

1 **Development and verification of a real-time stochastic**
2 **precipitation nowcasting system for urban hydrology in**
3 **Belgium**

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10 **Abstract**

11 The Short-Term Ensemble Prediction System (STEPS) is implemented in real-time at the
12 Royal Meteorological Institute (RMI) of Belgium. The main idea behind STEPS is to quantify
13 the forecast uncertainty by adding stochastic perturbations to the deterministic Lagrangian
14 extrapolation of radar images. The stochastic perturbations are designed to account for the
15 unpredictable precipitation growth and decay processes and to reproduce the dynamic scaling
16 of precipitation fields, i.e. the observation that large scale rainfall structures are more
17 persistent and predictable than small scale convective cells. This paper presents the
18 development, adaptation and verification of the system STEPS for Belgium (STEPS-BE).
19 STEPS-BE provides in real-time 20 member ensemble precipitation nowcasts at 1 km and 5
20 min resolution up to 2 hours lead time using a 4 C-band radar composite as input. In the
21 context of the PLURISK project, STEPS forecasts were generated to be used as input in sewer
22 system hydraulic models for nowcasting urban inundations in the cities of Ghent and Leuven.
23 Comprehensive forecast verification was performed in order to detect systematic biases over
24 the given urban areas and to analyze the reliability of probabilistic forecasts for a set of case
25 studies in 2013 and 2014. The forecast biases over the cities of Leuven and Ghent were found
26 to be small, which is encouraging for future integration of STEPS nowcasts into the hydraulic
27 models. Probabilistic forecasts of exceeding 0.5 mm hr^{-1} are reliable up to 60-90 min lead
28 time, while the ones of exceeding 5.0 mm hr^{-1} are only reliable up to 30 min. The STEPS
29 ensembles are slightly under-dispersive and represent only 75-90% of the forecast errors.

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1 Introduction

2 The use of radar measurements for urban hydrological applications has substantially increased
3 during the last years (e.g. Berne et al., 2004; Einfalt et al., 2004; Bruni et al., 2015). Given the
4 fast response time of urban catchments and sewer systems, radar-based very short-term
5 precipitation forecasting (nowcasting) has potential to extend the lead time of hydrological
6 and hydraulic flow predictions.

7 Nowcasting concerns the accurate description of the current weather situation together with
8 very-short term forecasts obtained by extrapolating the real-time observations. Quantitative
9 precipitation nowcasting (QPN) is traditionally done by estimating the apparent movement of
10 radar precipitation fields using optical flow or variational echo tracking techniques and
11 extrapolating the last observed precipitation field into the future (e.g. Germann and Zawadzki,
12 2002; Bowler et al., 2004a). During recent years there has been significant progress in NWP
13 modelling with radar data assimilation techniques (see a review in Sun et al., 2014), which
14 reduces the useful lead time of extrapolation-based nowcasts compared with NWP forecasts.
15 The development of seamless forecasting systems that optimally blend the extrapolation
16 nowcast with the output of NWP models makes the definition of the nowcasting time range
17 even fuzzier (see e.g. Pierce et al., 2010).

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18 Due to the lack of predictability of rainfall growth and decay processes at small spatial scales
19 (Radhakrishna et al., 2012), it is very important to provide together with a forecast an
20 estimation of its uncertainty. The established method to represent the forecast uncertainty in
21 Numerical Weather Prediction (NWP) is to generate an ensemble of forecasts by perturbing
22 the initial conditions of the model in the directions exhibiting the largest error growth, which
23 amplify more the spread of the obtained ensemble. However, in the nowcasting range the
24 computation of large NWP ensembles (50-100 members) that resolve features at the scales of
25 1 km and are updated every 5 min is still impossible to achieve. Consequently, the efforts in
26 nowcasting research have recently focused on developing heuristic techniques for
27 probabilistic precipitation nowcasting, which was the topic of the *Heuristic Probabilistic*
28 *Forecasting Workshop* that was organized in Munich, Germany (Foresti et al., 2014).

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29 Probabilistic QPN methods can be categorized into three main classes: analogue, local
30 Lagrangian and stochastic approaches. The analogue-based approach derives the forecast
31 probability density function (p.d.f.) by retrieving a set of similar situations from an archive of
32 precipitation events (Panziera et al., 2011; Foresti et al., 2015), the local Lagrangian approach

1 derives the p.d.f. by collecting the precipitation values in a neighborhood of a given grid point
2 in Lagrangian frame of reference (Hohti et al., 2000; Germann and Zawadzki, 2004) and the
3 stochastic approach exploits a random number generator to compute an ensemble of equally
4 likely precipitation fields, for example by adding stochastic perturbations to a deterministic
5 extrapolation nowcast (Pegram and Clothier, 2001a, 2001b; Bowler et al., 2006; Metta et al.,
6 2009; Berenguer et al., 2011; Seed et al., 2013; Atencia and Zawadzki, 2014; Dai et al.,
7 2015). The stochastic approach is also extensively used to produce ensembles of precipitation
8 fields that characterize the radar measurement uncertainty (e.g. Jordan et al., 2003; Germann
9 et al., 2009) and for design storm studies (e.g. Willems, 2001a; Paschalis et al., 2013).

10 Uncertainty quantification is nowadays an integral part of both weather and hydrological
11 forecasting (Pappenberger and Beven, 2006). Not surprisingly, an important part of hydro-
12 meteorological research aims at understanding how to propagate the uncertainty of
13 precipitation observations and forecasts into the hydrological models (e.g. Willems, 2001b;
14 Cloke and Pappenberger, 2009; Collier, 2009, Zappa et al., 2010).

15 Several studies already analyzed the value of deterministic nowcasting systems for catchment
16 hydrology (e.g. Berenguer et al., 2005) and for better control of urban drainage systems (e.g.
17 Achleitner et al., 2009; Verworn et al., 2009; Thorndahl and Rasmussen, 2013). Since an
18 important fraction of the uncertainty of hydrological predictions is due to the uncertainty of
19 the input rainfall observations and forecasts, radar-based ensemble nowcasting systems are
20 increasingly used as inputs for flood and sewer system modeling (e.g. Ehret et al., 2008;
21 Silvestro and Rebora, 2012; Silvestro et al., 2013; Xuan et al., 2009; Xuan et al., 2014). At
22 longer forecast ranges, the NWP ensembles are also exploited for uncertainty propagation into
23 hydrological models (see Roulin and Vannitsem, 2005; Thielen et al., 2009; Schellekens et
24 al., 2011).

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25 The Short-Term Ensemble Prediction System (STEPS) is a probabilistic nowcasting system
26 developed at the Australian Bureau of Meteorology and the UK MetOffice (see the series of
27 papers Seed, 2003; Bowler et al., 2006; Seed et al., 2013). STEPS is operationally used at
28 both weather services and provides short-term ensemble precipitation forecasts using both the
29 extrapolation of radar images and the downscaled precipitation output of NWP models. The
30 main idea behind STEPS is to represent the uncertainty due to the unpredictable precipitation
31 growth and decay processes by adding stochastic perturbations to the deterministic
32 extrapolation of radar images. The stochastic perturbations are designed to represent the scale-

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1 dependence of the predictability of precipitation and to reproduce the correct spatio-temporal
2 correlation and growth of the forecast errors.

3 One of the first applications of STEPS in hydrology is presented in Pierce et al. (2005), who
4 used the STEPS ensemble nowcasts to quantify the accuracy of flow predictions in a medium-
5 sized catchment in UK. The value of STEPS nowcasts for urban hydrology was extensively
6 analyzed by Liguori and Rico-Ramirez, 2012; Liguori et al., 2012; Liguori and Rico-Ramirez,
7 | 2013; Xuan et al., 2014). Liguori and Rico-Ramirez (2012) concluded that the performance of
8 the radar-based extrapolation nowcast can be improved after 1 hour lead time if blended with
9 | the output of a NWP model. They also found that, according to the Receiver Operating
10 | Characteristic (ROC) curve, the probabilistic nowcasts have more discrimination power than
11 the deterministic ones. Liguori et al. (2012) integrated STEPS nowcasts as inputs into sewer
12 system hydraulic models in an urban catchment in Yorkshire (UK). They concluded that the
13 blending of radar and NWP forecasts has potential to increase the lead time of flow
14 predictions, but is strongly limited by the low accuracy of the NWP model in forecasting
15 small scale features. Liguori and Rico-Ramirez (2013) performed a detailed verification of the
16 accuracy of flow predictions and concluded that the STEPS ensembles provide similar
17 | performance than using a deterministic STEPS control forecast, but the ensembles lead to a
18 slight underestimation of the flow predictions. Xuan et al. (2014) used ensemble STEPS
19 | nowcasts as inputs in a lumped hydrological model for a medium-sized catchment in the
20 South-West of UK. The hydrological model calibrated with rain gauges had lower RMSE
21 than the one using radar data, but the ability of STEPS in accounting for the forecast
22 uncertainty was useful to capture some of the high flow peaks and extending the forecast lead
23 time. However, the conclusions of the previous studies are strongly affected by the limited
24 number of flood events analyzed. An extensive review of the usage of precipitation forecast
25 systems for operational hydrological predictions in UK from very-short to long range
26 (including STEPS) is provided in Lewis et al. (2015).

27 The goal of this paper is to present the development and verification of the STEPS system at
28 the Royal Meteorological Institute of Belgium (RMI), referred to as STEPS-BE. STEPS-BE
29 provides in real-time 20 member ensemble precipitation nowcasts at 1 km and 5 min
30 | resolutions up to 2 hours lead time on a 512x512 kilometer domain using the Belgian 4 C-
31 band radar composite as input. It was developed in the framework of the Belspo project
32 | PLURISK for better management of rainfall-induced risks in the urban environment. With

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1 respect to the original implementation of STEPS (Bowler et al., 2006), STEPS-BE includes
2 two main improvements, which are designed to generate better STEPS nowcasts without
3 NWP blending. The first one is related to the optical flow algorithm, which is extended with a
4 kernel-based interpolation method to obtain smoother velocity fields. The second one
5 concerns the generation of stochastic noise only within the advected radar composite. While
6 the verification of STEPS nowcasts with NWP blending has already been extensive (Bowler
7 et al., 2006; Seed et al., 2013), this paper analyzes the accuracy of STEPS ensemble nowcasts
8 without NWP blending in the 0-2 hours forecasting range.

9 Ensemble STEPS nowcasts are computed for a set of sewer overflow cases that affected the
10 cities of Leuven and Ghent in 2013 and 2014. The accuracy of the ensemble mean forecast is
11 verified using both continuous verification scores (multiplicative bias, RMSE) and categorical
12 scores derived from the contingency table (probability of detection, false alarm ratio and
13 Gilbert skill score). However, the most interesting part of this paper is the probabilistic and
14 ensemble verification of STEPS nowcasts using both stratiform and convective rainfall
15 events. Probabilistic nowcasts are verified using reliability diagrams and ROC curves. On the
16 other hand, the dispersion of the nowcast ensembles is verified using rank histograms and by
17 comparing the ensemble spread to the error of the ensemble mean.

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18 The paper is structured as follows. Section 2 presents the radar data processing and case
19 studies that are used to generate and verify the STEPS forecasts. Section 3 describes the
20 nowcasting system STEPS, its extension and local implementation for Belgium (STEPS-BE).
21 Section 4 illustrates the forecast verification results. Section 5 concludes the paper and
22 discusses future perspectives.

23

24 **2 Radar data and precipitation case studies**

25 STEPS-BE integrates as input a composite image produced from the C-band radars of
26 Wideumont (RMI, single-pol), Zaventem (Belgocontrol, single-pol), Jabbeke (RMI, dual-pol)
27 and Avesnois (Meteo-France, dual-pol). The composite is produced on a 500 m resolution
28 grid by combining single-radar pseudo Constant Altitude Plan Position Indicators (CAPPI) at
29 a height of 1500 m.a.s.l. The compositing algorithm takes the maximum reflectivity value
30 from each radar at each grid point.

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1 The radars have different hardware, scanning strategies and are operated by different agencies
2 (RMI, Belgocontrol and ~~Meteo-France~~), which inevitably leads to differences in the data
3 processing. The Wideumont and Zaventem radars eliminate the non-meteorological echoes
4 using standard Doppler filtering. The Jabbeke radar includes an additional clutter filtering
5 which uses a fuzzy logic algorithm based on the dual-polarization moments (essentially the
6 co-polar correlation coefficient, the texture of the differential reflectivity and the texture of
7 the specific differential phase shift). A static ground clutter map and a statistical filter are used
8 by ~~Meteo-France~~ to remove the non-meteorological echoes of the Avensois radar. The French
9 radar data processing chain is described in Tabary (2007) and in Figueras i Ventura and
10 Tabary (2013).

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11 Since the Zaventem radar is mainly used for aviation applications, its scanning strategy is
12 optimized for the measurement of winds. Except for the lowest elevation scan, a dual PRF
13 mode (1200/800 Hz) is used. The azimuths that are scanned with a high PRF (1200 Hz) only
14 have a maximum range of 125 km and are more affected by the second trip echoes caused by
15 convective cells located beyond the 125 km range.

16 All radars use the standard Marshall-Palmer relationship $Z=200R^{1.6}$ to convert the measured
17 reflectivity to rainfall rate. A composite image with more advanced radar-based quantitative
18 precipitation estimation (QPE), that includes better ground clutter removal algorithms and
19 also a correction for the bright band, was recently developed and the verification of the new
20 product is ongoing.

