasts.

# The ecPoint methodology and the ecPoint-Rainfall forecasts

Let’s consider the rainfall forecast from an NWP model grid-box. Let’s also assume that the observed average rainfall over that grid-box is about 17 mm, whilst the minimum and maximum observed rainfall amounts are 2 and 60 mm, respectively. There are two issues that can be encountered with rainfall forecasts from NWP models.

Firstly, there is an issue of sub-grid variability. NWP models provide rainfall forecasts that correspond only to a grid-box average. If correct, an NWP model will provide a forecast of 17 mm for the grid-box but will not provide any information about the variability of the point rainfall values within that grid-box (which ranges from 2 to 60 mm in the example). The entity of rainfall sub-grid variability within a grid-box is associated to the type of weather affecting that grid-box, which from now on will be called “grid-box weather type” (G\_WT). For example, a grid-box with a G\_WT that correspond to mainly convective rainfall and slow steering winds might have a higher probability to be affected by a higher rainfall sub-grid variability than a grid-box affected by mainly large-scale rainfall and fast steering winds. In the second the case, the rain might indeed tend to be more uniformly distributed within the grid-box.

Secondly, there is an issue of bias at grid-scale. Whatever is the extend of the observed rainfall variability within a grid-box, a completely accurate NWP model will predict 17 mm for the grid-box. However, depending on the G\_WT, the average grid-box rainfall forecast could be over-predicted (or under-predicted) by a 15%, delivering a forecast of 19.55 mm (or 14.45 mm) instead of 17 mm. For example, the model orography has smaller peaks than real orography. Therefore, it might not be able to constrain the moisture to condense in the upwind area, allowing the downwind flow to have more moisture than it would have in reality. Therefore, on the one hand, a grid-box with a G\_WT that correspond to a moist upwind flow might have a higher probability to be affected by a rainfall underestimation bias. On the other hand, the correspondent downwind G\_WT might have a higher probability to be affected by a rainfall overestimation bias.

Both issues, model sub-grid variability and the bias at grid scale, can be enhanced in models with coarse resolutions (Lavers et al. 2021), e.g. global or climate models. Km-scale models might be able to provide more realistic distribution of point rainfall values. However, they might not be more accurate when verified at specific locations (Roberts 2008). Therefore, raw NWP rainfall forecasts, from global or km-scale models, might benefit of statistical post-processing that could help to address imperfections in the underlying prediction system (Hamill et al. 2017).

ecPoint is a statistical post-processing technique that provides probabilistic, bias-corrected forecasts at point scale. Different hydro-meteorological variables, from ensemble or deterministic numerical weather prediction (NWP) models, could be post-processed using this technique. ecPoint-Rainfall is the product branch of the “ecPoint family” that generates rainfall forecasts that mirror rain gauge measurements (Hewson and Pillosu 2020).

The ecPoint technique can help to anticipate model sub-grid variability and correct model biases at grid-scale by correcting the raw rainfall forecasts at each grid-box according to the correspondent G\_WT.

From each raw single model grid-box forecast, ecPoint creates a distribution of X equally probable point-rainfall realizations (see Fig. 1, right-green panel). The value of X depends on available computational and storage capacity.

# Methods

## Participants

The participants to the pilot study on ecPoint usefulness and training are operational weather forecasters in two NHMSs (IMN and OMSZ) with experience in issuing extreme weather-related events. A maximum of two contact people was identified at each NHMS to insure as efficient communication between the operational forecasters and the ecPoint experts. Such contact people will be referred as intermediaries from now on. The intermediaries were required to be operational forecasters themselves or have direct experience on the operational forecasters’ procedures and preferences when forecasting extreme (localized) rainfall events.

## Experiment design

The data was collected through a 2-step experiment design (see flowchart in Fig. 2), run in two consecutive phases: a “real-time” and an “offline” phase.

The aim of the “real-time” phase was to collect forecasters’ feedback on aspects that are important if a product is meant to be used operationally, such as the ecPoint-Rainfall performance and perceived usefulness, crucially under real-time operational constraints. Moreover, this phase also aimed to collect information on technical aspects such as forecasters were not familiar with probabilistic forecasts, so they preferred to keep looking at deterministic outputs; there were little or no resources to introduce the new forecasts in the NHMSs’ operational forecasting systems; it was initially challenging to manage the big amounts of data delivered daily by the ecPoint system.

The aim of the “offline” phase was to bring together the reflections of the participants and the ecPoint developers on the performance and perceived usefulness of ecPoint-Rainfall forecasts, but especially reflections on how to improve ecPoint-Rainfall guidelines to help the adoption process of the forecasts in the NHMSs’ operational environments. The analysis in this phase was not carried out under real-time constraints.

### “Real-time” phase

The “real-time” phase started by sending via file transfer protocol (ftp), for 12 months, real-time ecPoint-Rainfall forecasts to the NMHSs. All participants received the same information (e.g. files formats, runs, lead times) but for their region of interest only (see Table 1). The participants modified themselves the files’ original format (gridded binary, grib) if they were not compatible with their operational systems.

Training material on the ecPoint methodology and the ecPoint-Rainfall product was supplied to the intermediaries (see Table 2). The training included (1) links to ECMWF Newsletters articles published up to the date of the experiment start (in 2018) to explain the scientific developments of the ecPoint methodology and the ecPoint-Rainfall products, and (2) especially created material describing the structure of the ecPoint-Rainfall forecasts. The intermediaries were finally encouraged to ask questions to the ecPoint experts about the training material and do so via email. This “email-exchange” approach is consistent with how the bulk of User Support functions at ECMWF. Direct contact with product developers is also consistent with how support is provided at ECMWF in case of new products. The developers, and not the User Support, are indeed the main responsible for dealing with questions from users.

In the same email, the intermediaries were finally encouraged to create their own products from the provided ecPoint-Rainfall forecasts. However, if requested, ecPoint developers volunteered to provide information on what basic products (e.g. map plots for percentiles or probabilities of not exceeding a rainfall threshold) could be developed from the forecasts provided. IMN requested further explanations on how to interpret the percentiles, how to compute the probabilities of not exceeding a rainfall threshold, and how to interpret them. Initially, it was provided a generic background on the topics. Later, it was provided an explanation of what are the direct implications in the interpretation of ecPoint-Rainfall forecasts. The explanations are shown in Table 2.

The intermediaries were asked to provide, the end of the “real-time” phase, a summary report on the forecasters’ experience on using and testing ecPoint-Rainfall forecasts operationally. They were left free to organize the report as preferred, e.g. show all or a sub-group of the case studies analysed during the “real-time” phase or run a conditional verification study on the whole or a sub-group of the data provide. This approach is consistent on how ECMWF requests Member States to provide feedback on standard ECMWF products.

Although the intermediaries were free to organize the report as they deemed appropriate, they were nonetheless asked to answer to the following questions:

* Did you develop products from ecPoint-Rainfall to be used by forecasters in you operational environment? If so, describe them.
* What were the forecasters’ impressions about such products?
* Did you evaluate ecPoint-Rainfall forecasts, e.g. via case studies or objective verification?
* How could forecasters use the results of such evaluation in their operational work?
* Do you think the provided ecPoint-Rainfall guidelines were clear or useful?

The following points were evaluated in the reports:

* To what extent did the participants appreciate the difference in scale between ecPoint-Rainfall forecasts and rainfall forecasts from NWP models, either raw or post-processed? The main difference to appreciate is that the latter are forecasts that represent average rainfall values over the model grid-box, whilst ecPoint-Rainfall forecasts represent a value at a point within the grid-box even if no information can be provided on where that point is within the grid-box.
* To what extent did the participants appreciate the difference between the spread in ecPoint-Rainfall forecasts and rainfall forecasts from NWP, either raw or post-processed? This aspect is linked to the previous one because the spread provided by ecPoint-Rainfall refers to a point-scale, whilst the spread provided by other NWP model outputs refer to the grid-scale of the model.
* To what extent did the participants focus on high percentiles (i.e. > 90th percentile) to assess the location and the magnitude of extreme localized rainfall? Lower percentiles will not indeed represent extreme localized events, which by definition are very low-probability.

To what extent did the participants appreciate the difficulties on verifying low-probability extreme localized rainfall events in small regions? For example, the 99th percentile represents rainfall events with a 1 in 100 chance of happening. However, they might not be observed in not dense observational networks, and this doesn’t mean the forecasts were wrong.

The outcomes of the “real-time” phase are summarized in two parts. The “products developed from ecPoint-Rainfall forecasts” are presented in section 5.a. The results of the “Independent verification of ecPoint-Rainfall forecasts” are presented in section 5.b.

### “Offline” phase

The “offline” phase allowed to have an informal discussion between ecPoint experts and intermediaries on the content of the summary reports and the overall participants’ experience during the “real-time” phase. Moreover, it allowed to collect the participants’ view on what might limit the adoption of ecPoint-Rainfall forecasts in operational environments in their NHMSs. An “informal discussion” approach was chosen as opposed to other more structured interview formats. Informal discussions can help interviewers to put respondents at ease and do not inhibit or constrain their comments about the topic of the discussion (Harding 2018). The informal discussions were conducted over three main steps.

The first step consisted in a three-hours videocall discussion between the intermediaries and the ecPoint experts. The videocalls were conducted on each NHMS in turn. The conversation was guided by a list of open-ended questions (see Appendix A), which was sent to the intermediaries one week before the videocall. This was to stimulate the conversation whilst at the same allowing the discussion of critical topics for the participants to arise naturally (Harding 2018). The list of open-ended questions was structured in two main sections. The first section focused on formalizing the ecPoint experts’ pre-existing understanding pf the participants’ experience in areas such as probabilistic forecasting and statistical post-processing. The aim was to understand the context under which forecasters at IMN and OMSZ formulate generally their predictions for extreme (localized) rainfall events. This background information is presented in section 4, ahead of the results section, in order to put the outcomes of the experiment in a more meaningful context. The second section focused mainly on the content of the reports sent to ECMWF at the end of the “real-time” phase. The aim was to understand what the participants thought about the ecPoint-Rainfall performance, its perceived usefulness, and the guidelines provided the beginning of the “real-time” phase.

When the first concluded, a second step consisted in highlighting the similarities and differences in the participants answers during the informal discussions to identify new products and recommendations for guidelines that are tailored to the user needs. This step was conducted only by ecPoint experts. The main aspects that were of interest for were:

* Were there any similarities/differences in the approaches taken when using ecPoint-Rainfall forecasts? For example, did they consider similar percentiles? Would they decide to act upon similar probabilities of exceeding a certain threshold?
* Did the approaches taken by the participants were influenced by training provided at the beginning of the “real-time” phase, or they were influenced also by the participants’ experience with probabilistic forecasts?
* Were there any similarities/differences in the ecPoint-Rainfall products used/developed by the participants?

The outcomes of this analysis would allow ecPoint experts to create sets of tailored ecPoint-Rainfall according to participants’ needs. Moreover, such outcomes would also allow ecPoint experts to produce ecPoint-Rainfall guidelines that are more tailored to the participants’ needs.