21 STEPS forecasts were generated and verified for a set of sewer system overflow cases that
22 affected the cities of Ghent and Leuven (see Table 1). The Ghent cases have a more stratiform
23 character and occurred in late autumn and winter. On the other hand, the Leuven cases are
24 more convective and occurred in summer months. A detailed climatology of convective
25 storms in Belgium can be found in Goudenhoofd and Delobbe (2009).

26

27 **3 Short-Term Ensemble Prediction System (STEPS)**

28 **3.1 STEPS description**

29 The Short-Term Ensemble Prediction System (STEPS) was jointly developed by the
30 Australian Bureau of Meteorology (BOM) and the UK MetOffice (Bowler et al., 2006).

1 STEPS forecasts are produced operationally at both weather services and are distributed to
2 weather forecasters and a number of external users, in particular the hydrological services.

3 The key idea behind STEPS is to account for the unpredictable rainfall growth and decay
4 processes by adding stochastic perturbations to the deterministic extrapolation of radar images
5 (Seed, 2003). In order to be effective, the stochastic perturbations need to reproduce important
6 statistical properties of both the precipitation fields and the forecast errors:

- 7 1. Spatial scaling of precipitation fields,
- 8 2. Dynamic scaling of precipitation fields,
- 9 3. Spatial correlation of the forecast errors,
- 10 4. Temporal correlation of the forecast errors.

11 The *spatial scaling* considers the precipitation field as arising from multiplicative cascade
12 processes (Schertzer and Lovejoy, 1987; Seed, 2003). The presence of spatial scaling can be
13 demonstrated by computing the 2D Fourier power spectrum (PS) of a precipitation field. A
14 1D PS can be obtained by radially averaging the 2D PS. The precipitation field is said to be
15 *scaling* if the 1D PS draws a straight line on the log-log plot of the power against the spatial
16 frequency (power law), which can be parametrized by a one or two spectral exponents (see
17 e.g. Seed et al. 2013; Foresti and Seed, 2014). Within the multiplicative framework, a rainfall
18 field is not represented as a collection of convective cells of a characteristic size but rather as
19 a hierarchy of precipitation structures embedded in each other over a continuum of scales.
20 STEPS considers the spatial scaling by decomposing the radar rainfall field into a
21 multiplicative cascade using a fast Fourier transform (FFT) to isolate a set of 8 spatial
22 frequencies (Seed, 2003; Bowler et al., 2006, Seed et al., 2013). The top cascade levels (0, 1
23 and 2) represent the low spatial frequencies (large precipitation structures), while the bottom
24 cascade levels (5, 6, 7) represent the high spatial frequencies (small precipitation structures).
25 Another important behavior of rainfall fields is known as *dynamic scaling*, which is the
26 empirical observation that the rate of temporal development of rainfall structures is a power
27 law function of their spatial scale (Venugopal et al., 1999; Foresti and Seed, 2014). This
28 means that large precipitation features are more persistent and hence predictable compared
29 with small precipitation cells, which is closely related to concept of scale-dependence of the
30 predictability of precipitation (Germann and Zawadzki, 2002; Turner et al., 2004).

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1 The stochastic perturbations should be able to reflect the properties of the forecast errors.
2 Generating spatially and temporally correlated forecast errors is mandatory for hydrological
3 applications, in particular when the correlation length of the errors is comparable or superior
4 to the size and response time of the catchment. *Spatially correlated stochastic noise* can be
5 constructed by applying a power law filter to a white noise field (Schertzer and Lovejoy,
6 1987). In practice it consists of three steps: computing the FFT of a white noise field,
7 multiplying the obtained components in frequency domain by a given filter and applying the
8 inverse FFT to return back to the spatial domain. The 1D or 2D power spectra of the rainfall
9 field can be used as filter to obtain noise fields that have the same scaling and spatial
10 correlation of the rainfall field. The 1D PS of the precipitation fields often appears to be a
11 power law of the spatial frequency and explains why the procedure is also called power law
12 filtering of white noise. In order to represent the anisotropies of the precipitation field the 2D
13 PS can also be used as filter. In the absence of a target precipitation field from which to derive
14 the PS, the filter can be parametrized by using a climatological power law (see Seed et al.,
15 2013). Finally, the *temporal correlations* are imposed by auto-regressive (AR) filtering. A
16 hierarchy of AR processes defines the temporal evolution of the cascade levels. With the
17 exception of forecast lead times beyond 2-3 hours (Atencia and Zawadzki, 2014), an AR
18 process of order 1 or 2 is already a good approximation to describe the temporal decorrelation
19 of the forecast errors.

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20 The practical implementation of STEPS to reproduce these important properties consists of
21 the following steps (see Bowler et al., 2006; Foresti and Seed, 2014):

- 22 1. Estimation of the velocity field using optical flow on the last two radar rainfall images
23 (Bowler et al., 2004a).
- 24 2. Decomposition of both rainfall fields into a multiplicative cascade using an FFT to
25 isolate a set of 8 spatial frequencies.
- 26 3. Estimation of the rate of temporal evolution of rainfall features at each level of the
27 cascade (Lagrangian auto-correlation).
- 28 4. Generation of a cascade of spatially correlated stochastic noise using as filter the 1D or
29 2D power spectra of the last observed radar rainfall field. A Gaussian filter is used to
30 isolate a given spatial frequency (see Foresti and Seed, 2014).
- 31 5. Stochastic perturbation of the rainfall cascade using the noise cascade (level by level).

- 1 6. Extrapolation of the cascade levels using a semi-Lagrangian advection scheme.
- 2 7. Application of the AR(1) or AR(2) model for the temporal update of the cascade levels
- 3 at each forecast lead time using the Lagrangian auto-correlations estimated in step (3).
- 4 8. Recomposition of the cascade into a rainfall field.
- 5 9. Probability matching of the forecast rainfall field with the original observed field
- 6 (Ebert, 2001).
- 7 10. Computation of the forecast rainfall accumulations from the instant forecast rainfall
- 8 rates. This procedure is known as advection correction and consists of advecting the
- 9 instant rainfall rate forward over the 5 min period by discretizing the advection into
- 10 smaller time steps.

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12 3.2. STEPS implementation at RMI (STEPS-BE)

13 Bowler et al. (2006) introduced a general framework for blending a radar-based extrapolation
14 nowcast with one or more outputs of downscaled NWP models (see also Pierce et al., 2010,
15 and Seed et al., 2013). Because of being designed for urban applications, the maximum lead
16 time of STEPS-BE is restricted to 2 hours. The operational NWP model of RMI (ALARO)
17 runs only 4 times daily using a grid spacing of 4 km. Considering the model spin-up time and
18 the absence of radar data assimilation, it is very unlikely that ALARO provides useful skill for
19 blending its output with a radar-based extrapolation nowcast within the considered
20 nowcasting range. It must also be reminded that the effective resolution of NWP models is
21 much larger than the grid spacing. For instance, Grasso (2000) estimates the effective
22 resolution to be at least 4 times the grid spacing, while Skamarock (2004) estimates it to be up
23 to 7 times the grid spacing. ALARO would then only be able to resolve features that are
24 greater than 20 km. For all these reasons, STEPS-BE only involves an extrapolation nowcast
25 without NWP blending.

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26 The STEPS-BE forecast domain is smaller than the extent of the 4 C-band radars composite
27 (see Fig. 1). The radar field was upscaled from the original resolution of 500 m to 1 km and a
28 sub-region of 512x512 grid points centered over Belgium was extracted. The forecast domain
29 was extended by 32 pixels on each side to reduce the edge effects due to the FFT. This leads
30 to an 8-levels multiplicative cascade representing the following spatial scales (rounded to the
31 nearest integer): 576-256, 256-114-51, 114-51-23, 51-23-11, 23-11-4, 11-4-2, 4-2-1 and 2-1

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1 km. Italic characters mark the scales on which the Gaussian filter is centered (see Foresti and
2 Seed, 2014, for a more detailed explanation and visualization of the Gaussian FFT filter). One
3 can notice that the spatial scales are not exact multiples of 2. In fact, a multiplication factor of
4 2,246 was employed to match the enlarged STEPS-BE domain size.

5 STEPS-BE includes a couple of improvements compared with the original implementation of
6 the BOM:

- 7 1. Kernel interpolation of optical flow vectors,
- 8 2. Generation of stochastic noise only within the advected radar mask.

9 The optical flow algorithm of Bowler et al. (2004a) estimates the velocity field by dividing
10 the radar domain into a series of blocks within which the optical flow equation is solved. The
11 minimization of the field divergence is only performed at the level of the block, which leaves
12 sharp discontinuities in the velocity field between the blocks. In order to overcome this issue,
13 a Gaussian kernel regression was applied to interpolate the velocity vectors located at the
14 center of the blocks onto the fine radar grid. The bandwidth of the Gaussian kernel was
15 chosen to be $\sigma = 24\text{km} = 0.4k$, where $k=60$ grid points is the block size. This setting has the
16 advantage of obtaining velocity fields that are less affected by the differential motion of small
17 rainfall features and the presence of ground clutter. A too precise velocity field would provide
18 increased predictability at very-short lead times but worse forecasts at longer lead times due
19 to excessive convergence and divergence of precipitation features during the advection.
20 Smooth velocity fields could also be obtained by using a smaller block size and by
21 compensating with a larger bandwidth of the smoothing kernel.

22 In STEPS-BE the 1D power spectrum of the last observed rainfall field is used as filter to
23 generate the spatially correlated stochastic perturbations. The PS is parameterized using two
24 spectral slopes to account for a scaling break that is often observed at the wavelength of 40
25 km (see Seed et al., 2013; Foresti and Seed, 2014). To simplify the computations, an auto-
26 regressive model of order 1 (AR(1)) was employed for imposing the temporal correlations
27 and to model the growth of forecast errors.

28 The original STEPS implementation (Bowler et al., 2006) was designed to blend the radar
29 extrapolation nowcasts with the output of NWP models. However, the domain covered by the
30 radars is smaller than the rectangular domain of the NWP model and small amounts of
31 stochastic noise are generated by default also outside of the radar composite. This setting was

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1 not adapted for radar-based nowcasts without NWP blending and needed some adaptation. In
2 fact, when advecting the radar mask over several time steps, large areas with small amounts
3 of stochastic rain appear outside of the validity domain of the forecast and perturb the
4 probability matching. In STEPS-BE the stochastic perturbations are only generated within the
5 advected radar domain and set to zero elsewhere.

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6 STEPS-BE can also account for the uncertainty in the estimation of the velocity field. The
7 STEPS version that is implemented in UK (Bowler et al., 2006) includes a detailed procedure
8 to generate velocity perturbations that reproduce various statistical properties of the
9 differences between the forecast velocity and the actual future diagnosed velocity (see details
10 in Bowler et al., 2004b). In the BOM and RMI implementations a simpler procedure is
11 applied. The diagnosed velocity field is multiplied by a single factor C that is drawn from the
12 following distribution:

13 $C = 10^{1.5N/10}$, (1)

14 where N is a normally distributed random variable with zero mean and unit variance. In other
15 words, the velocity field is accelerated or decelerated by a single random factor without
16 affecting the direction of the vectors. In fact, the uncertainty on the diagnosed speed was
17 observed to be higher than that of the direction of movement (Bowler et al., 2006).

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18 The BOM and RMI versions of STEPS also include a stochastic model for the radar
19 measurement error, a broken-line model to account for the unknown future evolution of the
20 mean areal rainfall and the possibility to use time-lagged ensembles. However, a nowcasting
21 model with too many components is harder to calibrate and complicates the interpretation of
22 the forecast fields. Because of these reasons, STEPS-BE only exploits the basic stochastic
23 model for the velocity field and for the evolution of rainfall fields (due to growth and decay
24 processes).

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25 The core of STEPS-BE is implemented in C/C++ and the production of figures in python.
26 Bash scripts were written to call multiple STEPS instances and compute the ensemble
27 members in parallel over several processors. Once all the ensemble members are computed, a
28 separate script collects the corresponding netCDF files and calculates the forecast
29 probabilities. Most of the computational cost of STEPS consists of filtering the white noise
30 field with FFT, advecting and updating the radar cascade with the AR model. The re-

1 calculation of optical flow fields on each processor takes less than 10% of the total
2 computational time.

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3 The python matplotlib library is used to read the netCDF files, export the PNG figures and the
4 time series of observed and forecast rainfall at the location of major cities and weather
5 stations. A single STEPS nowcast generates more than 600 figures, which takes a significant
6 fraction of the total computational time. In order to optimize the timing, a bash script
7 monitors continuously the directory with incoming radar composites and triggers STEPS-BE
8 once a field with a new time stamp is found. All these implementation details ensure that the
9 user/forecaster can have access to an ensemble STEPS nowcast in less than 5 min after
10 receiving the radar composite image.

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11 The visualization system of STEPS-BE is very similar to the one of INCA-BE, the local
12 Belgian implementation of the Integrated Nowcasting through Comprehensive Analysis
13 system (INCA, Haiden et al., 2011) developed at the Austrian weather office (ZAMG). Figure
14 1 illustrates the web interface with an example of an ensemble mean nowcast. The user can
15 highlight the major cities, weather stations and click to visualize the time series of observed
16 and forecast precipitation/probability, which appears at the bottom of the web page. The
17 navigation through the observations and forecast lead times is facilitated by the scroll wheel
18 of the mouse. On the other hand, by clicking on the image it is possible to easily scroll
19 through the various ensemble members or probability levels for a given lead time. Scrolling
20 the ensemble members at different lead times is very instructive and can make the user aware
21 of the forecast uncertainty. In fact, at a lead time of 5 min the ensemble members agree very
22 well on the intensity and location of precipitation. This means that the ensemble spread is
23 small and the probabilistic forecast is sharp, i.e. most of the forecast probabilities are close to
24 1 or 0 (see an explanation in Appendix A). On the other hand, at 1 or 2 hours lead time the
25 ensemble members disagree on the location and intensity of rainfall, which enhances the
26 ensemble spread and decreases the sharpness of the probabilistic forecast. The web page
27 includes extensive documentation to guide the user and a set of case studies to help
28 understanding the strengths and limitations of STEPS. The visualization system was
29 implemented with great attention to take full advantage of the multi-dimensional information
30 content of probabilistic and ensemble forecasts.

31

1 4 Forecast verification

2 4.1 Verification set-up

3 This section presents the verification of STEPS-BE forecasts using a set of case studies (see
4 Sect. 2). The accumulated radar observations were employed as reference for the verification.

5 The rainfall rates are accumulated over the last 5 min by reversing the field vectors based on
6 the observations and then performing the advection correction. The 30 min ensemble mean
7 forecast was verified against the observed 30 min radar accumulations using both continuous
8 and categorical verification scores. The deterministic verification procedure follows the one
9 presented in Foresti and Seed (2015), which was designed to analyze the spatial distribution
10 of the forecast errors. More details about the forecast verification setup and scores are given
11 in Appendix A.

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12 The continuous scores include the multiplicative bias and the root mean squared error
13 (RMSE), while the categorical scores include the probability of detection (POD), false alarm
14 ratio (FAR) and Gilbert skill score (GSS) derived from the contingency table for rainfall
15 thresholds of 0.5 mm hr⁻¹ and 5.0 mm hr⁻¹. The rainfall thresholds are given in equivalent
16 intensity independently of the forecast rainfall accumulation. Thus, a threshold of 5.0 mm hr⁻¹

17 on a 30 min accumulation corresponds to 2.5 mm of rain. The multiplicative bias and the
18 RMSE were evaluated only at the locations where the forecast or the verifying observations
19 exceeded 0.1 mm hr⁻¹, which can be referred to as a *weakly conditional verification*. The
20 probabilistic forecast of exceeding 0.1, 0.5, 5.0 mm hr⁻¹ was verified using the reliability
21 diagrams and ROC curves. Finally, the dispersion of the ensemble was analyzed by
22 comparing the ensemble spread to the RMSE of the ensemble mean and by using rank
23 histograms. The probabilistic and ensemble verification does not consider the spatial
24 distribution of the errors and pools the data together in both space and time to derive the
25 statistics.

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26 4.2 Deterministic verification

27 Figures 2 and 3 show the average forecast and observed rainfall rates corresponding to the 0-
28 30 min ensemble mean accumulation nowcast for the Ghent and Leuven cases respectively. In
29 other words, they represent the average forecast and observed rainfall rates over the duration

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1 | of the precipitation event (for the 0-30 min lead time). The average was computed using the
2 | weak conditional principle explained above.

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3 | The average forecast and observed accumulations generally agree very well for the 0-30 min
4 | lead time forecast. The Ghent case on 10 November 2013 (Figs. 2a and 2b) is the only one
5 | with northwesterly flows and is characterized by the lowest average rainfall rates. The
6 | Avesnois radar demonstrates very well the range-dependence of the average rainfall rates,
7 | which gradually decrease with increasing distance from the radar. On the contrary, the smaller
8 | ring of high rainfall rates around the Zaventem radar is mostly due to the bright band (Fig.
9 | 2b).

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10 | The bright band effect influences the radar observations and hence, the nowcasts based on
11 | their extrapolation. At longer lead times the larger rainfall estimates due to the bright band are
12 | extrapolated far from the location of the radar. The stochastic perturbations of STEPS can
13 | help to gradually dissolve the circular patterns introduced by the bright band effect. However,
14 | the bright band affects more the observations used for the verification, in particular when the
15 | rainfall is advected from upstream over the radar region. In such case, the local larger rainfall
16 | estimates lead to a verification bias and the forecasts are wrongly accused of rainfall under-
17 | estimation. In spite of these issues, bright band effects might not be so important for urban
18 | hydrological applications. In fact, except for one stratiform case presented in this paper,
19 | pluvial floods mainly happen in summer with convective precipitation events, during which
20 | the bright band is absent or negligible.

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21 | The Ghent case on 3 January 2014 has higher rainfall rates and the elongated structures of
22 | precipitation areas demonstrate well the southwesterly flow regime (Figs. 2c and 2d). For this
23 | case the measurements of the Zaventem radar are also affected by second trip echoes, which
24 | appear as a set of radially oriented rainfall structures North-West of the radar. These
25 | alternating patterns are explained by the dual PRF mode of Zaventem (see Sect. 2).

26 | The Leuven cases on 9 June 2014 and 19-20 July 2014 have an important convective activity
27 | (Figs. 3a, 3b, 3c and 3d). The maximum average rainfall rates are located over the Ardennes
28 | mountain range and the city of Leuven respectively. Since urban flash floods can be triggered
29 | by a single convective cell, the average rainfall rate over the duration of the event may not be
30 | as high in the considered city (e.g. Fig. 3b).

31 | Figure 4 illustrates the multiplicative bias of the 0-30 min nowcast averaged over each of the
32 | 4 events. A detailed interpretation of such forecast biases using Australian radar data and their

1 connection to orographic features is given in Foresti and Seed (2015), which point out that an
2 important fraction of the forecast errors is caused by the biases of the verifying radar
3 observations rather than systematic rainfall growth and decay processes due to orography. In
4 Fig. 4a it is easy to notice the effect of bright band, which causes a series of systematic
5 forecast biases around the Zaventem radar and perpendicularly oriented with respect to the
6 prevailing flow direction (NW). Systematic rainfall underestimation occurs along the Belgian
7 coast of the North Sea. One factor which contributes to this underestimation is the absence of
8 visibility of the radar at longer ranges. The incoming precipitation is suddenly detected by the
9 radar and therefore strongly underestimated by STEPS. The only situation where the range
10 dependence of the rainfall estimation does not affect the forecast verification occurs when the
11 velocity field is perfectly rotational and centered on the radar (assuming no beam blockage).
12 All the other cases have to deal with the fact that the rainfall nowcast also extrapolates the
13 biases of the radar observations! Contrary to expectation, on the upwind side of the Ardennes
14 there is overestimation, which may depict a region of systematic rainfall decay. The bias over
15 the city of Ghent is fortunately small and is included in the range from 0 to +0.5 dB (light
16 overestimation, rainfall decay). Having small systematic biases over the cities of interest is
17 very important for future integration of STEPS nowcasts as input in hydraulic models. In Fig.
18 4b the systematic underestimation is also located upstream with respect to the prevailing
19 winds (SW). The strong overestimations in Germany and The Netherlands are mostly due to
20 the underestimation of rainfall by the verifying radar observations rather than caused by
21 systematic rainfall decay. This is particularly visible after a range of 125 km from the
22 Zaventem radar, which demonstrates again that discontinuities and biases in the radar
23 observations lead to biases in the extrapolation forecast. Also in this case the bias over the
24 city of Ghent is small but in the range from -0.5 to 0 dB (light underestimation, rainfall
25 growth). A similar radar bias is visible in Fig. 4c but this time located at a range of 240 km
26 North of the Wideumont radar when entering the area covered by the Jabbeke radar. This
27 forecast bias is mainly explained by the negative calibration bias of the Jabbeke radar, which
28 is known to slightly underestimate the rainfall rates with respect to the Wideumont radar.
29 Strong underestimation occurs over the Ardennes due to the systematic initiation and growth
30 of convection that cannot be predicted by STEPS (Fig. 4c). Fortunately the city of Leuven is
31 located in a region with small biases in the range from -0.5 to +0.5 dB. Figure 4d is quite
32 interesting since strong underestimations are located in front of the rain band (from Charleroi
33 to Leuven and beyond) and overestimations at the rear of the rain band (West of the Jabbeke

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1 radar). The underestimations are due to systematic rainfall initiation in front of the rain band,
2 while the overestimations are probably caused by a too slow extrapolation of rainfall, which
3 tends to drag at the rear of the rain band. The two bands of underestimations South of Leuven
4 are caused by two different thunderstorms. The first one passed over the city of Leuven and
5 had a stronger westerly component with respect to the prevailing southerly flow. The second
6 thunderstorm was weaker and had a stronger easterly component. When isolated convection
7 does not follow the prevailing movement of the rainfall field, strong biases can appear in the
8 nowcast during the first lead times.

9 Figure 5 shows the spatial distribution of the RMSE for the stratiform event on 3 January
10 2014 in Ghent and the convective event on 20 July 2014 in Leuven. If compared with Figs. 2d
11 and 3d it is clear that the RMSE is strongly correlated with the regions having the highest
12 mean rainfall accumulations (proportional effect). Thus, it is not surprising that the RMSE of
13 the convective case (Fig. 5b) displays values exceeding 10 mm hr^{-1} over the city of Leuven.
14 The winter case only shows RMSE values below 2 mm hr^{-1} over the city of Ghent.

15 Figure 6 illustrates an example of categorical verification of the 30-60 min ensemble mean
16 forecast for the Leuven case on 19-20 July 2014 relative to the rainfall threshold of 0.5 mm
17 hr^{-1} . The probability of detection is high everywhere (mean of 0.75) except in the
18 neighborhood of Antwerp and South of Leuven, where the initiation of thunderstorms could
19 not be predicted by STEPS (Fig. 6a). The false alarm ratio is quite low (mean of 0.36) and the
20 regions with high values are mainly located at the rear of the front where the rainfall is
21 advected too slowly compared with the actual movement of the front (Fig. 6b). A high Gilbert
22 skill score generally coincides with the regions with the highest rainfall accumulations and
23 becomes lower at the edges of the rain areas (Fig. 6c). This finding can be explained
24 conceptually if one thinks about the verification of the future path of a single convective cell.
25 The regions with the highest uncertainty are located along the edges of the predicted
26 thunderstorm path and the highest skill is obtained in the center of the predicted path.

27 **4.3 Probabilistic verification**

28 Figure 7 shows the reliability diagrams relative to the probabilistic forecast of exceeding the
29 0.5 and 5.0 mm hr^{-1} rainfall thresholds for the Ghent case on 03 January 2014 (Figs. 7a and
30 7b) and the Leuven case on 19-20 July 2014 (Figs. 7c and 7d). The reference probabilistic
31 forecast is taken as the climatological frequency of exceeding a given rainfall threshold during

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1 | that precipitation event (horizontal dashed line). Unexpectedly, the forecasts of the stratiform
2 case in Ghent are less reliable than the ones of the convective case in Leuven for both rainfall
3 thresholds. Probabilistic forecasts of exceeding 0.5 mm hr^{-1} for the Ghent case have a good
4 reliability and positive Brier skill score (BSS) up to 60 min lead time (Fig. 7a). The higher
5 rainfall threshold of 5.0 mm hr^{-1} is harder to predict and there is skill only up to 30 min lead
6 time (Fig. 7b). The convective case in Leuven is more predictable and the probabilistic
7 forecast of exceeding 0.5 mm hr^{-1} exhibits skill up to 90 min lead time (Fig. 7c). It is
8 interesting to note that forecast probabilities that are close to the climatological frequency
9 (intersection of lines around the probability 0.15) often fall outside of the skillful region. In
10 fact, a small systematic forecast bias is likely to be worse than the event climatology at those
11 frequencies. The rainfall threshold of 5.0 mm hr^{-1} shows again a limit of predictability of 30
12 min (Fig. 7d). Despite having a negative BSS, the following lead times (Fig. 7d) have higher
13 resolution than the stratiform case in Ghent (Fig. 7b).

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14 Figure 8 illustrates the ROC curves relative to the probabilistic forecast of exceeding 0.1 mm
15 hr^{-1} for the Ghent case on 03 January 2014 (Figs. 8a) and the Leuven case on 19-20 July 2014
16 (Figs. 8b). All the ROC curves are very far from the diagonal line of no skill. The probability
17 level that is marked with a cross is the one which maximizes the difference between the hit
18 rate HR and the false alarm rate F (not to be confused with the false alarm ratio which is
19 conditioned on the forecasts). This point is located within the probabilities 0.1 and 0.2, which
20 means that an optimal forecast of the probability of rain is achieved when only 10-20% of the
21 ensemble members exceed the 0.1 mm hr^{-1} threshold. A forecaster who is not scared of
22 making false alarms would choose a lower probability level to increase the number of hits. On
23 the contrary, an unconfident forecaster who would like to minimize the false alarms would
24 choose a higher probability level, which has however the consequence of reducing the number
25 of hits. As expected, the area under the ROC curves (AUC) decreases for increasing lead
26 times. The discrimination skill for the convective event in Leuven is slightly higher than the
27 one of the stratiform event in Ghent, which confirms the findings on the reliability diagrams
28 (Fig. 7). This does not mean that small scale features are easier to forecast than larger scales
29 features, which is known to be false (see Foresti and Seed, 2014). It means that the
30 predictability of well defined and organized convective systems is higher than the one of more
31 moderate convection with shorter lifetime, at least for the cases analyzed in this paper.