The third step consisted in sending via email to the participants the new set of tailored products and guidelines to understand whether they might have found the new products and guidelines more aligned with their needs. The intermediaries were asked to provide a brief statement on whether they might have revised their conclusions in the report provided at the end of the “real-time” phase. The statement should include the answers to the following points:

* Would you change your initial forecast/verification results?
* If a case study was analysed, would you change the level of warning respect to your initial forecast?
* Do you think the revised products and correspondent guidelines are more useful than those provided at the beginning of the “real-time” phase?

The outcomes of the “offline” phase are summarized in two parts. The results from the “informal discussions” are presented in section 5.c. The “new set of user-tailored products and guidelines for ecPoint-Rainfall forecasts, and participants reactions” are presented in section 5.d.

# Pilot study background

This section provides background information on the NHMSs and their way to provide guidance for extreme (localized) rainfall in order to put the outcomes of the experiment in a more meaningful context.

## Instituto Meteorológico de Costa Rica (IMN, Costa Rica)

### Rainfall climatology

The climate of Costa Rica is mainly tropical. The mountains that run in a northwest-southeast direction split Costa Rica into two regions, Pacific and Caribbean, with their own rainfall regime. In the Pacific region, the wettest and the driest periods go from May to October and from December to March, respectively, being April and November transition periods. The Caribbean region is much wetter than the Pacific region, and it has not a defined wet season. However, the relatively wettest months are November to January and May to August. These two regions and their prevailing winds, the height and the orientation of the mountains, as well as the influence of the Pacific and Atlantic ocean divide Costa Rica into seven main climatic regions: Región Pacifico Norte, Central and Sur, Zona Norte, Valle Central and Región Caribe Norte and Sur (see Fig. 3a). Extreme rainfall events differ from region and time of year (see Fig. 3e). Extreme rainfall produced by cold fronts coming from the northern hemisphere affect typically the regions Zona Norte, Caribe Norte, Caribe Sur, and the eastern part of Valle Central, mainly between December-March. Extreme rainfall produced by low-pressure systems coming from the equatorial Pacific Ocean affect typically the regions Pacífico Norte, Pacífico Central, Pacífico Sur and the western part of Valle Central all year round. Hurricanes affect mainly the Pacific region due to winds circulation despite forming in the Caribbean Sea. They are typically observed between June and November and can generate rainfall events that last for several hours or days, accumulating large amounts of rain and generating severe riverine floods. Finally, all these three weather systems can then interact with the complex Costa Rican orography (see Fig. 3c) enhancing the rainfall amounts or producing severe localized storms which might generate severe flash floods.

### How extreme (localized) rainfall is predicted

Extreme (localized) rainfall predictions at IMN rely substantially on the examination of real-time observations of rainfall, river discharge and soil conditions, as they help experts to evaluate the impact that a certain rainfall event might have:

“Forecasts at IMN rely typically 60% on NWP guidance, and 40% on human expertise, also supported by research. Such expertise can provide more detailed information on the nature of the phenomenon affecting us (e.g. a cold front does not produce the same impact of a tropical wave), on which are the most vulnerable regions of the country and what is their state (e.g. if it has been raining in previous days and catchments are saturated, etc.)”

When IMN forecasters look at NWP model guidance, forecasts from global models are not used much:

“Costa Rica is a small country with complex orography. Global models have a too coarse spatial resolution to represent the details of the spatial variation of rainfall events, even more in Costa Rica. Furthermore, they parametrize convection and the rainfall values might not be correct. At occasions we will look at the GFS [Global Forecast System, developed by the National Centers for Environmental Prediction in the USA], and now we also have access [from 2018] to the IFS [Integrated Forecasting System from ECMWF] but our forecasters tend to rely mainly on guidance from our high-resolution models.”

From the Weather Research and Forecasting (WRF) system, IMN has developed a series of model versions (WRF-1.5, WRF-5, WRF-AR, WRF-Sarapiquí, WRF, WRF-8, WRF-15) with different spatial/temporal resolutions, domains, and model configurations to tailor their use for specific hazards (e.g. tropical waves, tropical cyclones, cold fronts, hail, and forest fires). For example, WRF-1.5, developed in 2018, produces forecasts at 1.5 km resolution, up to 5 days, and aims to improve predictions for convective systems which can produce extreme localized rainfall events.

Even if we [forecasters at IMN] know that sometimes the model can overestimate a lot the rainfall (we are talking sometimes of rainfall forecasts 40% times higher than what observed), the rainfall distributions are much better than the global models and the ecPoint-Rainfall [the intermediary referred to the product developed by them using the 85th percentile of ecPoint-Rainfall]. We [forecasters at IMN] know from experience that we just need to multiply the forecasts values from our deterministic model of a factor of 0.4.”

These models are, however, mainly deterministic:

“95% of predictions at IMN are created using deterministic guidance, and only 5% derives from probabilistic models.”

Although the main focus is in deterministic models, IMN forecaster are trained also to use and understand ensemble model outputs:

“50% of forecasters have attended the NOAA’s Weather Prediction Centre International Tropical Desk, training in weather and climate forecasting for the Americas. Other forecasters have attended other training centres over the years.”

## Országos Meteorológiai Szolgálat (OMSZ, Hungary)

### Rainfall climatology

Hungary is located at the centre of the Carpathian basin. About two thirds of the country is flat, and the rest is mainly hilly (see Fig. 3d). Peaks are all below 1000 m, except for the Kékes peak (1014 m) located in the Mátra mountains, in the “Heves” county (see Fig. 3b). The climate of Hungary is mainly warm continental, and it is influenced by three main different climates: continental from the northeast, oceanic from the northwest, and Mediterranean from southwest. Such influences make average rainfall vary in space and time (see Fig. 3f). May to September is the convective season, in which daily precipitation extremes can often exceeded 100 mm/day. June is often the wettest month, whilst February is the driest. The wettest areas in Hungary (> 850 mm, annual average) coincide with the hilliest parts of the country, mainly in the southwest (Vas, Zala, Veszprém, Somogy, and Baranya counties), and in the northeast (Pest, Nógrád, Heves and Borsod-Abaúj-Zemplén counties). On the contrary, the driest areas (< 500 mm, annual average) coincide with the flattest parts of the country in the southeast (Southern and Northern Great Plain), except for the east part of the Szaboics-Szatmár-Bereg county. In Hungary, extreme precipitation events are connected to large scale systems (e.g. cyclones, squall lines or cold fronts). However, local influences of the orography can enhance the rainfall amounts or produce severe localized storms. In certain occasions, small differences in the orography (e.g. 100-250 m) can be enough to trigger localized extreme rainfall in Hungary.

### How extreme (localized) rainfall is predicted

OMSZ has a long-standing experience (since the 1990s) in developing, using, and verifying ensemble model outputs:

*“At OMSZ, extreme rainfall predictions are mostly generated and disseminated to the public using ensembles. Forecasters would typically look at a suite of ensemble models, including AROME [with 2.5 km horizontal resolution], ALADIN [with 8 km horizontal resolution], and ECMWF ensemble [ENS, with 18 km horizontal resolution] and ECMWF high resolution [HRES, 9km horizontal resolution].”*

OMSZ forecasters also take part regularly in educational and training programmes at ECMWF to keep updated on the developments done to the ECMWF ENS and HRES and improve the use of probabilistic products.

OMSZ is also experienced in rainfall post-processing, which is regularly used at OMSZ to add value to forecasts for small-scale, low-predictability phenomena like extreme localized rainfall (Matrai and Ihász 2017; Ihász et al. 2018).

# Results

## From “real-time” phase: products developed from ecPoint-Rainfall

### Instituto Meteorológico de Costa Rica (IMN, Costa Rica)

IMN developed a product based on ecPoint-Rainfall which consists in a map plot displaying the ecPoint-Rainfall 85th percentile (Fig. 4a). IMN reported that it was not conducted a specific study to choose that specific percentile. They reported that, based on past experienced, the 85th percentile would have probably provided a “*balanced*” forecast, avoiding overestimations.

### Országos Meteorológiai Szolgálat (OMSZ, Hungary)

OMSZ created two products from ecPoint Rainfall. The first one is a meteogram (Fig. 4b) that displays 12-hourly precipitation from the ECMWF ENS in blue and ecPoint-Rainfall in orange (first panel), rate of convective precipitation ratio (second panel), 700 hPa wind speed (third panel), and CAPE (fourth panel) from ECMWF ENS. The second, third and fourth panel represent the values of three out of the five predictors used in the 12-hourly post-processed rainfall. The second product consists in a map plot that displays the 90th (top number), 75th, 50th, 25th and 10th (bottom number) percentiles for ecPoint-Rainfall for each grid box (of 0.5 degree resolution).

## From “real-time” phase: independent verification of ecPoint-Rainfall

### Instituto Meteorológico de Costa Rica (IMN, Costa Rica)

Whilst IMN had access to one year of forecasts, they decided to illustrate their feedback using one case study.

IMN chose an extreme rainfall event occurred between October 3rd and 5th, 2018 to evaluate the performance of ecPoint-Rainfall in predicting extreme localize rainfall events. A trough evolved into an almost stationary low pressure over the Caribbean Sea, generating extreme rainfall in Region Pacifico Norte (especially in the Nicoya Peninsula), Pacifico Central and Pacifico Sur. On October 3rd the Nicoya Peninsula was badly affected, especially near the coast with values up to 140 mm/24h. High rainfall totals were also observed in Region Pacifico Central and Sur. The most intense rainfall was observed on October 4th reaching 400 mm/24h in the south of the Nicoya peninsula, 200 mm/24h in the Region Pacifico Central, and 90 mm/24h in Region Pacifico Sur. On October 6th Costa Rica was out of the influence of the low-pressure system as it moved northwards. See 12-hourly rainfall observations for the event in Fig. 5a-f. The rainfall event caused severe flash floods and local landslides, generating severe widespread impacts: one person died, hundreds were moved to refuges, and around 1500 people were somehow affected, for example by electricity or water service interruption or road closures.

Forecasts (from the ecPoint-Rainfall product developed at IMN) from day 1 to 7 were used to evaluate both short and medium range forecasts (see Fig. 6, first column). IMN used only 12 UTC runs for ecPoint-Rainfall as those were the only ones usable for daily warnings considered the time difference between Europe and Central America (UTC-6). IMN’s conclusions on the performance of ecPoint-Rainfall for this case study can be summarized in the following main points:

* “ecPoint-Rainfall predicted well the beginning and the end of the rainfall event in every run from September 27th.”
* “On October 4th, ecPoint-Rainfall pointed out that Región Pacifico Central and Pacifico Sur would have been the most impacted areas, underestimating the rainfall amounts in Región Pacifico Norte, especially in the Nicoya peninsula where totals of up to 400 mm/24h were observed. No ecPoint-Rainfall forecasts [based on the 85th percentile of ecPoint-Rainfall] reached such totals. Only the run on October 4th predicted values higher than 100 mm/12h.”
* “Most runs [based on the 85th percentile of ecPoint-Rainfall] predicted with one day of delay [October 5th] the wettest day, which was October 4th instead.”

### Országos Meteorológiai Szolgálat (OMSZ, Hungary)

OMSZ provided two different verification studies for the ecPoint-Rainfall forecasts, subsequently published by Tóth and Ihász (2021). The first study consisted in an objective verification that analysed ecPoint-Rainfall reliability and ability to predict extreme (localized) rainfall events. The aim was to investigate what set of ecPoint-Rainfall percentiles would provide a better forecast for extreme (localized) rainfall events. The second study consisted in a subjective verification that aims to show, via a case study, how ecPoint-Rainfall forecasts could be used operationally by OMSZ forecasters.

#### Objective verification - ecPoint-Rainfall reliability

This analysis was run using ecPoint-Rainfall forecasts for the period between 1st June and 31st August 2018.

“This verification period was chosen because rainfall events in Hungary are mainly generated by convection during summertime. Since convective rainfall is difficult to predict with NWP models, especially global models, we thought it could be a good test for ecPoint-Rainfall and see whether it could improve the prediction of such events.”

Forecasts from the 00 UTC run were used. Finally, only the accumulation periods finishing at 00 and 12 UTC were used.

“In our domain, these two accumulation periods distinguish between rainfall fallen in morning or afternoon hours. We want to distinguish between these two day times because, in our experience, convective rainfall in afternoon hours can be problematic for NWP models to handle.”

The verification analysis extended to forecasts up to t+108 (i.e. day 4).

“We decided to stop our verification at t+108 because this is the max lead time OMSZ forecasters provide early warnings.”

12-hourly rainfall observations from 310 rain gauges (Fig.7a), provided by the Hungarian Meteorological Service Unit of Informatics Applications, were also used. Each rain gauge was assigned to the closest model grid-box. The aim was to have only one observation per model grid-box. This approach was possible because the number of rain gauges was similar to the number of grid-boxes covering the Hungarian domain.

“We took this approach because rainfall observations should be more representative of the forecast provided by their closest model grid-box.”

The majority of the grid-boxes contained only one rain gauge. Only 3% of grid-boxes contained more than one observation or no observations. In this case, the rain gauges that were not the closest to the model grid-box were distributed to near model grid-boxes with no observations provided that the distance was not exceeding 0.25 degrees (i.e. ~27 km). Due to the coverage of the observational network in Hungary (see Fig.7a), and the resolution of the ecPoint-Rainfall forecasts, each model grid-box had one rain gauge assigned, and all rain gauges were used. No interpolation of the point rainfall observations was operated during the assignment process.

OMSZ used the Talagrand diagram to evaluate the reliability of ecPoint-Rainfall forecasts. A Talagrand diagram represents the distribution of the probabilities of occurrence of each ensemble member. An ensemble is reliable if such distribution is uniform (i.e. flat), namely each member is equally-probable, with a probability of occurrence of

|  |  |
| --- | --- |
| p = 100 / x | (1) |
| x = (n. of ensemble member – 1) + 2 | (2) |

In the case of ecPoint-Rainfall, each member (represented by 99 percentiles) should have 1% probability of occurrence, whilst each of the 51 ECMWF ENS members should have ~2% probability of occurrence. If the Talagrand diagram has an L or J shape, the ensemble forecast system presents systematic errors of overestimation of the smallest rainfall values and errors of underestimation of the highest rainfall values, respectively. If the Talagrand diagram has a U shape, the observed rainfall values are mostly outside the ensemble spread.

Fig. 7b shows the Talagrand diagrams for ecPoint-Rainfall and ECMWF ENS at day 1 (accumulation period ending at t+12) and day 4 (accumulation period ending at t+108) for rainfall events greater than 0 mm/12h. The Talagrand diagram for ecPoint-Rainfall have been created with a similar number of bars of the diagram for ECMWF ENS (i.e. 50 and 52 bars, respectively) for an easier comparison. The values of adjacent bars in the ecPoint-Rainfall diagram were added up, which means that each pair of values should correspond to 2% of probabilities of occurrence in case of perfect reliability.

“In the report, we created the Talagrand diagram for dry and rainy points to show that ecPoint-Rainfall forecasts are reliable in general and not only in case extreme events.

The flatter Talagrand diagrams for ecPoint-Rainfall suggest that it provides more reliable forecasts than ECMWF ENS. The Talagrand diagram for ENS has a clear L shape, suggesting an overestimation of small rainfall values and an underestimation of the highest. However, ecPoint-Rainfall members show probabilities of occurrence between 2 and 4 %, suggesting low systematic failures in their reliability.”

#### Objective verification – ecPoint-Rainfall ability to predict extreme (localized) rainfall events

OMSZ developed a new verification methodology to estimate the ability of ecPoint-Rainfall forecasts to predict extreme (localized) rainfall. They used the same rainfall forecasts and observations of those used to study the reliability of ecPoint. They also used the same algorithm to assign the rainfall observations to each model grid-box.

For each grid-box, at a given day, the rainfall forecasts and observations were compared. When both forecast and observation exceeded or not exceeded a rainfall threshold Y (in mm/12h), the value 1 and 0 was assigned to the grid-box, respectively. Otherwise, the value -1 was assigned. To summarize the results in one map for the whole verification period, the daily indices were added up. Therefore, forecasts in regions with overall zero or positive values provided performed well, whilst regions with overall negative values showed an underestimation or an overestimation of the rainfall observations.

The following assumptions were considered in the calculation of the statistic. Since a forecast can be accepted even if it predicts extreme precipitation amounts few grid-boxes away, the forecasts were compared to observations covering a wider area of 3 grid-lengths in each direction. Moreover, in the early warning system at OMSZ there are three levels of alert: yellow for 20 mm/24h, orange for 30 mm/24h, and red for 50 mm/24h. It was not possible to use the same 24-hourly thresholds as the ecPoint-Rainfall forecasts were provided in 12-hourly accumulations. Therefore, OMSZ estimated that 15 mm/12h could represent an extreme rainfall event for Hungary. Finally, the 50th, 70th, 85th, 95th, and 99th percentiles were tested as they are typically used by forecasters at OMSZ to predict extreme rainfall events in Hungary.

Map plots for the 85th and the 95th percentile are shown in Fig. 7c.

*“The results show that, excluding the Great Plain regions, ecPoint-Rainfall performance quite well in the prediction of extreme rainfall events. The 95th percentile forecasts higher rainfall values than the 85th percentile. Therefore, the number of times the forecasts from the 95th percentile exceeds the rainfall threshold can be higher. Hence, it is not a surprise that the map for the 95th percentile presents higher scores. To conclude, the spread of the ecPoint-Rainfall forecast can inform the forecasters of the likelihood of extreme events.*

*However, it is worth highlighting that higher percentiles often overestimate the real rainfall observations.”*

OMSZ looked also at the extent of under- and overestimation of ecPoint-Rainfall forecasts. Again, for each model grid-box, the rainfall forecasts and observations were compared for a given day. However, this time the value 0 was assigned to the grid-box when both the forecast and the observation exceeded or not exceed the rainfall threshold; the value 1 was assigned when the observation was below the rainfall threshold whilst the forecast exceeded it (i.e. overestimation of the observations); the value -1 was assigned otherwise (i.e. underestimation).

Map plots for the 85th and the 95th percentile are shown in Fig.7d.

“The results show that the ecPoint-Rainfall 85th percentile provides the most accurate prediction of extreme rainfall events, whilst the higher percentiles overestimated the actual measured values. Indeed, the map related to the 85th percentiles is mainly white, while the map related to the 95th percentile is dominated by the orange colour, reflecting a systematic overestimation of the ecPoint-Rainfall forecasts.”

#### Case Study

In their second analysis, OMSZ examined a rainfall event occurred between 12 UTC on 10th June and 12 UTC on 11th June 2018, which caused severe impacts including flash floods in the whole Bükk area, especially in Szilvásvárad, in the Heves county (Tóth and Ihász 2021). On the morning of 10th June, a low-pressure system over Turkey moved gradually northwards. Its interaction with the Northern Central Mountains in Hungary (which include the Mátra and the Bükk mountains, see Fig.1d) made the atmospheric conditions more unstable over the afternoon, favouring a strong cumulonimbus formation over the Bükk area. The slow-moving system did not move from the general Bükk area for hours, generating very localized high rainfall amounts in places. In Bükkszentlélek (~10km east from Szilvásvárad, purple circle with a cross in Fig. 8a) was recorded the highest amount of the rainfall event, 92 mm/24h (however, the majority of the rain fell on 11th June, between 0 and 12 UTC).

Such events occur rarely in Hungary, approximately every 10-20 years, and are challenging to forecast even with km-scale NWP models. ecPoint-Rainfall probabilities (in %) of not exceeding 10 and 30 mm/12h for day 2 (Fig. 8b and Fig. 8d, respectively) and day 4 (Fig. 8c and Fig. 8e, respectively) were evaluated. OMSZ’s conclusions on the performance of ecPoint-Rainfall for this case study can be summarized in the following main points:

* “Based on the ecPoint-Rainfall forecasts, high rainfall amounts were expected in the Bükk area.
* The map for probabilities of not exceeding 30 mm/12h outlines well ~~nicely~~ where the local precipitation is likely to occur.
* Although the probabilities of not exceeding 30 mm/12h are relatively low [between 1 and 3%], this information is very important for forecasters. ecPoint-Rainfall could be a consequential tool for the early detection of such localized extreme rainfall events.”

## From “offline” phase: informal discussions

### IMN: on the selection of the 85th percentile for ecPoint-Rainfall forecasts to predict extreme (localized) rainfall

IMN reported that the 85th percentile was selected to predict extreme rainfall events because it looked a reasonable option. Higher percentiles (>95th percentile) were showing much higher rainfall values than the 85th percentile. Thus, IMN forecasters were afraid to overlook much more frequent events that can already cause impacts in some regions:

“Events of around 50 mm/12h can already cause some impacts on the Pacific coast of Costa Rica or in the capital city, San José. Those events are relatively frequent. If we only look at the 99th percentile, we will miss many more frequent events. The 85th percentile seemed to us a more reasonable choice.”

Two main objections may rise. First, by looking only at the 85th percentile, which would forecast events that have, on average, a 1 in 7 chance to occur, forecasters might not be aware of what could be the possible worst localized rainfall event that could be observed in the region, that from now on will be referred to as the “worst-case scenario”. Second, in the ecPoint experts’ experience examining different extreme rainfall cases around the world, the raw ENS and ecPoint-Rainfall’s CDFs tend to cross around the 85th percentile. This can be seen also for the case study presented by IMN, by comparing the forecasts of the 85th percentile of ecPoint-Rainfall (first column) and the 85th percentile of the Raw ENS (second column) in Fig. 6. This means that by using the 85th percentile of ecPoint-Rainfall, users will not be making the most of the post-processed product.

Recommended guidelines and mock-up products are presented in section 5.d.1.