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1 4.4 Ensemble verification

2 Figure 9 compares the error of the ensemble mean (RMSE) and the ensemble spread for the
3 Ghent case on 03 January 2014 and the Leuven case on 19-20 July 2014 (see interpretation of
4 ensemble spread in Appendix A). In both cases the RMSE increases up to a lead time of 50-
5 60 min and then starts a slow decrease, which can be counter-intuitive. However, it must be
6 reminded that the ensemble mean forecast becomes smoother for increasing lead times, which
7 reduces the double penalty error due to forecasting a thunderstorm at the wrong location. The
8 ensemble spread also increases up to 50-60 min lead time and then slowly stabilizes. For both
9 the Ghent and Leuven cases the ensemble spread is lower than the error of the ensemble mean
10 at all lead times, which suggests that the ensemble forecasts are under-dispersive. The degree
11 of under-dispersion is highest at a lead time of 5 min, with the spread values being equal to
12 60% of the forecast error for the winter event in Ghent (Fig. 9a) and 70% for the summer
13 event in Leuven (Fig. 9b). Except for the 5 min lead time, the ensemble spread represents 75-
14 90% of the forecast error for the Ghent case (Fig. 9a) and 75-80% for the Leuven case (Fig.
15 9b), which is a good result. It is not yet clear why the RMSE at a lead time of 5 min is higher
16 than the one at 10 min for the winter case in Ghent (Fig. 9a).

17 The under-estimation of the ensemble dispersion at the first lead time can be attributed to both
18 the under-estimation of the ensemble spread and the over-estimation of the ensemble mean
19 RMSE, but with different degrees according to the different causes. High RMSEs at the start
20 of the nowcast can be due to using a very smooth velocity field for the advection (see Section
21 3.2), which does not exploit sufficiently the very short term predictability of small scale
22 precipitation features, but is optimized for predictions at longer lead times. Another
23 explanation for this underestimation of ensemble dispersion could be due to the space-time
24 variability of the Z-R relationship. Spatial and temporal changes in the drop size distribution
25 (DSD) can lead to changes in the estimated rainfall rate that is used for the verification.
26 Therefore, there could be a mismatch between the "fixed" DSD of the forecasts and the
27 variable DSD underlying the verifying observations. Another possible source of mismatch
28 could be due to the advection correction with optical flow when computing the rainfall
29 accumulations. The forecast accumulations are computed by advecting forward the previous
30 rainfall field. On the other hand, the observed accumulations are computed by reversing the
31 optical flow vectors and advecting the rainfall field backwards (see Section 4.1). This choice
32 increases the differences when comparing the +0-5 min forecast accumulations (advection of

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1 | the 0 min image forward) with the +0-5 min observed accumulations a posteriori (advection
2 | of the +5 min image backwards). The ideal approach would be to derive the accumulation by
3 | advecting both the previous image forward and the last image backwards. An optimal
4 | accumulation could be computed by a weighted average of the two advected images by
5 | discretizing the 5 min interval. However, such approach is not very pragmatic and would
6 | require additional computational time in order to obtain a marginal improvement on the
7 | forecasts.

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8 | Figure 10 illustrates the rank histograms for the Leuven case on 19-20 July 2014 for lead
9 | times of 5 and 60 min. The U-shape of the rank histograms demonstrates again a certain
10 | degree of ensemble under-dispersion. In particular, all the ensemble members for the 5 min
11 | lead time are inferior to the observations in ~16% of the cases (Fig. 10a), while for the 60 min
12 | lead time it happens in more than ~30% of the cases (Fig. 10b). On the other hand, the
13 | fraction of observations falling below the value of the lowest ensemble member is only 8%
14 | for both lead times. Despite the fact that STEPS is designed to reproduce the space-time
15 | variability of rainfall, it underestimates a certain fraction of the observed rainfall extremes.
16 | This underestimation grows with increasing lead time and depicts an increasing smoothness
17 | of the STEPS ensembles, which is probably due to the advection of the radar rainfall cascade
18 | (see Sect. 3, step 6). In fact, the small scale rainfall features represented by the bottom
19 | cascade levels suffer more from numerical diffusion during the Lagrangian extrapolation,
20 | which is observed as a gradual loss of variability in the forecast ensembles.

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21 | 4.5 Verification summary of the events

22 | Table 2 provides a comparison of the verification scores for each event. The average standard
23 | deviation of the multiplicative biases of the 30 min lead time forecast is in the range 0.3-0.8.
24 | Except for the event on 19-20 July 2014 the biases remain well below 1 dB for all lead times,
25 | which is a positive result. Of course, these are average values and locally they can even
26 | exceed 3 dB (see Fig. 4).

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27 | On the other hand, the RMSE values mark more the distinction between the two winter cases
28 | in Ghent and the two summer cases in Leuven. For the winter cases the RMSE values
29 | increase from 0.38-0.95 at a lead time of 30 min to 0.78-1.48 at 120 min, while for the
30 | summer cases from 1.84-2.45 to 2.52-3.38 mm hr⁻¹. Thus, the RMSE of a 30 min lead time
31 | nowcast of the two convective cases is higher than the RMSE of a 120 min nowcast of the

1 | two stratiform cases, as might be expected. It is interesting to mention that linear verification
2 | scores such as the RMSE strongly depend on the variance of the data. Consequently, it would
3 | be difficult to compare the error of the STEPS ensemble mean nowcast with the one of a
4 | deterministic nowcast, for example computed by INCA-BE. In fact, the ensemble averaging
5 | process filters out the unpredictable precipitation features and is rewarded in terms of RMSE.
6 | Similar results were already observed in Foresti et al. (2015), who also pointed out the
7 | difficulty of comparing ensemble prediction systems having a different number of ensemble
8 | members.

9 | The probability of detection relative to the 0.5 mm hr⁻¹ threshold decreases from 78-86% to
10 | 33-58%, while the false alarm ratio increases from 10-17% to 46-65%. The Gilbert skill score
11 | starts with values of 0.58-0.64 and 0.29-0.40 at the 30 and 60 min lead times respectively and
12 | decays to values of 0.08-0.20 at 120 min. Wang et al. (2009) reported a Critical success index
13 | value of 0.45 for STEPS nowcasts of 0-60 accumulations relative to the 1 mm hr⁻¹ threshold.
14 | Considering that the GSS is the CSI corrected by random chance, this value is comparable
15 | with the ones of the 30-60 min accumulations obtained in this paper. The GSS values relative
16 | to the threshold of 5.0 mm hr⁻¹ are much lower. They oscillate between 0.15 and 0.44 for the
17 | first lead time and become very low and close to 0 afterwards. Thus, the predictability of
18 | rainfall structures exceeding 5.0 mm hr⁻¹ rarely exceeds 30 min according to the GSS.

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19 | The area under the ROC curve values characterizing the potential discrimination power of the
20 | probabilistic forecast of exceeding 0.5 mm hr⁻¹ start at 0.92-0.95 at 30 min lead time and
21 | decrease to 0.69-0.79 at 120 min. For the probabilistic forecast of exceeding 5.0 mm hr⁻¹ they
22 | start at 0.88-0.90 and decrease to 0.62 for the convective cases and to 0.50 for the stratiform
23 | cases (no discrimination).

24 | From all these results we can conclude that there is not much predictability beyond 2 hours
25 | lead time by extrapolating the 4 C-band composite radar image in Belgium. Therefore, a
26 | maximum lead time of 2 hours in STEPS-BE is a good choice. Extending this lead time
27 | requires blending the radar-extrapolation nowcast with the output of NWP models to increase
28 | the predictability of precipitation.

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1 5 Conclusions

2 The Short-Term Ensemble Prediction System (STEPS) is a probabilistic nowcasting system
3 based on the extrapolation of radar images developed at the Australian Bureau of
4 Meteorology in collaboration with the UK MetOffice. The principle behind STEPS is to
5 produce an ensemble forecast by perturbing a deterministic extrapolation nowcast with
6 stochastic noise. The perturbations are designed to reproduce the spatial and temporal
7 correlations of the forecast errors and the scale-dependence of the predictability of
8 precipitation.

9 This paper presented the local implementation, adaptation and verification of STEPS at the
10 Royal Meteorological Institute of Belgium, referred to as STEPS-BE. STEPS-BE produces in
11 real-time 20 member ensemble nowcasts at 1 km and 5 min resolutions up to 2 hours lead
12 time using the 4 C-band radar composite of Belgium. Compared with the original
13 implementation, STEPS-BE includes a kernel-based interpolation of optical flow vectors to
14 obtain smoother velocity fields and an improvement to generate stochastic noise only within
15 the advected radar composite to respect the validity domain of the nowcasts.

16 The performance of STEPS-BE was verified using the radar observations as reference on four
17 case studies that caused sewer system floods in the cities of Ghent and Leuven during the
18 years 2013 and 2014. The ensemble mean forecast of the next four 30 min accumulations was
19 verified using the multiplicative bias, the RMSE as well as some categorical scores derived
20 from the contingency table: the probability of detection, false alarm ratio and Gilbert skill
21 score (Equitable skill score). The spatial distribution of multiplicative biases revealed regions
22 of systematic over- and under-estimation by STEPS. The underestimations are often
23 associated with the locations of convective initiation and thunderstorm growth, which cannot
24 be predicted by STEPS. On the other hand, the regions of overestimation are mostly due to
25 the underestimation of rainfall by the verifying observations rather than systematic rainfall
26 decay (see Foresti and Seed, 2015, for a more detailed discussion). In order to disentangle the
27 forecast and observation biases, detailed knowledge about the spatial distribution of the radar
28 measurement errors for a given weather situation is needed. The multiplicative biases over the
29 cities of Leuven and Ghent are very low (from -0.5 dB to +0.5 dB), which is a good starting
30 point to integrate STEPS nowcasts as inputs into sewer system hydraulic models. The
31 categorical forecast verification helped discovering the places with low probability of
32 detection due to convective initiation at the front of the rain band and high false alarm ratio at

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1 the rear of the rain band, likely due to a too slow rainfall extrapolation by STEPS. Reliability
2 diagrams demonstrated that probabilistic forecasts of exceeding 0.5 mm hr^{-1} have skill up to
3 60-90 min lead time. On the contrary, convective features exceeding 5.0 mm hr^{-1} are only
4 predictable up to 30 min. In terms of reliability and discrimination ability, it was also
5 observed that the forecasts of convective events have more skill than the ones on stratiform
6 events. The STEPS ensembles are characterized by a certain degree of under-estimation of the
7 forecast uncertainty, with values of the ensemble spread close to 75-90% of the forecast error.

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8 The current contribution focused on the verification of STEPS-BE nowcasts using only four
9 precipitation cases of different character. The deterministic and categorical verification
10 require many more cases to analyze the climatological distribution of the forecast errors, e.g.
11 as done in Foresti and Seed (2015). On the other hand, the probabilistic and ensemble
12 verification pool the data in both space and time and converges much faster to stable statistics.

13 From a research perspective, STEPS-BE could also be extended by including a stochastic
14 model to account for the residual radar measurement errors, in particular to obtain more
15 accurate estimations of the forecast uncertainty at short range. The STEPS framework also
16 allows blending the extrapolation nowcast with the output of NWP models, which is a
17 necessary step to increase the predictability of precipitation for lead times beyond 2 hours.

1 **Appendix A: Forecast verification scores**

2 Forecast verification is an important aspect of a forecasting system. A forecast without an
 3 estimation of its accuracy is not very informative. For an in-depth description of forecast
 4 verification science and corresponding scores we refer to Jolliffe and Stephenson (2011) and
 5 the verification website maintained at the Bureau of Meteorology ([http://www.cawcr.gov.au/
 6 projects/verification/](http://www.cawcr.gov.au/projects/verification/)).

7 The STEPS *ensemble mean forecast* was verified using the following scores:

- 8 • Multiplicative bias:

9
$$bias = \frac{1}{N} \sum_{i=1}^N 10 \log_{10} \left(\frac{F_i + b}{O_i + b} \right), \quad (1)$$

10 where F_i is the forecast rainfall at a given grid point, O_i is the observed rainfall at a
 11 given grid point, $b=2 \text{ mm hr}^{-1}$ is an offset to eliminate the division by zero and to
 12 reduce the contribution of the forecast errors at low rainfall intensities, and N is the
 13 number of samples. For the specific case of the verification of the spatial distribution
 14 of forecast biases, the summation is performed over time. Thus, N corresponds to the
 15 number of forecasts where either the forecast or the observed rainfall are greater than
 16 0.1 mm hr^{-1} at a given grid point (denoted as weak conditional verification). The bias
 17 is given in decibels [dB] in order to obtain a more symmetric distribution of the
 18 multiplicative errors centered at 0, which is not possible with the simple power ratio
 19 F/O . The following table summarizes the correspondence between the decibel scale
 20 and the power ratio:

dB	-6	-3	-1	-0.5	0	+0.5	+1	+3	+6
Power ratio (F/O)	0.251	0.501	0.794	0.891	1	1.122	1.259	1.995	3.981

21 For example, a bias of +3 dB occurs when the forecast rainfall F is twice as much as
 22 the observed rainfall O .

- 23 • Root mean square error: $RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^N (F_i - O_i)^2}$. (2)

- 24 • Contingency table of a dichotomous (yes/no) forecast:

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		Observed		
		Yes	No	Total
Forecast	Yes	hits	false alarms	forecast yes
	No	misses	correct negatives	forecast no
Total		observed yes	observed no	total

2 where the *hits* is the number of times that both the observation and the forecast exceed
 3 a given rainfall threshold (at a given grid point), the *false alarms* is the number of
 4 times that the forecast exceeds the threshold but the observation does not, the *misses* is
 5 the number of times that the forecast does not exceed the threshold but the observation
 6 does and the *correct negatives* is the number of times that both the observation and the
 7 forecast do not exceed the threshold.

- 8 • Different scores can be derived from the contingency table to characterize a particular
 9 feature or skill of the forecasting system:

10 ○ Probability of detection (hit rate): $POD = \frac{hits}{hits + misses} = \frac{hits}{observed\ yes}$, (3)

11 The *POD* characterizes the fraction of observed events that were correctly
 12 forecast and is also known as hit rate (*HR*).