### IMN: on the underestimation of rainfall values by ecPoint-Rainfall

The observed rainfall patterns in the rainfall events between October 3rd and 5th (Fig. 5) typify a low-probability high-impact event with high spatial variability of rainfall totals and very localized extremes. As described by the intermediaries in section 4.4.2, forecasters at IMN tend to not look at global NWP model to forecasts these type of rainfall events. From the informal discussions, it transpired that, even if IMN forecasters used ecPoint-Rainfall to forecasts extreme (localized) rainfall events, ecPoint-Rainfall was included in the category of forecasts from global NWP models. For this reason, forecasters were not particularly surprised when they saw that the forecasts underestimated the highest rainfall observations.

“ecPoint-Rainfall has an 18 km resolution. That is too coarse. Global models do not handle convection properly, and do not represent the real orography. To forecast localized rainfall in Costa Rica, which is a small country with complex orography, we need very high resolution forecasts, otherwise the forecasts do not reach the observed values.”

The intermediaries provided the forecasts from WRF-1.5, typically used at IMN to forecast extreme (localized) rainfall events (shown in Fig. 6, last column) to demonstrate that km-scale models (in this case, of 1.5 km spatial resolution) are better at forecasting these type of rainfall events than global models.

One objection may arise, and it is connected to the content of the previous section. The fact that ecPoint-Rainfall did not show forecasts of the same magnitude of the observed rainfall totals, it was not because the ecPoint-Rainfall has the same problems of global NWP models regarding the underestimation of extreme (localized) rainfall events. It was due to the fact that the 85th percentile was used.

The assumption that ecPoint-Rainfall provide rainfall forecasts on the same spatial scale of the ECMWF ENS (because both are provided in grids of the same spatial resolution) is not correct. The ecPoint methodology will always provide forecasts on the same grid of the raw model, but their scales will be completely different: ecPoint-Rainfall will provide forecasts at point scale, and the raw model will provide average forecasts at its grid scale.

Recommended guidelines and mock-up products are presented in section 5.d.2.

### IMN: on the misplacement of the wettest day

IMN reported that the wettest day was October 4th because the observations recorded the rainfall peak (309.2 mm/12h) on that day. It was also reported that the 85th percentile of ecPoint-Rainfall indicated that October 5th would have been the wettest day instead, i.e. the day with the highest rainfall observation. Two main objections can be done.

First, the rainfall totals are more uniformly distributed over the Nicoya peninsula on October 5th (Fig. 5e) than on October 4th when there was much more variability in the rainfall totals (there are very small rainfall totals, although the rainfall peak (309.2 mm) was recorded on October 4th (Fig. 5d). Therefore, the average rainfall is higher on October 5th than October 4th. Since IMN used the 85th percentile for ecPoint-Rainfall, and as it was highlighted in section 5.c.1, the rainfall distributions of ecPoint-Rainfall and ENS tend to cross at such percentile, IMN saw what they would have seen inspecting the ECMWF ENS, i.e. that, on average, the Nicoya peninsula would have been wetter on October 5th than on October 4th. Therefore, IMN arrived at the right conclusion (i.e. predicting that October 5th would have been wetter) but from wrong premises (i.e. expecting to see the highest rainfall peak on October 5th). No information could have been provided by the 85th percentile of ecPoint-Rainfall on the worst-case scenario rainfall and on the expected sub-grid variability. To identify the worst-case scenario rainfall, it would have been more appropriate to look at much higher percentiles, as highlighted in sections 5.c1 and 5.c.2. Instead, to get an idea on the potential rainfall sub-grid variability, it would have been more appropriate to look at the rainfall distributions provided by the weather types for each ensemble member (Fig. 1b, single distributions). At very short lead times (i.e. day 1 or 2) when the ensemble members tend to be very similar to each other, the merge rainfall distribution provided (Fig. 1b, merged distribution) could be representative of the most likely rainfall sub-grid variability.

Second, the verification of extreme localized rainfall events in small regions is difficult. Only part of the sub-grid scale variability of the precipitation field can be known from observations, and the recording of local peaks can be a matter of chance. Denser observational networks or reliable radar-derived rainfall totals would provide a better representation of the rainfall sub-grid variability in small regions (Haiden and Duffy 2016), and unfortunately they are vital for the evaluation of ecPoint-Rainfall in the prediction of extreme localized rainfall events in small regions. Costa Rica has a good observational network. However, there are some uncovered spots, where could have been observed a higher peak on October 5th but it was simply not recorded because there was no rain gauge. Therefore, no deterministic conclusions can be drawn about ecPoint-Rainfall placing correctly the wettest day. Such information should be seen either over a much longer period of time or over a much bigger region, so the effects of the random measurement of rainfall extremes can be counterbalanced by the bigger number of cases examined.

Recommended guidelines and mock-up products are presented in section 5.d.3.

### OMSZ: on the methodology developed to define an ecPoint-Rainfall percentile to provide guidance for extreme (localized) rainfall

OMSZ developed a methodology (described in section 5.b.2.i and 5.b.2.ii.) to define an ecPoint-Rainfall percentile to provide guidance for extreme (localized) rainfall. Three main comments were risen with OMSZ.

First, the methodology is based on assigning one observation to the nearest model grid-box. It was assumed that the closer the observation to the model grid-box, the more representative the observation is of the forecast provided for that grid-box. This assumption could be relevant for traditional NWP model outputs, where the model grid-box forecast represents a rainfall average over the grid-box. In the case of ecPoint-Rainfall, the verification is much simpler. By construction, ecPoint-Rainfall mirrors what is provided by rain gauges, i.e. point rainfall observations. Therefore, it is more correct to compute any verification statistic using point rainfall observations and the forecasts from the nearest model grid-box.

Second, the verification methodology uses a box of 3X3 model grid-boxes to assess whether the forecasts provided a good guidance compared to observations. This is another very common technique used for the verification of traditional NWP model outputs. This approach is usually considered due to the need to compensate for the lack of ensemble members. This is not the case for ecPoint-Rainfall which, by construction, already expands the number of ensemble members for each raw member (see Fig. 1b).

Third, the verification methodology tries to identify which percentile could be used to provide guidelines on extreme (localized) rainfall events, which OMSZ identified as an event exceeding 15 mm/12h. OMSZ found that the 85th percentile provided the best performance as there is no under- or overestimation of the rainfall events exceeding 15 mm/12h (see Fig. 7d). First, one can say that this methodology employs the probabilistic information provided by ecPoint-Rainfall (or any other ensemble forecast) in a deterministic way as it defines a point in a two dimensional space (given by the combination of a percentile and a rainfall threshold), allowing only for a yes or not answer to the question “Did the X percentile exceed Y rainfall threshold?”. Whilst this approach can be useful at the early warning stages to identify the locations that could be affected by extreme (localized) rainfall, it would not exploit all the information contained in the full ecPoint-Rainfall distribution which could suggest different actions based on the impacts of the different probability structures of exceeding a rainfall threshold. Fig. 9 conceptualizes this aspect. The CDF (A) represents a typical convective rainfall event that would satisfy the criterion to issue a warning for extreme (localized) rainfall. Whilst the CDFs (B), (C), and (D) would also satisfy this criterion (i.e. 15 mm/12h are obtained at smaller percentiles than the 85th), they have different probability structures for rainfall values greater than 15 mm/12h. For example, (B) does not show any probabilities of having a rainfall event much higher than 15 mm/12h , while (D), although is very similar to (B) around the 85th percentile, it shows some (although small) probabilities of having a much more extreme (localized) rainfall event. This is an extremely important information for a forecaster because the impacts of the rainfall event in (D) can be much higher than those for the rainfall event represented by (B), even if the probabilities are very small (i.e. around 1 or 2%). The CDF (C) represents another possible rainfall event, this time with high probabilities of having much more rainfall on average at the grid-box scale than (B) and (D), although the tail is not as big as the tail in (D). Finally, the CDF (E) represents an event that would have not triggered any warning. However, it shows some chance to observe a very extreme (localized) rainfall event, and therefore its impacts could be severe. All this information would be lost if considering only one percentile and one rainfall threshold. Second, the verification methodology that brings to the conclusions that the 85th percentile provides the best guidance for extreme (localized) rainfall is wrong. The methodology still looks at the reliability of ecPoint-Rainfall forecasts, but it should not include the information about a rainfall event. The answer to the question which percentile is more reliable is simple. A forecast is reliable if, for an Xth percentile, (100-X)% of the times the observations exceed the forecasts at a location. Therefore, not only one percentile is reliable, all of them should be reliable. See Fig. 10 which shows that ecPoint-Rainfall 95th and 99th percentiles are reliable.

Recommended guidelines and mock-up products are presented in section 5.d.4.

## From “offline” phase: new set of user-tailored products and guidelines for ecPoint-Rainfall forecasts, and participants reactions

### Forecasting non-extreme events that can generate some impacts

This section relates to the issue presented in section 5.c.1.

#### General user-case

A user might want to forecast a rainfall event that, although it is not particularly extreme, it can already generate some impacts in the region of interest. However, at the same time, the user might still want to know what could be a possible “worst-case scenario”. This user-case could be experienced in regions with some protection that, however, were not designed for very extreme hazards (e.g. an event with 1 in 3 or 7 chance to be observed). In this case, the user might be inclined to analyse a map plot for the 70th or the 85th percentiles.

#### General recommended guidelines

It is suggested to combine (1) a map plot that shows the spatial distribution of probabilities of not exceeding a rainfall threshold, and (2) a map plot for a high percentile. The first one will provide the user with an idea on how likely it is to observe the event of interest. However, it will not provide any information on whether higher events are also likely to be observed, and with which likelihood. This information will be instead provided by the second product. The rainfall threshold is provided by the experience of the local forecasters who know what is the rainfall event that can generate some impacts in the region of interest. Furthermore, if the region of interest is big and rainfall events of different magnitude can generate impacts, the user can generate as many maps as the number of rainfall events. For the value of the percentile to choose, it is recommended to use the 98th or the 99th percentile to have an idea on what could the possible “worst-case scenario”. However, this is a choice that involves the level of warning at which the NHMS would act. If the NMHS requires at least 10% or 5% of probabilities of exceeding a certain rainfall value to act, the NMHS would then decide to use the 90th or the 95th percentile, respectively. However, they are not likely to provide the user with a picture of the possible “worst-case scenario”.

#### Mock-up product example and IMN reaction

The mock-up product (Fig. 11) refers to the IMN case study discussed in section 5.b.1. IMN was presented with a map plot of probabilities of not exceeding 50 mm/12h (which can generate impacts in the Pacific coast of Costa Rica as pointed out by the IMN intermediary). Moreover, a map plot of the 99th percentile (i.e. events with 1 in 100 chance to occur) was also presented to assess the magnitude of the possible “worst-case scenario” in the region.

“This product could help us to forecast an event that can already generate an impact in the Pacific coast but at the same time, have an idea what could be the local maxima. For example, the Nicoya peninsula was affected by much higher rainfall, but we did not have any idea of the possible amount by looking at the 85th percentile. In this way it is better.”

### Forecasting the “worst-case scenario”

This section is related to the issue presented in section 5.c.2.