- 13 ○ False alarm ratio:

14 $FAR = \frac{false\ alarms}{hits + false\ alarms} = \frac{false\ alarms}{forecast\ yes}$, (4)

15 The *FAR* characterizes the fraction of forecast events that were wrongly
 16 forecast.

17 ○ False alarm rate: $F = \frac{false\ alarms}{false\ alarms + correct\ negatives} = \frac{false\ alarms}{observed\ no}$. (5)

18 The false alarm rate *F* is conditioned on the observations, while the false alarm
 19 ratio *FAR* on the forecasts.

- Gilbert skill score (Equitable threat score):

$$GSS = \frac{hits - hits_{random}}{hits + misses + false\ alarms - hits_{random}}, \quad (6)$$

$$\text{where } hits_{random} = \frac{(hits + misses)(hits + false\ alarms)}{total} = \frac{(observed\ yes)(forecast\ yes)}{total} \quad (7)$$

is the number of hits obtained by random chance, which is calculated by multiplying the marginal sums of the observed and forecast events (such as computing the theoretical frequencies for the Chi-squared test). The GSS characterizes the detection skill of the forecasting system w.r.t. random chance. In practice it corresponds to the Critical success index (CSI) adjusted for the hits obtained by random chance.

The accuracy of probabilistic forecasts can be verified in various ways. In this paper we employ the reliability diagram and the Receiver Operating Characteristic curve (ROC). The reliability diagram compares the forecast probability with the observed frequency. Reliability characterizes the agreement between the forecast probability and observed frequency. For a reliable forecasting system the two values should be the same, which happens for example when we observe rain 80% of the time when it is forecast with 80% probability (in average, diagonal line of Fig. 8). Unreliable forecasts exhibit departures from this optimum (bias). Resolution characterizes the ability of the forecasts to categorize the observed frequencies into distinct classes. The complete lack of resolution occurs when the forecast probabilities are completely unable to distinguish the observed frequencies, which generally corresponds to the climatological frequency of exceeding a given precipitation threshold (horizontal dashed line in Fig. 8). The Brier skill score (BSS) characterizes the relative accuracy of the probabilistic forecast compared to a reference system (see Jolliffe and Stephenson, 2011). Although the climatology or sample climatology of the event is often used as a reference, the BSS can also be computed against other reference forecasts, e.g. another probability forecasting method or even a deterministic forecasting method treated as a probabilistic binary forecast. However, in such cases it is not possible to draw a unique horizontal line of no skill in Figure 8. The region where the probabilistic forecast has a positive BSS, i.e. it is better than the climatological frequency, is grayed out. In fact, the points located below the no skill line are closer to the climatological frequency and produce a negative BSS. Reliability diagrams usually contain the histogram of the forecast probabilities to analyze the sharpness of the forecasts (small inset in Fig. 8). Sharpness characterizes the ability to forecast

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Deleted: The Brier skill score characterizes the relative skill of the probabilistic forecast compared with the one obtained by using the climatological frequency (see Jolliffe and Stephenson, 2011)

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1 | probabilities that are different from the reference forecast. Sharp forecasting systems are
2 | “confident” about their predictions and give many probabilities around one and zero.

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3 | The ROC curve is used to analyze the discrimination power of a probabilistic forecast of
4 | exceeding a given rainfall threshold. It is constructed by plotting the hit rates and false alarm
5 | rates evaluated at increasing probability thresholds to make the binary decision whether it will
6 | rain or not. The ROC curve of a random probabilistic forecast system lies on the diagonal
7 | where the hit rate equals the false alarm rate (no skill): the forecast probabilities do not have
8 | discrimination power. When the false alarm rate is higher than the hit rate the forecast is
9 | worse than that obtained by random chance (below the diagonal). A skilled forecasting system
10 | is observed when the hit rates are higher than the false alarm rates, which draws a
11 | characteristic curve. The area under the ROC curve (AUC) measures the discrimination power
12 | of the probabilistic forecasts, with a maximum value of 1 (100% of hits and 0% of false
13 | alarms) and a minimum value of 0.5 for a random forecasting system. Values below 0.5
14 | denote a forecasting system that performs worse than random chance. The AUC is computed
15 | by integrating over all the trapezoids that can be drawn below the ROC curve. The AUC is
16 | not sensitive to the forecast bias and the reliability of the forecast could be still improved
17 | through calibration. For this reason the AUC is only a measure of potential skill.

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18 | The ensemble forecasts are verified to detect whether there is over- or under-dispersion. It is
19 | common practice to compare the “skill” (error) of the ensemble mean with the ensemble
20 | spread (Whitaker and Loughe, 1998; Foresti et al., 2015):

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$$21 \quad spread = \frac{1}{N} \sum_{i=1}^N \sqrt{\frac{1}{M-1} \sum_{m=1}^M (F_{im} - \bar{F}_i)^2} \quad (9)$$

22 | where M is the number of ensemble members (ensemble size), F_{im} is the forecast of a given
23 | ensemble member and \bar{F}_i is the ensemble mean forecast (at a given grid point). Since we are
24 | not analyzing the spatial or temporal distribution of the ensemble spread, N corresponds to the
25 | total number of samples in space and time, which is the number of forecasts within a rainfall
26 | event multiplied by the number of grid points within a radar field. The weak conditional
27 | verification is also applied to the computation of the spread. The ensemble spread
28 | characterizes the variability of the ensemble members about the ensemble mean (standard
29 | deviation). For a good ensemble prediction system, the ensemble spread should be equal to
30 | the average variability of the observations about the ensemble mean, as measured by the

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1 RMSE of the ensemble mean (Eq. (2)). If the spread is larger than the RMSE, the ensemble is
2 overestimating the forecast uncertainty (over-dispersion), otherwise it is underestimating it
3 (under-dispersion). It is interesting to mention that the ensemble mean RMSE and ensemble
4 spread could also be computed starting from the logarithm of rainfall rates to account for the
5 skewed distribution of precipitation (not used in this paper).

6 Another way to analyze the spread of ensemble forecasts is based on rank histograms (also
7 known as Talagrand diagram). First, the precipitation values of the ensemble members are
8 ranked in increasing order. Then, the rank of the observation is evaluated by checking in
9 which of the $M+1$ bins it falls. By repeating the operation for a large number of cases and
10 forecasts it is possible to construct a histogram. A good ensemble prediction system displays a
11 flat histogram, i.e. the observations are indistinguishable from the forecasts and each
12 ensemble member is an equi-probable realization of the future state of the atmosphere. A bell-
13 shaped histogram with a peak in the middle is observed in case of ensemble over-dispersion.
14 On the contrary, a U-shape histogram with peaks at the edges is observed in case of ensemble
15 under-dispersion, which is more common (in particular for NWP ensembles). In this case the
16 values of the observations often fall below or above the lowest or highest value of the ranked
17 ensemble, which is not dispersive enough to capture the extremes.

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19 Acknowledgments

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21 “Forecasting and management of rainfall-induced risks in the urban environment”
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23 implementation and the guidance for various code improvements. We also acknowledge
24 Meteo-France for providing the Avesnois data.

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1 | Table 1. List of precipitation events that caused sewer system floods in Ghent and Leuven.

City	Date	Event start [UTC]	Event end [UTC]	Duration	Predominant precipitation	Main wind direction
Ghent	10 Nov. 2013	13:50	22:00	8h 10min	Stratiform	WNW → NNW
Ghent	3 Jan. 2014	03:00	14:00	11h	Stratiform	SW → WSW
Leuven	9-10 June 2014	06:30, 9 th	15:30, 10 th	33h	Convective	SW
Leuven	19-20 July 2014	22:00, 19 th	06:30, 20 th	8h 30min	Convective	SSW

1 Table 2. Summary of the forecast verification scores of the next four 30 min accumulation
 2 forecasts for the precipitation events in Ghent and Leuven. The lead time shown is the end of
 3 the 30 min accumulation period (e.g. 60 min is relative to the 30-60 min accumulation). The
 4 bias values correspond to the standard deviation of the multiplicative bias, which is more
 5 interesting than its mean (often close to 0).

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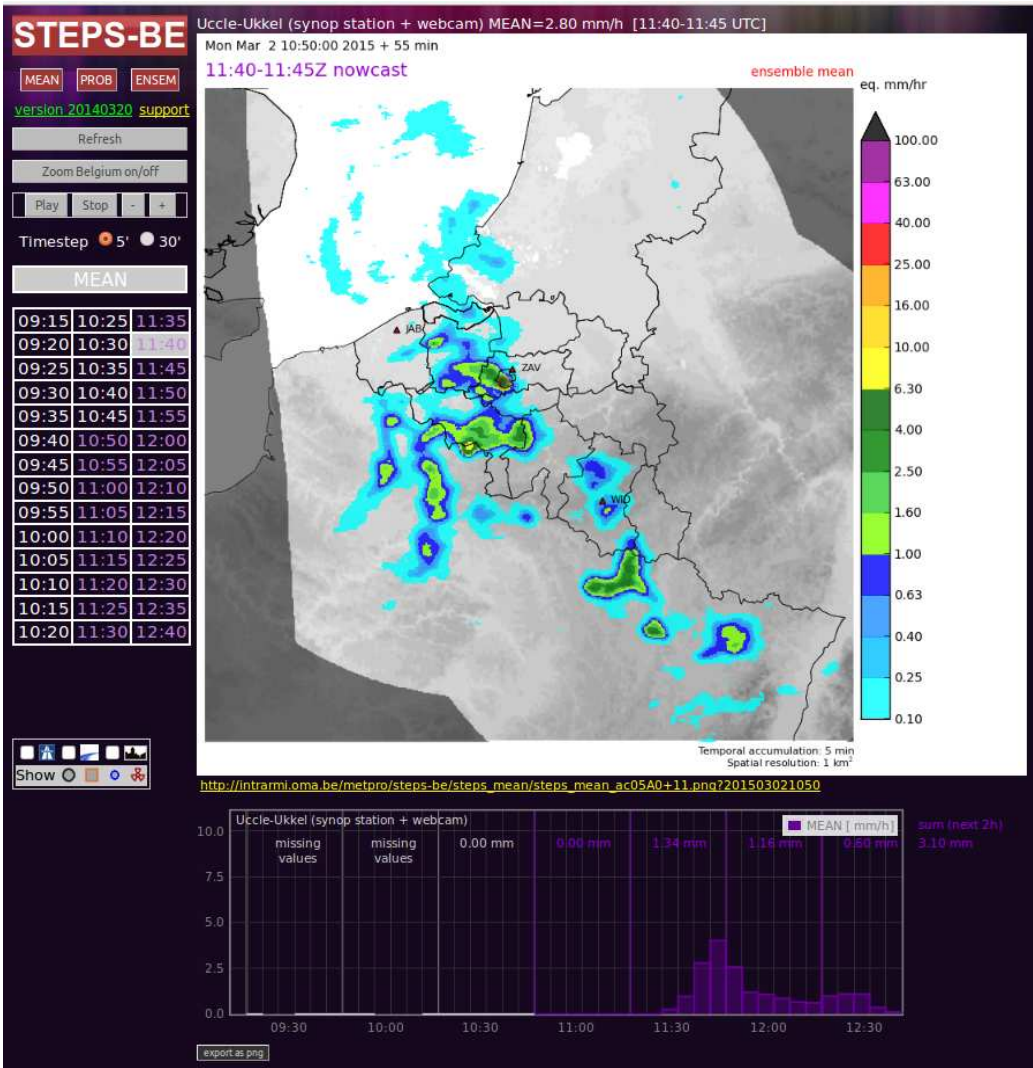
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Event	Bias 30min	Bias 60min	Bias 90min	Bias 120min	RMSE 30min	RMSE 60min	RMSE 90min	RMSE 120min
	[dB]				[mm hr ⁻¹]			
10.11.2013	0.30	0.49	0.61	0.70	0.38	0.59	0.71	0.78
03.01.2014	0.54	0.74	0.82	0.89	0.95	1.39	1.53	1.48
9-10.06.2014	0.52	0.63	0.66	0.69	2.45	3.26	3.40	3.38
19-20.07.2014	0.84	1.18	1.30	1.35	1.84	2.36	2.49	2.52
Event	POD 30min	POD 60min	POD 90min	POD 120min	FAR 30min	FAR 60min	FAR 90min	FAR 120min
	Forecast >= 0.5 mm hr ⁻¹				Forecast >= 0.5 mm hr ⁻¹			
10.11.2013	0.83	0.71	0.62	0.54	0.17	0.30	0.38	0.46
03.01.2014	0.80	0.63	0.49	0.33	0.10	0.25	0.45	0.65
9-10.06.2014	0.78	0.65	0.55	0.46	0.15	0.32	0.44	0.54
19-20.07.2014	0.86	0.75	0.66	0.58	0.17	0.36	0.50	0.61
Event	GSS 30min	GSS 60min	GSS 90min	GSS 120min	GSS 30min	GSS 60min	GSS 90min	GSS 120min
	Forecast >= 0.5 mm hr ⁻¹				Forecast >= 5.0 mm hr ⁻¹			
10.11.2013	0.58	0.38	0.27	0.20	0.15	0.02	0.0	0.0
03.01.2014	0.64	0.40	0.20	0.08	0.28	0.06	0.0	0.0
9-10.06.2014	0.59	0.38	0.26	0.17	0.44	0.20	0.09	0.04
19-20.07.2014	0.58	0.29	0.14	0.07	0.27	0.09	0.04	0.02
Event	AUC 30min	AUC 60min	AUC 90min	AUC 120min	AUC 30min	AUC 60min	AUC 90min	AUC 120min
	Forecast >= 0.5 mm hr ⁻¹				Forecast >= 5.0 mm hr ⁻¹			
10.11.2013	0.95	0.89	0.84	0.79	0.88	0.67	0.56	0.50
03.01.2014	0.92	0.85	0.78	0.69	0.90	0.72	0.57	0.50
9-10.06.2014	0.93	0.86	0.81	0.76	0.89	0.77	0.68	0.62
19-20.07.2014	0.94	0.87	0.82	0.77	0.88	0.75	0.68	0.62

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Figure 1. Web platform of STEPS-BE showing the ensemble mean forecast.