#### General user-case

A user might want to know what could be the magnitude of the highest rainfall that could be possibly observed, i.e. the worst-case scenario.

#### General recommended guidelines

A vital information to convey to users is that, although ecPoint-Rainfall and raw ENS are provided with the same grid resolution, they do not refer to the same spatial scale. It should be stressed that raw ENS (as any other NWP model) provides rainfall averages over the grid-box and ecPoint-Rainfall provides point-wise probabilistic rainfall forecasts at a location within a grid-box, even though ecPoint-Rainfall does not provide any information on where that point is within the grid-box. In particular, the post-processing technique aims to anticipate sub-grid variability and provide a wider distribution of equiprobable values that ideally captures in its tail those extreme events typically missed by global models. For this reason, ecPoint-Rainfall is particularly useful to providing guidance for events like those occurred in Costa Rica at the beginning of October. Such extreme events have a low probability of occurrence, and using a product based on the 85th percentile (~ 1 in 7 chance) suggests that ECMWF did not convey properly the message that percentiles below the 95th (1 in 20 chance) are usually not so well suited to providing guidance on low-probability high-impact events. During the dialogue with the forecasters, it was recommended to use the 98th (1 in 50 chance) or the 99th (1 in 100 chance) percentiles to identify the areas at most risk of extreme localized rainfall. The third and the fourth column in Fig. 6 show, respectively, the 99th percentile of ecPoint-Rainfall and the wettest member of the raw ENS for the rainfall observed on October 5th between 0 am and 12 am. ecPoint-Rainfall provides from day 4 a more consistent guidance on the location of the areas at most risk of localized extreme rainfall, i.e. the whole Pacific coast (including the Nicoya peninsula), with a better signal on the actual observed values from day 2 (i.e. better location and magnitude of the extreme rainfall event). On the contrary, the raw ENS and WRF-1.5 provide a noisier and jumpier signal Furthermore, the raw ENS underestimated the rainfall observations of ~50\% also at day 1, whilst WRF-1.5 overestimated the observed rainfall values.

#### Mock-up product example and IMN reaction

The mock-up product (Fig. 6, 3rd column) refers to the IMN case study discussed in section 5.b.1. IMN was presented with the map plots of the 99th percentile to show that ecPoint-Rainfall forecasted the extreme rainfall event in the Nicoya peninsula.

“The map plots for the 99th percentile provides forecasts that are very similar to the rainfall amounts shown on our WRF-1.5, and it is easy to interpret the two outputs in the same way. However, we realize now they are not. Focusing this difference in the documentation is important to avoid misinterpretations of the forecasts.”

### Forecasting the possible wettest day in a multi-day event

This section is related to the issue presented in section 5.c.3.

#### General user-case

A user might want to know what the wettest day could be within a multi-day rainfall event. With wettest day it is intended the day with the highest localized rainfall observation.

#### General recommended guidelines

It is suggested to look at the whole rainfall distribution (e.g. 99 percentiles for ecPoint-Rainfall), in a CDF format, for different forecasts. First, the spread of the CDF will allow to identify the range of rainfall values that could be observed. Second, the shape of the CDF will allow to identify what rainfall values are more likely to be observed. For example, a CDF with a more vertical shape would typically indicate a more confident forecast.

#### Mock-up product example and IMN reaction

CDFs for ecPoint-Rainfall (in blue) and raw ENS (in red), representative of the rainfall values in the south coast and inland parts of the Nicoya peninsula on October 4th and 5th are presented in Fig. 12a-d. The conclusions that can be drawn from the comparison of the CDFs are twofold and are related to the spatial scale that ecPoint-Rainfall and the raw ENS refer to.

First, the raw ENS CDFs suggest that a big range of (grid-scale) rainfall totals (from 0 to 200 mm/12h) could be observed over the Nicoya peninsula on both days. However, a bigger area to the left of the raw ENS CDF (which is proportional to the ensemble mean), for both coast and inland parts of the peninsula, suggests that bigger rainfall averages at grid-scale should be expected on October 5th rather than on October 4th. This is supported in the observations (Fig. 5d and Fig. 5e).

Second, ecPoint-Rainfall CDFs suggest that the rainfall variability at point-scale can be much higher (from 0 to 450 mm/12h) than the one observed at grid-scale. So, even if with low probabilities (e.g. 1% or 2%), severe localized events could be observed in the Nicoya peninsula, either on October 4th or 5th. However, ecPoint-Rainfall CDFs suggest that the probabilities of having an extreme localized event is very similar on both days. Therefore, on the basis of the CDFs no conclusion could be drawn on which day could be the wettest, and the fact that the highest rainfall peak was observed on October 4th instead than on October 5th could be a only matter of chance. If the observational network would have been denser, perhaps, it would have captured a higher peak on October 5th.

### Defining a strategy to provide guidance on extreme (localized) rainfall events

This section is related to the issue presented in section 5.c.4.

#### General user case

A user might want to define a strategy to provide guidance on extreme (localize) rainfall events from ecPoint-Rainfall. However, not knowing the new product, the user might want to experiment with the forecasts before deciding on the best strategy.

#### General recommended guidelines

It is suggested to proceed in two different ways depending on the knowledge of the user about the rainfall events that can create an impact in the region of interest.

**First case: the user does not know which rainfall event might generate impacts in the region of interest.** This case is very common in those situations when the forecaster must provide forecasts for unfamiliar regions. In this case, it would be suggested to define the level of risk (e.g. 5%) that the user is prepared to accept for exceeding a certain rainfall amount and, consequently, plot a map for the correspondent percentile (i.e. the 95% for the proposed example). Such map will provide an overview of the rainfall amounts with 5% probability of being exceeded over the whole region of interest. It needs to be stressed out that such rainfall values do not mean that they will generate an impact. If the 95th percentile shows rainfall amounts of 2 mm/12h, they will rarely generate any impact. Since the user does not know which rainfall values could generate an impact, it would be very helpful to overlap the percentile map with a rainfall climatology. The user would ideally use an ecPoint-Rainfall climatology to compare rainfall amount at the same scale. However, as this product is not available yet, the user could use other available (observational or model) climatologies to get a feeling on what rainfall amounts could generate some impacts and define the regions where those rainfall amounts have a 5% probability to be exceeded.

**Second case: the user knows which rainfall values might generate some impact in the region of interest**. In this case it would be suggested to plot the probabilities of exceeding the rainfall value that might generate some impacts. The user can define the regions for which a “high enough” probabilities are provided, and alerts might be issued. The user will need to define what is the value for “high enough” (e.g. 50%, 10%, 1% probability). However, it needs be highlighted that such map would not provide any information on the probability distribution for an event exceeding the predefined rainfall threshold. This would be useful to estimate the level of impacts of different rainfall events. To do so, it would be useful to look at a CDF for a location of a particular concern to see whether there is some probabilities of having a much more extreme (localized) rainfall event (see conceptual examples in Fig. 9).

#### Mock-up product example and OMSZ reaction

A mock-up product for the first case was provided in section 5.d.2. for the IMS case study. In that case, the 99th percentile was plotted to show the possible “worst-case” scenario. However, other percentiles can be chosen. Nonetheless, as previously mentioned, it would be suggested to not go below the 90th percentile to provide guidance on extreme (localized) rainfall.

For the second case, OMSZ provides a really good example on how to use probability maps of exceeding 10 mm/12h (Fig. 8b and c) and 30 mm/12h (Fig. 8d and e). However, closer to the event, it would be very useful to complement this map with the CDF for the location that might be at higher risk of sever impacts to inspect the full structure of probabilities for different rainfall amounts. Examining the forecasts from the OMSZ case study, Bükkszentlélek was likely to have the most severe impacts (see box in Fig. 8f). The comparison of the CDFs for ecPoint-Rainfall (in blue) and ECMWF ENS (in red) in Bükkszentlélek show that ENS forecast predicts high amounts of rainfall, on average, at the grid-box scale. However, its tail is not as big as the one for ecPoint-Rainfall (ecPoint-Rainfall worst-case scenario predicts a rainfall amount up to ~70 mm/12h, whilst ENS remains below ~30 mm/12h). This suggests, that although with small probabilities, ecPoint-Rainfall is predicting a (localized) rainfall event that can have much more sever impacts than the one predicted by ENS. The observations eventually supported ecPoint-Rainfall forecasts (see fuchsia circle with the cross in Fig. 8a). This example is similar to the conceptual cases (C) and (D) shown in Fig. 9.

Since CDFs for single locations are currently not available for ECMWF users, a solution could be to combine the probability map with a map plot of a particular percentile, as it was suggested in section 5.d.1.

# Discussion and concluding remarks

The aim of this study was to collect information (1) on the performance of ecPoint-Rainfall forecasts in the prediction of extreme localized rainfall and flash floods in diverse regions, (2) on the perceived usefulness of ecPoint-Rainfall forecasts, and (3) on the perceived usefulness of ecPoint-Rainfall forecasts when the guidelines were subsequently modified to accommodate users’ needs.

Regarding aim n.1, the study showed that ecPoint-Rainfall forecasts can provide good forecasts for extreme (localized) rainfall events in both Costa Rica (representative of a tropical region) and Hungary (representative of an extra-tropical region).

Regarding aim n.2, the study showed that, notwithstanding that documentation about the ecPoint methodology and the ecPoint-Rainfall forecasts was written and provided to users, such documentation must be improved because the potential for misuse or misinterpretation of the ecPoint-Rainfall forecasts is quite high. Moreover, future additions to the documentation should be the result of a closer interaction with users about their needs. Two main concepts should be stated very clearly in any ecPoint documentation:

* Don’t misinterpret: ecPoint-Rainfall is provided in the same resolution of the raw forecast; however, their resolutions are completely different. This aspect should be stressed more to users as the visual representation of the ecPoint-Rainfall products can trick the user. ecPoint-Rainfall forecasts correspond to a point scale, as opposed to the finite grid length of the raw forecasts. Therefore, when a map plot for a percentile is shown to the user, it should be stressed that the rainfall value that correspond to the chosen percentile is not valid for the whole grid-box (as it would be for the visual representation of traditional NWP model outputs) but only for a point within the grid-box. In this way, users will not think that ecPoint-Rainfall overestimates the rainfall event. Ultimately, this should also help to encourage users to look at the higher percentiles if the user is interested in forecasting the “worst-case scenario”.
* Don’t mis-verify: ecPoint-Rainfall is easier to verify that other NWP forecasts because it was created to mirror what rain gauges measure. On the contrary, traditional NWP models produce rainfall averages over the model grid-box. With this in mind, it should be clearer to the users that ecPoint-Rainfall can be directly verified against rain gauge observations.

To reach these goals, including user cases (in a video or written format) can be a really good way to make more digestible the product and reach forecasters which can be busy and might not have much time to dedicate to read complicated documentation about a new product (Novak et al. 2008; Demuth et al. 2020). Moreover, it will help the users to focus on the practical applications of the product. Q&A forums can also be an extremely helpful resource to have a more direct contact with users, especially those with less experience with probabilistic forecasts which might require a much closer interaction to incorporate ecPoint-derived products in their operational systems. For example, ECMWF is considering including ecPoint-Rainfall in the new ECMWF Forecast User Forum.

Regarding aim n.3, if the documentation is created in a way that users can understand better the power and the limitations of ecPoint-derived products, they would understand them better and it might be more appealing for users to incorporate them into their systems and daily forecasting routines:

“If all these changes are applied to the way the new ecPoint-Rainfall forecasts are presented to us, forecasters, the new product would be extremely useful to forecast extreme (localized) rainfall events.” (IMN)

Finally, the informal discussions during this study have allowed ecPoint developers to draw more conclusions that go beyond the initial aims of the study.

First, the most important aspect learnt by the ecPoint experts is that the most efficient way to communicate how the ecPoint methodology work is to draw a parallelism to how forecasters around the world mentally post-process raw NWP model outputs (see Fig. 13). During the informal conversations with the intermediaries, it was possible to observe their immediate reaction when such parallelism was presented since it speaks their language and forecasters can directly relate what ecPoint does to forecasts as it is exactly the same to what forecasters do to raw forecasts on daily basis to correct biases and provide forecasts for point locations.

Second, ecPoint developers should strive to provide some new products to users to help them create better forecasts for extreme (localized) rainfall events using ecPoint-Rainfall forecasts. For example, the full information content from ecPoint-Rainfall lies in its distribution provided by the CDFs. Moreover, users have requested the release of the G\_WTs as they would allow the forecasters to see how the uncertainty at local scale for the raw forecast can vary depending on certain weather scenarios. The meteograms created by OMSZ show how important is the latter aspect in operational forecasting. . So far, the G\_WTs were considered only as a useful internal diagnostic tool. ECMWF will therefore consider providing new variants of products.

Third, ecPoint developers should strive to highlight more the teaching value of the ecPoint methodology. ecPoint-Rainfall could indeed be considered also as a data-based training tool for probabilistic forecasts. Above was mentioned how forecasters mentally post-process raw forecasts on daily basis. Yet, mental models, including those from experts, can be incomplete or biased by misconceptions or false beliefs (Vicente 2000). The ecPoint methodology instead could show forecasters how NWP models work in certain weather scenarios. The ecPoint methodology builds indeed on the local expertise about the uncertainty of local weather and builds upon that using a large database that goes beyond the local area of interest, using global data.

Fourth, ecPoint developers need to be cognizant of the tools available to forecasters (e.g. high-resolution NWP models, ensembles) e.g. what do you use at different lead times and how ecPoint-Rainfall can be blended. One example is given by the “Meteo Italian supercomputing portal” (MISTRAL) project in which 6-hourly ecPoint-Rainfall forecasts were blended with the 2.2 km COSMO-2I-EPS forecasts for Italy via a new state-of-the-art scale-selective neighbourhood technique (Gascón et al. 2021). We must acknowledge that ecPoint-Rainfall has some limitations, e.g. local geographical settings (specific configurations of mountains or islands), and global rainfall extremes where the global calibration that underpins ecPoint-Rainfall will not work so well. It is in those cases when one might want to give more weigh to a km-scale NWP model if available.

The findings of this study might not to be generalizable to other NHMSs that may operate in different circumstances. However, it can help ecPoint developers to start building an idea on the length of tailoring that ecPoint guidelines will need to make forecasters understand the data they are presented with and to favour the adoption of ecPoint-Rainfall forecasts in diverse operational contexts.

# TABLES

|  |  |  |
| --- | --- | --- |
|  | **IMN (Costa Rica)** | **OMSZ (Hungary)** |
| **Domain (N/S/W/E coordinates)** | (12°N / 7°N / 87°W / 82°W) | (49°N / 45°N / 15°E / 24°E) |
| **Forecasts received** | ecPoint-Rainfall percentiles (from 1st to 99th) | ecPoint-Rainfall percentiles (from 1st to 99th) |
| **Runs** | 00 and 12 UTC (IMN used only the 12 UTC run) | 00 and 12 UTC |
| **Rainfall Accumulation** | 12 hours | 12 hours |
| **Number of accumulation periods** | 4 overlapping accumulation periods per day, with valid times ending at 0, 6, 12, and 18 UTC. | 4 overlapping accumulation periods per day, with valid times ending at 0, 6, 12, and 18 UTC. |
| **Lead time** | Up to (t+246) | Up to (t+246) |
| **Files format** | Grib (IMN converted the files to netCDF) | Grib |

Table 1 – Characteristics of the ecPoint-Rainfall forecasts provided to the NMHSs at the beginning of the “real-time” phase. In red it is specified whether the NHMSs used a sub-group of the forecasts provided or change something in the files provided to incorporate the ecPoint-Rainfall products in their operational systems. Whilst IMN and OMSZ received the same products during the real-time phase, IMN decided to use only the forecasts from the 12 UTC run as those were the only ones usable for daily warnings considered the time difference between Europe and Central America (UTC-6). Moreover, grib files were converted to netCDF as the latter is the format used at IMN.

|  |  |  |
| --- | --- | --- |
| **Training material** | **IMN (Costa Rica)** | **OMSZ**  **(Hungary)** |
| Links to ECMWF Newsletters articles, published before 2018, on the scientific developments of the ecPoint methodology and the ecPoint-Rainfall products:   * <https://www.ecmwf.int/en/newsletter/153/news/new-point-rainfall-forecasts-flash-flood-prediction> * <https://www.ecmwf.int/en/elibrary/18331-ecpoint-rainfall-global-probabilistic-rainfall-point-scale-ecmwf-ensemble> * <https://www.ecmwf.int/en/newsletter/152/news/ecmwf-supports-flood-disaster-response-peru> | X | X |
| Description, via email, of the ecPoint-Rainfall forecasts’ structure:  “The ecPoint-Rainfall forecasts are produced twice a day (for a 00 and 12 UTC run) in four 12-hourly overlapping periods, with valid times finishing at 00, 06, 12, 18 UTC. The maximum lead time computed is t+246 (i.e. day 10). Therefore, at each run, 40 files are produced. Please, let us know which runs and accumulation periods you might prefer to receive (all or a sub-group, e.g. only the 00 UTC run and only the accumulation periods with valid times ending at 00 and 12 UTC), and up to what lead time.  Each file contains 99 global fields, which correspond to ecPoint-Rainfall percentiles (from 1st to 99th). The files are produced in gridded binary (grib) format (WMO standard).  The size of each file (400 MBs) doesn’t allow us to send global fields via file transfer protocol (ftp). Therefore, you will receive forecasts only for your domain of interest. Please, let us know the N/S/W/E coordinates of such domain, and the forecast will be extracted in a regular lat-lon format.”  Finally, the names of the files indicate the date (YYYYMMDD format) and the UTC time (HH format) in which the forecasts were computed. The name also contains the step at which the 12-hourly accumulation period ends (in hours, hhh format). This is an example: ecPointRain\_12h\_YYYYMMDD\_HH\_hhh.grib. The file ecPointRain\_12h\_20180101\_00\_024.grib contains forecasts valid for the period between 20180101 at 12 UTC and 20180102 at 00 UTC).” | X | X |
| How to interpret ecPoint-Rainfall percentiles. The following text correspond to a typical answer when interrogated on this topic:  “ecPoint-Rainfall forecasts provide percentiles, from 1st to 99th. For example, a map plot for the 99th percentile displays the rainfall values (in mm/12h) at each grid-box that have 1% risk of being exceeded.  When looking at extreme localized rainfall events, please refer to high percentiles, namely typically >90th percentile. Preferably, use the 98th or 99th percentiles as extreme localized rainfall events are by definition very low-probability events. Nonetheless, the percentile to choose depends on the level of risk your institution would act upon. For example, if you require that an event is forecast with at least 10% risk of exceedance to issue a warning, you might choose to look at the 90th percentile. However, such percentile might not provide the highest localized rainfall value that could fall in your area of interest.  Another important aspect to consider is that, although the rainfall value for a percentile is assigned to the whole grid-box, the rainfall value is in reality valid for a point within the grid-box. Moreover, nothing can be said about the location of such point within the grid-box.” | X | - |
| How to compute the probabilities of not exceeding a certain rainfall threshold from ecPoint-Rainfall forecasts, and how to interpret them. The following text correspond to a typical answer when interrogated on this topic:  “Let’s consider a grid-box and its correspondent 99 percentiles values. Check which rainfall values, at each percentile, are greater or equal than the chosen rainfall threshold (e.g. 50 mm/12h) and assign them the value 1; otherwise, assign the value 0. In this way, a list of 99 values, containing 0s and 1s, is created. Repeat the procedure for each grid-box in the domain. Compute the mean of the values in each list and multiply it by 100 to obtain probabilities in %.  The rainfall threshold depends on the magnitude of an event that can generate some impacts (e.g. flash floods) in the area of interest.  Notice that extreme rainfall thresholds are likely to have very small probabilities of occurrence, namely <5%, as extreme localized rainfall events are by definition very low-probability events.  Another important aspect to consider is that, although the probability of occurrence is assigned to the whole grid-box, it actually refers to a rainfall value observed at a point with the grid-box, and nothing can be said about its location with the grid-box. | X | - |

Table 2 - ecPoint guidelines provided via email to participants at the beginning of the “real-time” phase. The mark “X” under the name of the NHMSs indicates that the correspondent guidelines were provided; the mark “-” indicates when they were not, generally because the NHMS was already familiar with the specific topic.

# FIGURES

Diagram

Description automatically generated

Fig. 1 - ecPoint workflow. Panel (a) represents the ecPoint's offline calibration process, panel (b) represents the ecPoint's forecast generation process, and panel (c) represents an example of two products that can be derived from the post-processing output (i.e. the map plot for percentile Xth, or the map for the probabilities of exceeding the rainfall threshold Y). The variable "rainfall" was used in this figure two illustrate both processes, calibration and forecast generation, but they can be used to post-process also other variables, e.g. "temperature".

Diagram

Description automatically generated

Fig. 2 - Experiment design. The grey boxes describe the different steps carried out during the “real-time” and the “offline” phase of the experiment. The yellow rhombus contained the questions asked at key moments of the study to define the path to take in the experiment. The green boxes represent the actions taken based on the followed path. The fuchsia, blue, green, and cyan frames encompass the steps done by, respectively, the ecPoint experts, NMHS forecasters, the intermediaries, and the ecPoint experts and intermediaries together.

Map

Description automatically generated

Fig. 3 - Panel (a) shows Costa Rican climatological regions. The box shows the location of Costa Rica in Central America. Panel (b) shows the Hungarian administrative regions (colours shades) and counties (white lines). The box shows the location of Hungary in Europe. Panels (c) and (d) show the orography in Costa Rica and Hungary, respectively, and panels (e) and (f) show the annual rainfall amounts in mm.