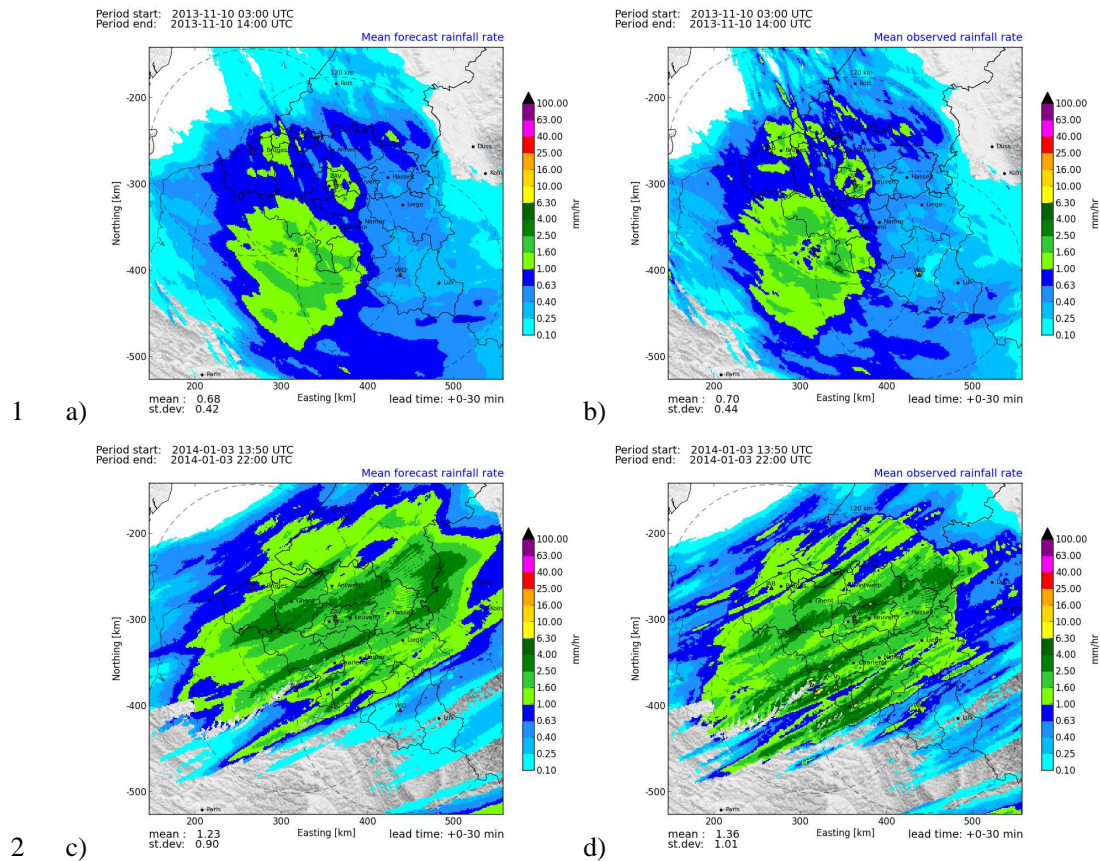


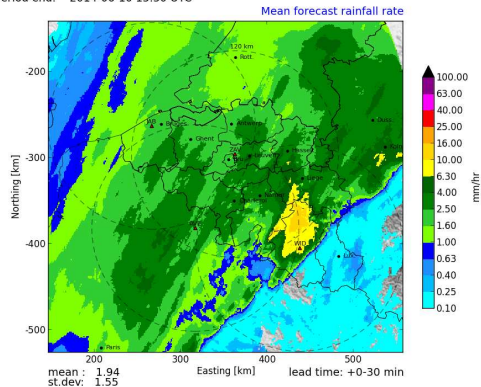
Figure 2. Average forecast and observed rainfall accumulations for the Ghent cases.

a) Forecast and b) observed 0-30 min rainfall accumulations on 10 November 2013.

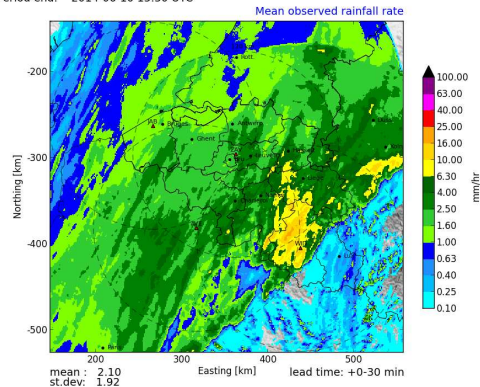
c) Forecast and d) observed 0-30 min rainfall accumulations on 03 January 2014.

The mean and standard deviation of the field within the 120 km range of the radars are shown on the bottom left corner. Field values are shown only if there are at least 10 samples for the computation of the mean. The red triangles denote the location of the Wideumont (WID, coordinates: 438 km East / -405 km North), Zaventem (ZAV, 363/-296), Jabbeke (JAB, 266/-263) and Avesnois (AVE, 317/-382) radars. The 120 km range from the radar is displayed as a dashed circle. The mountain range of the Ardennes covers the three most southern districts of Belgium and Luxembourg (LUX).

Period start: 2014-06-09 06:30 UTC
Period end: 2014-06-10 15:30 UTC

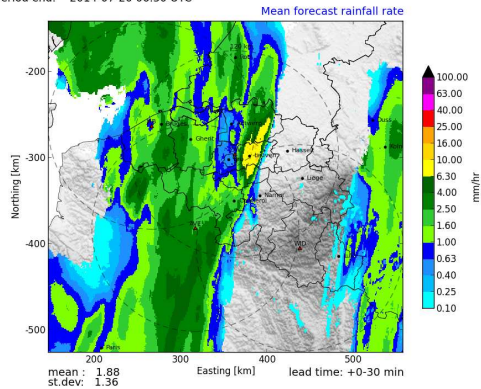


Period start: 2014-06-09 06:30 UTC
Period end: 2014-06-10 15:30 UTC

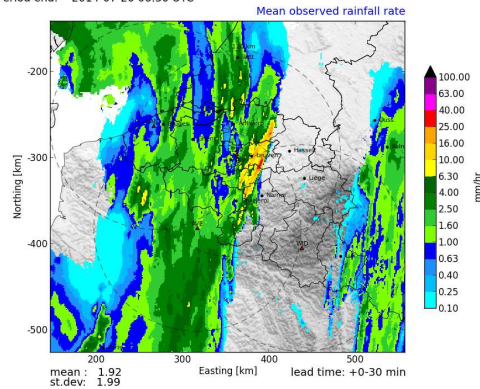


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Period start: 2014-07-19 22:00 UTC
Period end: 2014-07-20 06:30 UTC



Period start: 2014-07-19 22:00 UTC
Period end: 2014-07-20 06:30 UTC



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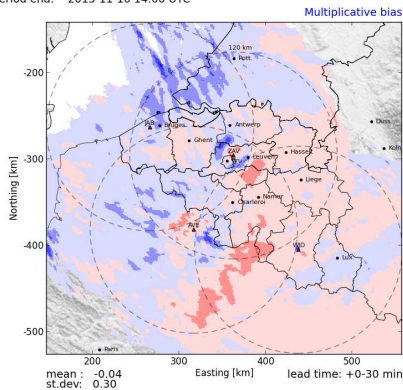
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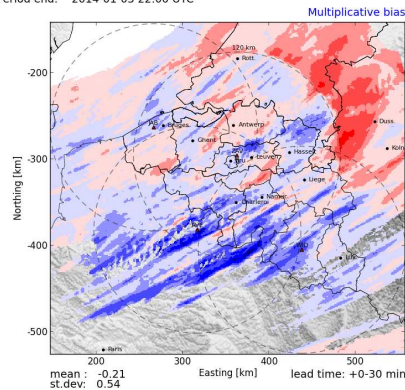
Figure 3. Average observed and forecast rainfall accumulations for the Leuven cases.
a) Forecast and b) observed 0-30 min rainfall accumulations on 9-10 June 2014.
c) Forecast and d) observed 0-30 min rainfall accumulations on 19-20 July 2014.

Period start: 2013-11-10 03:00 UTC
Period end: 2013-11-10 14:00 UTC



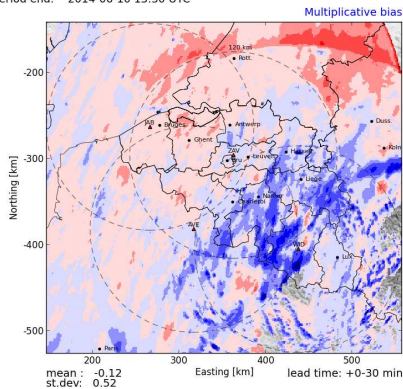
1 a)

Period start: 2014-01-03 13:50 UTC
Period end: 2014-01-03 22:00 UTC



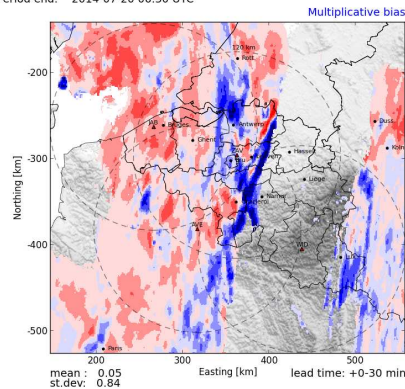
b)

Period start: 2014-06-09 06:30 UTC
Period end: 2014-06-10 15:30 UTC



2 c)

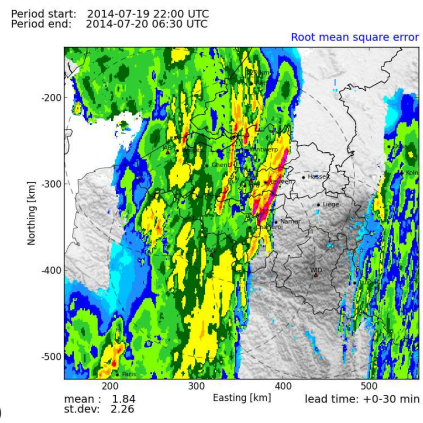
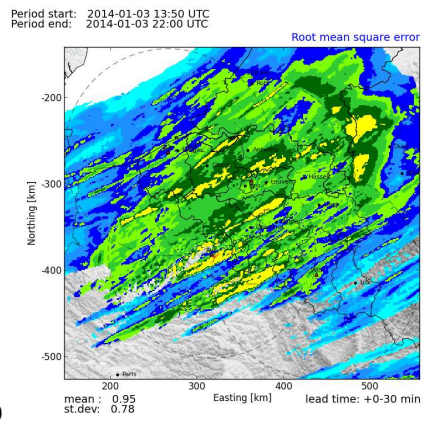
Period start: 2014-07-19 22:00 UTC
Period end: 2014-07-20 06:30 UTC



d)

3 Figure 4. Average 0-30 min multiplicative forecast biases for
4 the Ghent cases on a) 10 November 2013 and on b) 03 January 2014 and
5 the Leuven cases on c) 9-10 June 2014 and on d) 19-20 July 2014.

6 The interpretation of under- and over-estimations by STEPS as systematic rainfall growth and
7 decay or simply as radar measurement biases is subject to interpretation as explained in text.

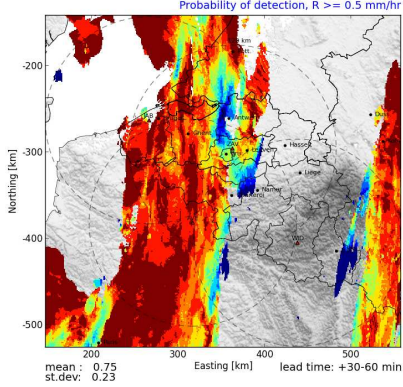


1 a)

b)

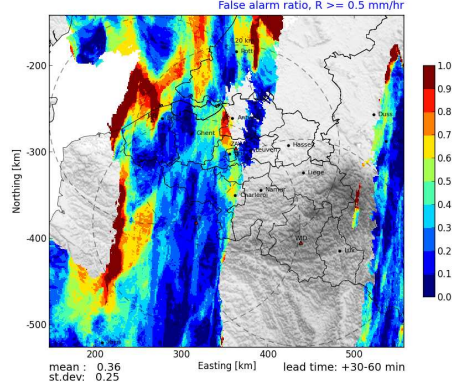
2 Figure 5. Average 0-30 min forecast RMSE for a) the Ghent winter case on 03 January 2014
 3 and b) the Leuven summer case on 19-20 July 2014.