Graphical user interface, chart

Description automatically generated

Fig. 4 – Products developed by IMN and OMSZ based on ecPoint-Rainfall. Panel (a) is a map plot displaying the 85th percentile of ecPoint-Rainfall over Costa Rica. Panel (b) is a meteogram displaying 12-hourly precipitation from the ECMWF ENS in blue and ecPoint-Rainfall in orange (first panel), rate of convective precipitation ratio (second panel), 700 hPa wind speed (third panel), and CAPE (fourth panel) from ECMWF ENS. Panel (c) is a map plot displaying the 90th  (top number), 75th, 50th, 25th and 10th (bottom number) percentiles for each grid box (of 0.5 degree resolution).

Diagram, map

Description automatically generated

Fig. 5 - Panels from (a) to (f) show 12-hourly rainfall observations during the extreme rainfall event occurred between October 3rd and 5th, 2018. The times the figure refer to are indicated in UTC time and local time (LT).

A picture containing background pattern

Description automatically generated

Fig. 6 - Forecast evolution (from day 7 to day 1) for the rainfall event occurred between October 4th at 12am and October 5th at 0am (local time, LT). See Fig. 5d to compare the forecasts with the observations. From the left, the first column shows the 85th percentile for ecPoint-Rainfall (as used operationally by IMN), the second column shows the 85th percentile for the raw ENS, the third column shows the 99th percentile for ecPoint-Rainfall, the fourth column shows the wettest member of the raw ENS, and the fifth column shows the deterministic forecast from WRF-1.5 (spatial resolution of 1.5 km) typically used by IMN in the forecasts of extreme localized rainfall events. The shown raw ECMWF ENS and ecPoint-Rainfall forecasts correspond to runs at 12 UTC, which is the first available run from Europe to IMN forecasters in the morning due to time difference between Europe and America (UTC-6). The WRF-1.5 forecasts correspond to runs at 18 UTC, which are the first run available to IMN forecasters in the morning. The colour scheme of the first column plots have been modified, compared to the original IMN products (see Fig. 4a), to standardize all the plots in this figure, and make easier the forecasts comparison between models.

Map

Description automatically generated

Fig. 7 – Results of the OMSZ objective verification for ecPoint-Rainfall forecasts. The verification period goes from June 1st to August 31st, 2018. Panel (a) shows the relative position between OMSZ rain gauges (coloured circles) and ecPoint-Rainfall and ECMWF ENS grid-boxes (grey squares). The colours associated to the rain gauges indicate their heigh in meters above sea level. Panel (b) shows the Talagrand diagrams for ecPoint-Rainfall (left column) and ECMWF ENS (right column). The first and the second row correspond, respectively, to forecasts for the accumulation period (t+0,t+12; i.e. day 1) and (t+96,t+108; i.e. day 4). Panel (c) shows the overall performance of ecPoint-Rainfall in the prediction of rainfall exceeding 15 mm/12h using the 85th percentile (top) and 95th percentile (bottom). The number of days with overall good performance for each grid-box (i.e. days with no overall rainfall under- or overestimation) are coloured in shades between white and blue. Black indicates grid-boxes with no associated observations. Grey indicates grid-boxes with overall rainfall over- or underestimation. Panel (d) shows the overall rainfall under- and overestimation of ecPoint-Rainfall in the prediction of rainfall exceeding 15 mm/12h using the 85th percentile (top) and 95th percentile (bottom). The number of days with overall under- and overestimation for each grid-box are coloured in shades of blue and orange, respectively. Black indicates grid-boxes with no associated observations. White indicates grid-boxes with no overall rainfall under- or overestimation.

Map

Description automatically generated

Fig. 8 – Panel (a) shows the 12 hourly observations for the intense rainfall event on June 11th, 2018 between 0 and 12 UTC time. The purple circle with a cross refers to a manually added record of 92 mm/24h in Bükkszentlélek between 12 UTC June 10th and 12 UTC June 11th (most of the rain fell on June 11th between 0 and 12 UTC). Panels (b), (c), (d), (e) show forecasts for day 2; (b) and (d) show the probabilities of not exceeding 10 mm/12h for ecPoint-Rainfall and ECMWF ENS, respectively; (c) and (d) show the probabilities of not exceeding 30 mm/12h for ecPoint-Rainfall and ECMWF ENS, respectively. The inserted box shows the CDF for ecPoint-Rainfall (in blue) and ECMWF ENS (in red) for day 2 rainfall forecasts for Bükkszentlélek. Panels (f), (g), (h), (i) are the same but for day 4 forecasts.

Chart

Description automatically generated

Fig. 9 – Conceptual CDFs for possible ecPoint-Rainfall output scenarios (indicated by the colour shades). The CDF (A) corresponds to a typical convective rainfall event. Assuming the criterion for issuing warnings for extreme (localized) rainfall is having at least 15% probability of exceeding 15 mm/12h, the red point at the interception of the 85th percentile and 15 mm/12h provides the its lower limit. The solid-line CDFs (i.e. A, B, C, and D) correspond to those rainfall events that would satisfy the criterion (i.e. 15 mm/12h is obtained at lower percentiles than the 85th); the dashed-line CDFs correspond to those rainfall events that would not (i.e. 15 mm/12h is obtained at higher percentiles than the 85th).

A picture containing map

Description automatically generated

Fig. 10 – ecPoint-Rainfall reliability for the 95th percentile (left panel) and the 99th percentile (right panel). The maps show, for each observation location, the times (in %) that the observations exceeded the forecasts for a percentile Xth. To be reliable, the observations need to exceed the forecasts (100-X)% of the time. A smaller frequency would indicate a forecast overestimation; a higher frequency would indicate a forecast underestimation. Since the considered region and verification period are small, a buffer around the value (100-X)% has been applied to allow for randomness in the sample. The buffer is proportional to the percentile considered, and it is given by (100-X). The values within the buffer are shown in grey. The values outside the buffer, indicating forecast underestimation are shown in shades from yellow to purple. On the right, the computations to determine, at a location, the times (in %) that the observations exceeded the forecasts from percentile Xth are shown.

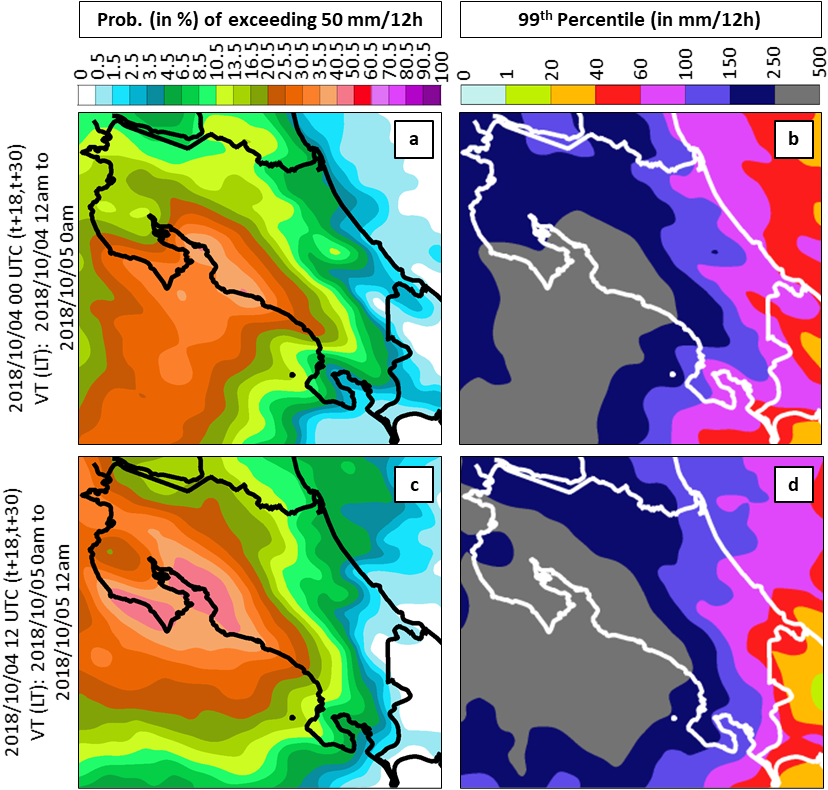


Fig. 11 - Panels (a) and (c) show the probabilities of not exceeding 50 mm/12h, and panels (b) and (d) show the 99th percentile, both for ecPoint-Rainfall forecasts. Panels (a) and (b) correspond to the forecast on 2018/10/04 at 00 UTC (t+18, t+30), which correspond to the rainfall observed between 2018/10/04 12 am and 201/10/05 0 am (local time, , see Fig. 5d). Panels (c) and (d) correspond to the forecast on 2018/10/04 at 12 UTC (t+18, t+30), which correspond to the rainfall observed 2018/10/05 0am and 201/10/05 12am (local time, see Fig. 5e).

Diagram

Description automatically generated

Fig. 12 - CDFs for ecPoint-Rainfall (in blue) and raw ENS (in red). Panels (a) and (b) display the CDFs for a location representative of the south coast of the Nicoya peninsula (lat=9.82, lon=-84.94). Panels (c) and (d) display the CDFs for a location representative of the inland parts of the Nicoya peninsula (lat=10.08, lon=-85.47). Panel (a) and (c) correspond to the forecast on 2018/10/04 at 00 UTC (t+18,t+30), which correspond to the period between 2018/10/04 12am and 2018/10/05 0am (local time). Panel (b) and (d) correspond to the forecast on 2018/10/04 at 12 UTC (t+18,t+30), which correspond to the period between 2018/10/05 0am and 201/10/05 12am (local time).

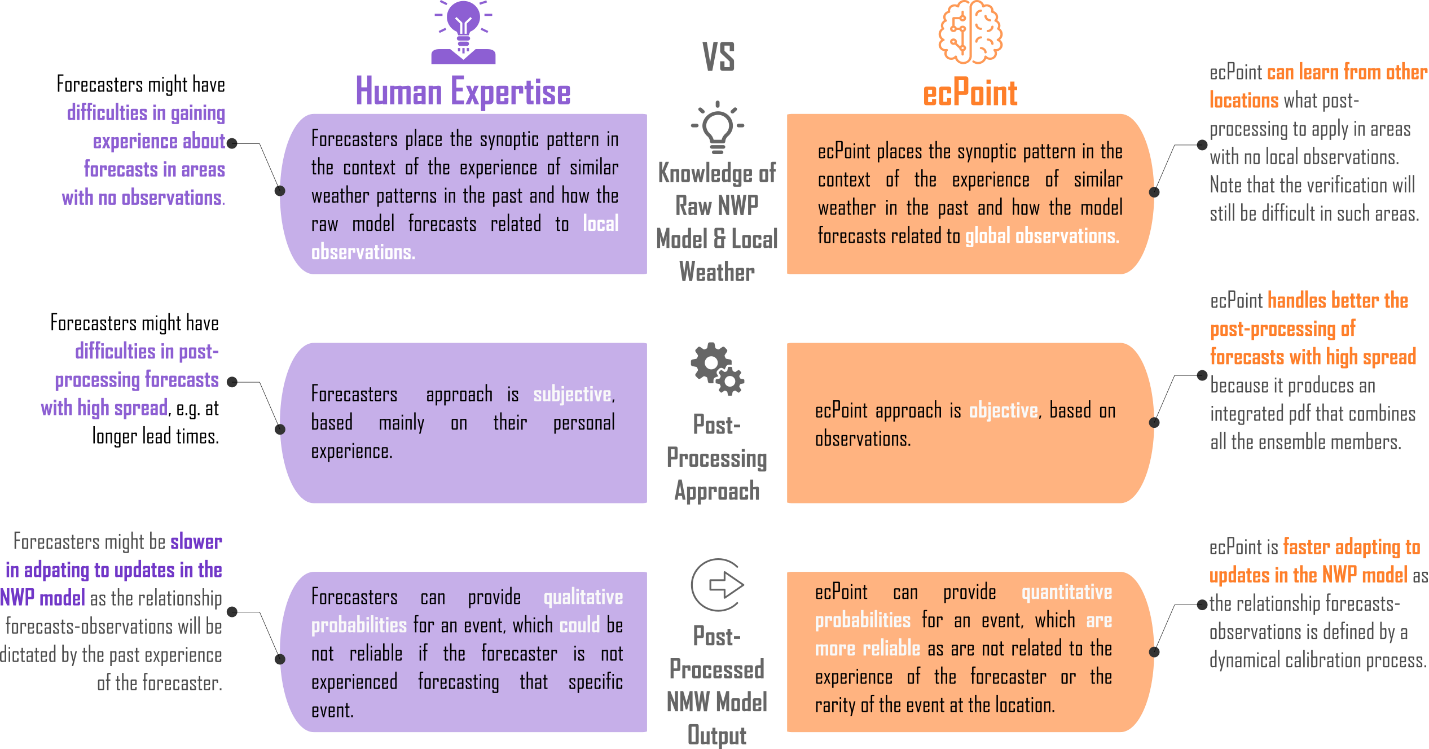


Fig. 13 – Correlation between mental post-processing operated by forecasters and the ecPoint post-processing.

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# Appendix A – Guide questions for the informal discussions during the “offline” phase

**BACKGROUND QUESTIONS**

**PREGUNTAS DE CONTEXTO**

***On the general Met-Service experience with ensemble forecasts***

***Sobre la experiencia general del servicio meteorológico con pronósticos de conjunto***

1. Has the Met-Service any experience with ensemble forecasts? If so, which ensemble forecasts are mainly used?

¿El servicio meteorológico tiene experiencia con pronósticos de conjunto? Si es así, ¿qué pronósticos de conjunto utilizan principalmente?

1. If there is some access to ensemble forecasts in the Met-Service, how are they used? Are they used as the primary source to issue alerts and create products for end-users and inform them also about the uncertainty on the forecast? Or are they used as a background knowledge to complement the information provided by a deterministic model, and if so, why?

Si tiene acceso a pronósticos de conjunto, ¿cómo los usan? ¿Los usan como fuente primaria para emitir alertas y crear productos para usuarios finales e informarlos también sobre la incertidumbre en los pronósticos? ¿O los usan para complementar la información proporcionada por un modelo determinista? Si es así, ¿por qué?

1. What is the general impression of ensemble forecasts and their use in operational environments? Is there any internal disagreement on the practical value of ensemble forecasts (e.g. due to issues in the communication of probabilistic forecast or their reception by end-users)? Is there any discomfort surrounding how to deal with probabilistic forecasts in an operational environment?

¿Cuál es la impresión general sobre las predicciones de conjunto y su uso en entornos operativos? ¿Existe algún desacuerdo interno sobre el valor práctico de los pronósticos de conjunto (por ejemplo, debido a problemas en la comunicación del pronóstico probabilístico o su recepción por parte de los usuarios finales)? ¿Hay alguna molestia sobre cómo lidiar con pronósticos probabilísticos en el entorno operativo?

***On the general Met-Service experience with rainfall forecasts calibration***

***Sobre la experiencia general del servicio meteorológico con calibración de pronósticos de lluvia***

1. Has the Met-Service any experience of post-processing or calibrating rainfall forecasts? If so, for what purpose (e.g. improving quality of operational forecasts for end-users, making the forecasts more suitable for downstream applications such as hydrological forecasts)?

¿El servicio meteorológico tiene experiencia con el postproceso o calibración de pronósticos de lluvia? Si es así, ¿con qué propósito se hacen (por ejemplo, para mejorar la calidad de los pronósticos operativos para los usuarios finales, hacer que los pronósticos sean más adecuados para segundas aplicaciones como pronósticos hidrológicos)?

***On the background of the forecasters who worked with ecPoint-Rainfall***

***Sobre las predictores que trabajaron con ecPoint-Rainfall***

1. Who has been receiving ecPoint-Rainfall forecasts? What is their background (e.g. operational, research)?

¿Quién recibió los pronósticos de ecPoint-Rainfall? ¿Cuáles son sus antecedentes (por ejemplo, operativos, investigación)?

1. Do those particular people have general experience working with ensemble forecasts? Do they have experience working with post-processed forecasts? If not, do they have much time to devote to learning?

¿Las personas que recibieron las predicciones de ecPoint-Rainfall tienen experiencia de trabajo con predicciones de conjunto? ¿Tienen experiencia trabajando con predicciones calibradas? Si no es así, ¿tienen tiempo para dedicar al aprendizaje?

**QUESTIONS ON ECPOINT-RAINFALL**

**PREGUNTAS SOBRE ECPOINT-RAINFALL**

1. Was ecPoint-Rainfall used operationally, experimentally, or for research?

¿Se usó ecPoint-Rainfall de manera operacional, experimental o para investigación?

1. Was it difficult to become accustomed to the meaning/structure of ecPoint-Rainfall forecasts? Did the fact that ecPoint-Rainfall products you received did not provide grid box forecasts create any issues?

¿Fue difícil acostumbrarse al significado o a la estructura de ecPoint-Rainfall? ¿El hecho que los productos de ecPoint-Rainfall que recibieron no proporcionan predicciones a escala de celda creó problemas?

1. If ecPoint-Rainfall was used operationally, were there any technical issues to integrate the forecasts in your operational workflows? Evaluation would include configuration of ecPoint-Rainfall, data volumes, run times, displaying the forecasts, etc.

Si se utilizó ecPoint-Rainfall operacionalmente, ¿hubieron problemas técnicos para integrar las predicciones en sus sistemas operativos? La evaluación incluiría configuración de ecPoint-Rainfall, volúmenes de datos, tiempos de ejecución, o representar gráficamente productos, etc.

1. Did you develop products from ecPoint-Rainfall? Did you use percentiles? Which percentiles? Why? Did you use probabilities? Which probabilities? Why?

¿Desarrollaron productos basados en ecPoint-Rainfall? ¿Usaron percentiles? ¿Cuáles percentiles? ¿Por qué? ¿Usaron probabilidades? ¿Qué probabilidades? ¿Por qué?

1. Where (e.g. over mountainous, coastal, flat areas), in which weather situations or for which type of events (e.g. deep convection, flash floods, etc.) do you think you could get most benefit from ecPoint-Rainfall? Why?

¿Dónde (por ejemplo, en zonas montañosas, costeras y planas), en qué situaciones climáticas, o para qué tipo de eventos (por ejemplo, convección, inundaciones, etc.) creen que podría obtener mayor beneficio de ecPoint-Rainfall? ¿Por qué?

1. Was ecPoint-Rainfall found useful? Do you think it added value to raw ECMWF ensemble and/or the model used in-house?

¿Se encontró ecPoint-Rainfall útil? ¿Te parece que añade valor a las predicciones de ECMWF y/o al modelo que utilizan comúnmente?

1. Do you think that ecPoint-Rainfall could change the way that alerts are issued for localized extreme rainfall, flash floods, etc? Perhaps increasing the lead-time at which alerts are issued (e.g. up to medium ranges)? Why?

¿Cree que ecPoint-Rainfall podría cambiar la forma en que se emiten las alertas para lluvias extremas localizadas, inundaciones repentinas, etc.? ¿Quizás podrían aumentar el plazo con el que se emiten las alertas (por ejemplo, hasta un plazo medio)? ¿Por qué?

1. Do you think ecPoint-Rainfall is useful information to have? If so, in which way, as preliminary information to raise internal awareness to prompt increase preparedness within the forecasting centre? Or would it also be used to trigger early actions to mitigate or manage high risk events?

¿Cree que ecPoint-Rainfall proporciona información útil? Si es así, ¿de qué manera? ¿Cómo información preliminar usada internamente para aumentar rápidamente la preparación el centro de predicción? ¿O también se usaría para activar acciones tempranas con el objetivo de mitigar o gestionar eventos de alto riesgo?

1. If you think ecPoint-Rainfall has improved raw model rainfall forecasts, based on your experience, what aspects stand out as being better (e.g. less false alarm rates, better representation of point rainfall values, etc)?

Si cree que, en base a su experiencia, ecPoint-Rainfall ha mejorado las predicciones de lluvia, ¿cuáles son lo que aspectos se destacan por ser mejores (por ejemplo, la menor frecuencia de falsas alarmas, una mejor representación de los valores puntuales de lluvia, etc.)?

1. Can you think of other useful applications for ecPoint-Rainfall (e.g. predicting dry weather)?

¿Tiene sugerencias para otra útil aplicaciones para ecPoint-Rainfall (por ejemplo, la predicción de no-lluvia)?

1. Currently the maximum percentile available is 99th (1 in 100 chance). We could in principle deliver up to percentile 99.98th (1 in 5000 chance), or, let’s say, we could even restrict the maximum available percentile to 95th (1 in 20 chance). What level do you think we should use as the maximum?

Actualmente el percentil máximo disponible es el 99° (1 entre 100 posibilidades). En principio, podríamos computar hasta el percentil 99,98° (1 en 5000 posibilidades) o podríamos restringir el percentil máximo al 95° (1 en 20 posibilidades). ¿Qué nivel cree que deberíamos usar como máximo?

1. Have you used/verified ecPoint-Rainfall for a particular event or case study? Briefly describe the geographical region and the weather conditions for which the tests were conducted.

¿Ha utilizado/verificado ecPoint-Rainfall para un evento o un caso de estudio en particular? Describa brevemente la región geográfica y las condiciones climáticas para las cuales se realizaron las pruebas.

1. Why was this particular case study or event chosen (e.g. the forecasts for the region or the particular synoptic situation are usually not very good)?

¿Por qué fue elegido ese particular caso de estudio o evento (por ejemplo, los pronósticos para la región o para la situación sinóptica considerada no son muy buenos por lo general)?

1. With hindsight, did ecPoint-Rainfall provide useful guidance for this particular situation? How would you rate its performance?

En retrospectiva, ¿ecPoint-Rainfall proporcionó información útil para esta situación en particular? ¿Como evaluaría su rendimiento?

1. Are there any improvements that you would like to see in ecPoint-Rainfall (e.g. 12-hourly rainfall accumulations were ok for your needs, or would you like to see other durations, etc.)?

¿Hay alguna mejora que le gustaría ver en ecPoint-Rainfall (por ejemplo, las acumulaciones de lluvia de 12 horas fueron adecuadas para sus necesidades o le gustaría ver otras acumulaciones, etc.)?