Period start: 2014-07-19 22:00 UTC
Period end: 2014-07-20 06:30 UTC



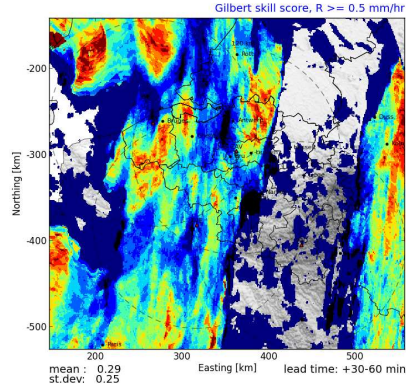
1 a)

Period start: 2014-07-19 22:00 UTC
Period end: 2014-07-20 06:30 UTC



b)

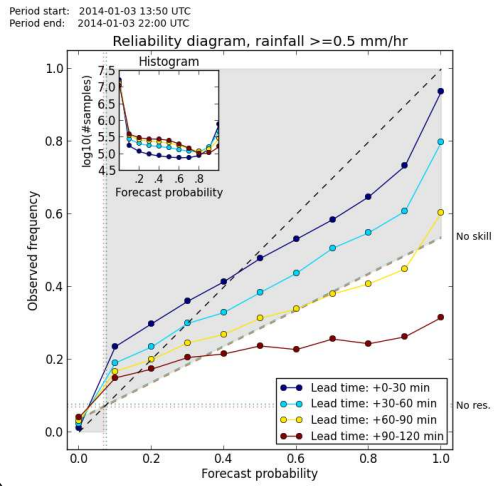
Period start: 2014-07-19 22:00 UTC
Period end: 2014-07-20 06:30 UTC



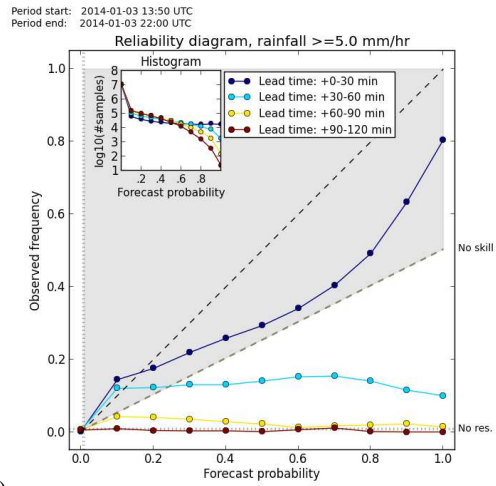
2

c)

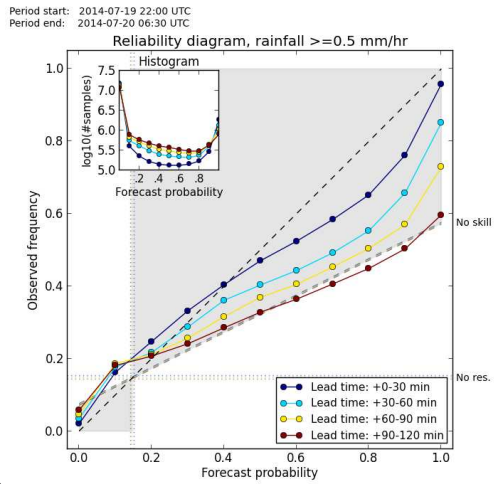
3 Figure 6. a) POD, b) FAR and c) GSS of the 30-60 min ensemble mean forecast of exceeding
4 0.5 mm hr^{-1} for the Leuven case on 19-20 July 2014.



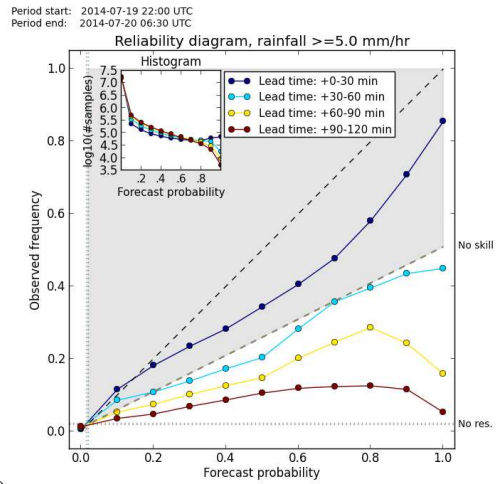
1 a)



b)



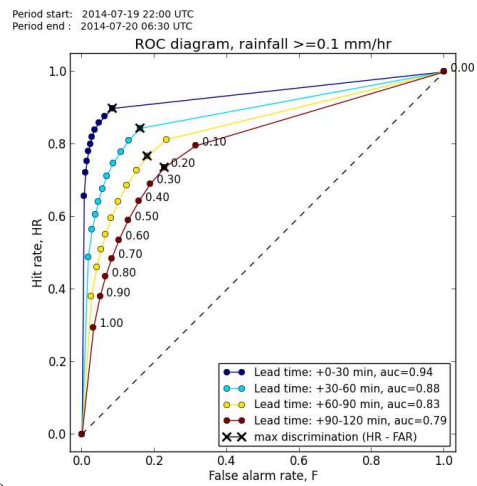
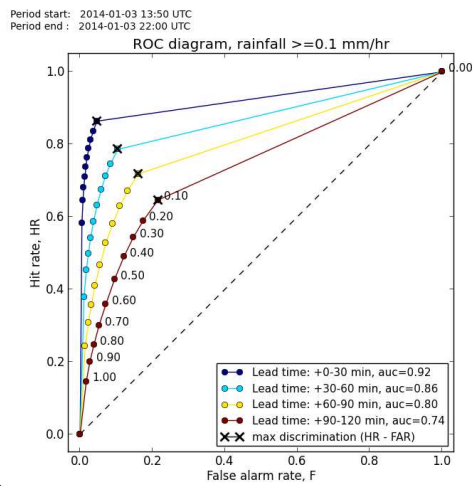
2 c)



d)

Figure 7. Reliability diagrams for the Ghent case on 03 January 2014 relative to the probabilistic forecast of exceeding a) 0.5 mm hr^{-1} and b) 5.0 mm hr^{-1} .

c, d) Same as a, b) but for the Leuven case on 19-20 July 2014.

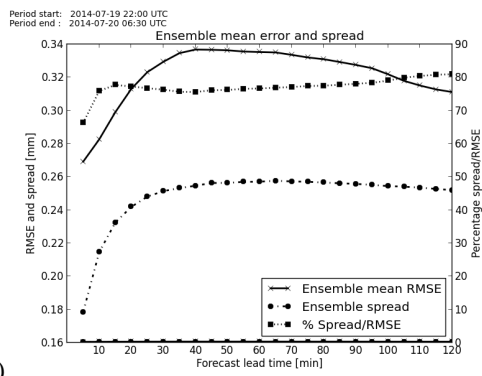
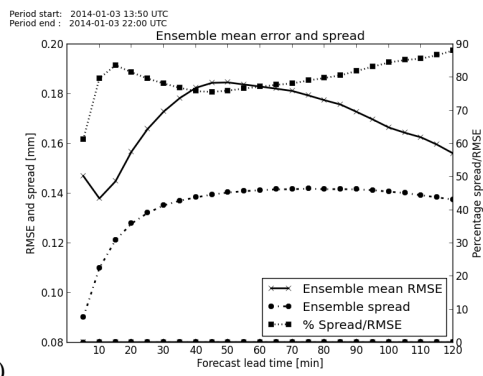


1 a)

b)

2 Figure 8. ROC curves relative to the probabilistic forecast of exceeding 0.1 mm hr^{-1} for
 3 a) the Ghent case on 03 January 2014 and b) the Leuven case on 19-20 July 2014.

4

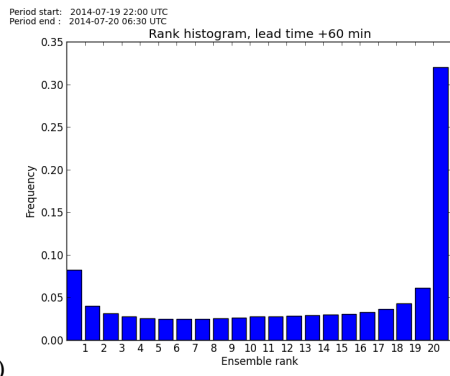
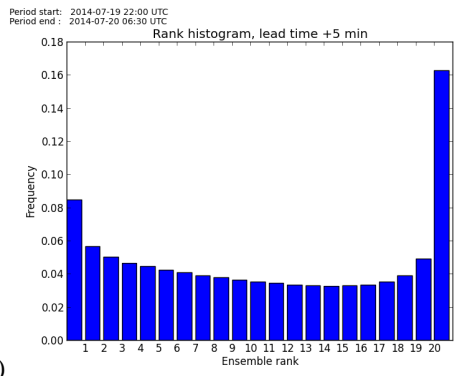


1 a)

b)

2 Figure 9. Comparison of ensemble spread and RMSE of the ensemble mean forecast at 5 min
 3 resolution for a) the Ghent case on 03 January 2014 and
 4 b) the Leuven case on 19-20 July 2014.

5



1 a)

b)

2 Figure 10. Rank histograms for the Leuven case on 19-20 July 2014 for a lead time of

3 a) 5 minutes and b) 60 minutes.

1 *We thank Geoff Pegram for his positive review. It helped us clarifying some*
2 *additional details and confirming some of our conclusions. Below we present the*
3 *answers to each question point by point.*
4
5 6836, 4: 512x512 kilometer?
6 *Well spotted. We will specify that the domain size is given in kilometers.*
7
8 6837, 2: does the compositing algorithm select from the lowest CAPPI, at what level,
9 and what about the bright band? I think more detail is required.
10 *The used CAPPI is at 1500 m.a.s.l. The correction for the bright band and for the*
11 *vertical profile of reflectivity is only taken into account in a more advanced*
12 *quantitative precipitation estimation (QPE) product. Unfortunately, this new product is*
13 *not yet used as input in STEPS because it only works on single radars at the moment*
14 *(there is no composite yet).*
15
16 6841, 24: 'a series of blocks' of what size?
17 *The block size is 60x60 grid points (see page 6842, line 2). The block size was*
18 *adapted to obtain a robust optical flow estimation of the large precipitation scales,*
19 *which is expected to increase the predictability of the Lagrangian extrapolation at*
20 *longer lead times.*
21
22 6842, 10: 'previous' in place of 'last'
23 *Corrected.*
24
25 Same page , 17 - 19: The sentence 'Since ... radars.' Needs rewording
26 *The original STEPS implementation (Bowler et al., 2006) was designed to blend the*
27 *radar extrapolation nowcasts with the output of NWP models. The domain covered*
28 *by the radars is smaller than the rectangular domain of the NWP model and small*
29 *amounts of stochastic noise are generated by default also outside of the radar*
30 *composite. This setting was not adapted for radar-based nowcasts*
31 *without NWP blending and needed some adaptation. We will give more details in text*
32 *to explain this issue.*
33
34 6843, 6: 'that' in place of 'the one'
35 *Corrected.*
36
37 6845, 6: 'field vectors based on the observations and then' in place of 'field vectors
38 and'
39 *Corrected as proposed.*
40
41 Same page: It would help the reader if the last sentence (omitting the word 'More') i.e
42 'Details about the forecast verification setup and scores are given in Appendix A.'
43 was placed after 'scores.' in line 10
44 *Good suggestion. We will move the sentence.*
45
46 Same page, 25: comment - It is not clear to me what the figures show - is Fig 2(a)
47 showing the average of 30 min accums over 35 hours? Please revise the text as it is
48 muddling. Aha - I get the explanation in line 17 on the next page

1 *We will try explain this concept at the beginning so that the reader does not have to*
2 *wait for the explanation.*
3
4 6847, 5: 'Contrary to expectation' in place of 'Contrarily to the expectations'
5 *Corrected.*
6
7 Same page [lines 8, 12, 25] and elsewhere, the use of the word 'comprised' is not
8 good grammar in this context - in many cases it can be omitted.
9 *We will use a more appropriate term or remove it.*
10
11 6848 last sentence. That makes sense, so the model is good, but please check my
12 remark below on the passage on page 6853, lines 4 & 5.
13 *The observation that the skill of nowcasting systems is higher along the path of a*
14 *thunderstorm compared to its edges should not depend on small biases that appear*
15 *at low rainfall intensities (see answer below).*
16
17 6849, 14: 'likely' in place of 'sufficient' ?
18 *Much better alternative.*
19
20 6850, 7-9: this last sentence is a result which makes good sense
21 *Thank you for agreeing with our statement.*
22
23 Same page, 20: remove 'the' before 'highest'
24 *Corrected.*
25
26 6851, 13: 'grows' in place of 'augments'
27 *Corrected.*
28
29 Same page, 16: 'lowest cascade level' I thought that the highest spatial frequencies
30 were in the top level of the multiplicative cascade ...?
31 *Good point. The terminology may be misleading but it was already used in the*
32 *previous STEPS papers. We will specify that the top levels are the lowest*
33 *frequencies (levels 0-1-2) and the bottom levels are the*
34 *highest frequencies (levels 6-7-8).*
35 And 21: 'comprised' again - please remove
36 *Ok.*
37
38 6852, 2: ' .. of the two stratiform cases' please add 'as might be expected'
39 *Added.*
40
41 Same page, 17: a comment. Overall, what is the summarised take-home message of
42 this complex and compact paragraph? In my opinion, it is a bit abrupt and needs
43 another sentence or two, drawing conclusions, before the overall 'Conclusions'
44 *The take-home message is that there is not much predictability in the small*
45 *precipitation scales beyond 2 hours lead time. Therefore, a maximum lead time of 2*
46 *hours in STEPS-BE is a good choice.*
47 *Extending this lead time would require blending the radar-extrapolation nowcast with*
48 *the output of NWP models to gain some predictability. It is a good idea to add a small*
49 *paragraph discussing these points.*

1
2 6853, 4-5: 'an improvement to generate stochastic noise only within the advected
3 radar composite'. Please remind me - is the noise variance linked to the reflectivity -
4 i.e. is a constant noise added to the log of reflectivity? If not, the low rainfall values
5 will be penalised. In fact, the low rainfall values will be biased upward and spoil the
6 error scores ...
7 *The noise is not added to the log of reflectivity (dBZ) but is added to the log of rainfall*
8 *intensity (dBR). The noise is thus multiplicative when working in original units of*
9 *rainfall intensity (R). We did not detect strong biases at low rainfall rates, although*
10 *the small and light rainfall cells have tendency to gradually dissipate, which has more*
11 *to do with the numerical diffusion of the highest frequencies during the advection of*
12 *the levels at the bottom of the cascade (e.g. levels 6-7-8).*
13
14 6854, 16: 'Fi is the forecast rainfall accumulation' is this over the whole field? It
15 seems from Figure 4 this is done per pixel, so needs a mention.
16 *We will remove the word "accumulation" to avoid confusion. Fi is the forecast rainfall*
17 *at a single pixel and the summation is performed over time using the rules for the*
18 *online computation of the statistics.*
19
20 6858, eq (8): why not just square the first bracket under the square root sign?
21 *Thanks for the suggestion.*
22
23 6859, 13: 'is not enough dispersive to' should read 'is not dispersive enough to'
24 *Corrected.*

1 *We thank Pekka Rossi for the useful remarks and also for spotting some mistakes in*
2 *the paper (reference+equation). Below you will find the answers to your questions.*
3

4 1. Introduction: I think it is quite widely accepted that the term “nowcasting” refers to
5 very short range forecasting in the time range 0-6 hours (e.g.
6 <https://www.wmo.int/pages/prog/amp/pwsp/Nowcasting.htm>). To avoid confusion, it
7 would be better to first define the term nowcasting with this definition, and then
8 specify that this paper considers only the first two nowcasting hours.

9 *Good idea. We will define the term nowcasting in the introduction and mention that*
10 *we only focus on the first two hours. Nowcasting is strongly based on the use and*
11 *extrapolation of real-time observations. During recent years there has been*
12 *significant progress in NWP modelling with radar data assimilation techniques, which*
13 *reduces the length of the nowcasting time range (e.g. the AMS glossary of*
14 *meteorology cites 3 hours). In the future we expect to have a seamless transition*
15 *between the observations, empirical and NWP forecasts, which will make the*
16 *definition of the nowcasting time range even fuzzier.*
17

18 2. Introduction: The paper underlines advantages of radar-based nowcasting over
19 NWP during the first nowcasting hours. To be fair, authors should better
20 acknowledge that NWP typically outperform radar-based nowcasting after a few
21 forecast hours, which is still in the nowcasting time range (assuming that the
22 definition of 0-6 hours is adopted). I also think the paper should acknowledge that
23 NWP community working very hard to improve the nowcasting of rainfall (see e.g.
24 Sun, J., and Coauthors, 2014: Use of NWP for Nowcasting Convective Precipitation:
25 Recent Progress and Challenges. Bulletin of the American Meteorological Society,
26 95, 409-426.).

27 *Exactly, NWP can already provide useful skill over extrapolation techniques after 2-3*
28 *hours lead time. We will cite the progress in the NWP community, but also the*
29 *practical fact that rapid-update (5-10 minutes) high-resolution radar-data assimilating*
30 *ensembles in the nowcasting range are not yet a reality nowadays. Thunderstorms*
31 *can exhibit significant evolution over a few tens of minutes and the current*
32 *operational NWP systems are not able to reach the resolution, update frequency and*
33 *skill of empirical nowcasting techniques in the first couple of hours.*
34

35 3. The verification was performed with four case studies. This is not very extensive
36 verification, given the availability of radar data and low computational costs
37 nowadays. I do not feel strongly enough about this to make it a major issue, but
38 perhaps Authors could underline that more extensive evaluation would be needed to
39 capture full performance of the system.

40 *Yes, indeed we verified only 2 convective and 2 stratiform precipitation cases. The*
41 *deterministic verification can give quite different results depending on the cases.*
42 *More data would be needed to better highlight the climatological spatial distribution of*
43 *STEPS forecast errors (e.g. as done in Foresti and Seed, 2015). On the other hand,*
44 *the probabilistic verification converges much faster to stable statistics. This is due to*
45 *the fact that the probabilistic verification pools the data in both space and time, which*
46 *gives many more samples to compute the statistics.*
47

1 4. I was a bit surprised that Authors did not do any comparison against a reference
2 system (e.g. basic deterministic extrapolation). It would have been interesting to see
3 differences between a legacy system and STEPS-BE (e.g. in terms of RMSE, GSS).
4 *Indeed, it could have been an additional analysis. In Foresti and Seed (2015) we*
5 *presented a comparison of the STEPS ensemble mean and the Eulerian persistence*
6 *forecast. The STEPS ensemble mean was better most of the time except for the*
7 *regions with reduced visibility due to orography and far from the radar. Comparing*
8 *the ensemble mean forecast to a deterministic control forecast in terms of pixel-*
9 *based RMSE would reward the ensemble mean. In fact, the smoothing effect due to*
10 *ensemble averaging filters out the unpredictable features and reduces the double*
11 *penalty error occurring when forecasting for example a storm at the wrong location.*
12 *Comparing the probabilistic forecast error of*
13 *STEPS against the probabilistic error of a single deterministic forecast (issuing only 0*
14 *or 100% probability of rain) also suffers from the dependence of scores with the*
15 *ensemble size. In fact, larger is the ensemble size smaller is the Brier score (Ferro,*
16 *2007), which complicates the comparison of ensemble prediction systems composed*
17 *of different members (20 for STEPS and "1" for the deterministic control forecast).*
18 *We could have done a comparison to show that STEPS is better than a deterministic*
19 *nowcast, but a fair comparison that considers the influence of ensemble size and the*
20 *different statistical properties of the competing forecast models (e.g. smoothness)*
21 *would have been much more complex.*

22
23 5. P. 6850: "Another explanation for this underestimation is due to not using a model
24 for the radar measurement errors, in particular due to the space– time variability of
25 the Z–R relationship". It is not clear to me how errors due to initial conditions can be
26 observed in this verification, because the reference data applied in the verification
27 data is obtained from the same erroneous radar data.
28 *We will add some sentences to better formulate this concept. The last observed*
29 *rainfall field is extrapolated using a fixed Z-R relationship. The same Z-R relationship*
30 *is used to convert the observed reflectivity to the rainfall rates that are used for the*
31 *verification. However, spatial and temporal changes in the drop size distribution*
32 *(DSD) can lead to changes in the estimated rainfall rate that is used for the*
33 *verification. Therefore, there could be a mismatch between the "fixed" DSD of the*
34 *forecasts and the variable DSD underlying the verifying observations.*
35 *Another possible source of mismatch could be due to the advection correction with*
36 *optical flow. The forecast accumulations are computed by advecting forward the*
37 *previous rainfall field. On the other hand, the observed accumulations are computed*
38 *by reversing the optical flow vectors and advecting the rainfall field backwards. This*
39 *choice increases the differences when comparing the +0-5 min forecast*
40 *accumulations (advection of the "0" min image forward) with the +0-5 min observed*
41 *accumulations a posteriori (advection of the "+5" min image backwards). We will add*
42 *these details to the text.*

43
44 6. Authors might want to revise the use of the term skill. Isn't it by definition a
45 measure of forecast accuracy with respect to the accuracy of a reference forecast?
46 The term is quite widely used throughout the text.
47 *Good remark. We will revise the text and replace the term skill with a more*
48 *appropriate one to be consistent with the terminology used in forecast verification.*
49

1 7. P. 6587 and p. 6849 (Brier score and Brier skill score), also related to my previous
2 comment. Brier score (BS) is a measure of accuracy, and BSS compares BS of two
3 systems. Thus, I believe it would be better to say that “The Brier skill score
4 characterizes the relative accuracy of the probabilistic forecast compared to a
5 reference system”. Although climatology or sample climatology is often used as a
6 reference, BSS can also be computed against other reference forecasts, e.g. another
7 probability forecasting method or even a deterministic forecasting method treated as
8 a probabilistic binary forecast.

9 *Thanks. We will specify that the reference can be different than the sample*
10 *climatological frequency.*

11
12 8. P. 6858: Foresti et al. (2013). I couldn't find it in the reference list. Foresti et al.
13 (2014)?

14 *Well spotted. It is the paper on the analogues written in 2013 but published in 2015.*

15
16 9. eq. (8). It seems that index m is not defined. Shouldn't the index i under the square
17 root be replaced with m ?

18 *Thanks for remarking the typo in the equation. The second summation is done from*
19 *$m=1$ to M .*

20
21 References

22 Ferro, CAT. (2007) Comparing probabilistic forecasting systems with the Brier score.
23 *Wea. Forecasting*, 22:1076–1088.

24 Foresti, L., and Seed, A. (2015) On the spatial distribution of rainfall nowcasting
25 errors due to orographic forcing. *Meteorological Applications*, 22(1):60–74.

26

1 *We thank the anonymous reviewer for the positive feedback. Below we present the*
2 *answers to the raised issues point by point.*
3

4 1) A major concerns that I have with this work is that the authors have failed to
5 discriminate the impact of work with respect to previous contributions where STEPS
6 was used. Sure the area of focus is different (Belgium in this case), but it would be
7 nice if the authors could address this issue a bit further in the manuscript.

8 *Thanks for the remark. A comparison of STEPS-BE and the original STEPS*
9 *implementation is provided in Section 3.2. We will try to specify better what is the*
10 *contribution of our paper w.r.t. the use of STEPS in other countries (e.g. UK,*
11 *Australia, etc) and related publications.*
12

13 2) Page 6846 lines 7-8 and Fig. 2 a,b: The authors mention here the impact of the
14 bright band resulting in high rainfall rates around the radar. For the current example
15 in Fig. 2 a,b the impact of hitting the bright band is rather smaller, as the forecasted
16 accumulation is quite similar to the observed accumulation around the Zaventem
17 radar. I get the feeling that this is mainly due to the relatively low horizontal velocity
18 field of this event. I am wondering what the quality of the forecast is for larger lead
19 times or for cases where the horizontal velocity is larger.

20 *The bright band effect influences both the radar observations and the nowcasts*
21 *based on their extrapolation. At longer lead times the local rainfall over-estimation*
22 *due to the bright band is extrapolated far from the location of the radar. However, the*
23 *stochastic perturbations of STEPS gradually damp this effect and reduce the amount*
24 *of over-estimation. The bright band affects more the observations used for the*
25 *verification, in particular when the rainfall is advected from upstream over*
26 *the radar region. In such case, the forecast is detected as if it under-estimates the*
27 *rainfall, which is not true. However, bright band effects might not be so important for*
28 *urban hydrological applications. In fact, except for the two stratiform cases presented*
29 *in this paper, pluvial floods mainly happen in summer with convective precipitation*
30 *events, during which the bright band is absent or negligible.*
31

32 3) In line with the previous remark, I was wondering whether the authors have opted
33 to apply some kind of bright band correction method as the bright band is observed
34 at relatively low elevation (500-2000) during the fall and winter season in Belgium
35 (see Hazenberg et al., 2013). For this period of the year my expectation is that many
36 CAPPI images are contaminated with the impact of the bright band and its impact will
37 be extrapolated while running the STEPS-BE algorithm. As the precipitation
38 intensities are overestimated within the bright band, these forecasts will lead to
39 incorrect urban hydrological model simulations.

40 *The correction for the bright band and for the vertical profile of reflectivity is only*
41 *taken into account in a more advanced quantitative precipitation estimation (QPE)*
42 *product. Unfortunately, this new product was not yet working in real-time when*
43 *developing STEPS and it currently works only on single radars (there is no composite*
44 *available yet, which significantly reduces the nowcast lead time).*
45

46 4) Page 6850 lines 26-29 Another explanation ... Z-R relationship: Since all the
47 Marshall-Palmer relationship was used to convert radar reflectivities into rainfall
48 estimates, I do not understand why space time variations in Z-R lead to a higher
49 under-dispersion at a lead times of 5 minutes. Please elaborate on this in the text.

1 *We will add some sentences to better formulate this concept. The last observed*
2 *rainfall field is extrapolated using a fixed Z-R relationship. The same Z-R relationship*
3 *is used to convert the observed reflectivity to the rainfall rates that are used for the*
4 *verification. However, spatial and temporal changes in the drop size distribution*
5 *(DSD) can lead to changes in the estimated rainfall rate that is used for the*
6 *verification. Therefore, there could be a mismatch between the "fixed" DSD of the*
7 *forecasts and the variable DSD underlying the verifying observations.*
8 *Another possible source of mismatch could be due to the advection correction with*
9 *optical flow. The forecast accumulations are computed by advecting forward the*
10 *previous rainfall field. On the other hand, the observed accumulations are computed*
11 *by reversing the optical flow vectors and advecting the rainfall field backwards. This*
12 *choice increases the differences when comparing the +0-5 min forecast*
13 *accumulations (advection of the "0" min image forward) with the +0-5 min observed*
14 *accumulations a posteriori (advection of the "+5" min image backwards). We will add*
15 *these details to the text.*

16
17 - Page 6837 lines 1-2: Please add the elevation of the CAPPI.
18 *The CAPPI is at 1500 m.a.s.l. We will specify it in text.*

19
20 -Page 6843 lines 22-23: I would suggest to remove the line "Thus, a ... MPI
21 implementations)."
22 *We will remove this sentence.*

23
24 -Page 6850 line 26: Add a "." after times.
25 *Corrected.*

26
27 References:
28 Hazenberg, P., P.J.J.F. Torfs, H. Leijnse, G. Delrieu and R. Uijlenhoet, 2013:
29 Identification and uncertainty estimation of vertical reflectivity profiles using a
30 Lagrangian approach to support quantitative precipitation measurements by weather
31 radar, J. Geophys. Res. Atm., 118(18), 10243-10261.

32