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Extended tests with a limited area ensemble prediction system at the Norwegian Meteorological Institute - LAMEPS

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Abstract

Extended tests running a limited area ensemble prediction system (LAMEPS) has been done using ECMWF EPS to perturb both the initial conditions and the lateral boundary conditions in the model. First the ECMWF EPS has been running with Northern Europe and adjacent sea areas as target area to make 20 ensemble perturbations for each case. Both regular singular vectors and evolved singular vectors are used as a basis for the EPS runs which in turn are used to make the perturbations (resulting in TEPS and TEPS_ESV, respectively). LAMEPS showed best results using TEPS_ESV, specially for large total precipitation rates. The extended experiments have therefore been done using TEPS_ESV to do the perturbations in the LAMEPS. These experiments include 54 cases covering parts of the 4 different seasons. LAMEPS_ESV has been compared to the operational ECMWF's EPS and TEPS_ESV. Adding TEPS_ESV and LAMEPS_ESV give 41 ensemble members and very good results particularly for medium and large precipitation rates.

Keywords

EPS, TEPS, LAMEPS

Disiplinary signature	Responsible signature

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1. Introduction

Probabilistic forecasting has been operational for about a decade, and first mainly in connection with global weather prediction models with modest resolution (Buizza et al.,1993; Toth and Kalnay ,1993). As running ensembles with a global model with high resolution is very expensive, ensemble systems using limited area models have been tested at different centers over the last years (Marsigli et al., 2001, Molteni et al., 2001, Frogner and Iversen 2002). Du et al. (1997) and Stensrud et al. (1999 and 2000) also use ensembles for short-range forecasting.

Although the global ensemble prediction systems in resent years have increased the resolution, mesoscale (especially orography-related processes) are still not very well captured. As forecasting of localized and severe weather events, such as heavy rainfall, strong winds and temperature anomalies achieve more and more attention, an ensemble prediction system with a limited area model with relative high resolution could give helpful additional information.

Ideally an ensemble prediction system should take into account all the different sources of uncertainty in the model system. That is, in addition to the unavoidable inaccuracies in the initial conditions, also e.g. errors due to uncertainties in the model formulation and in the necessary parameterization of physical processes. The ensemble prediction system (EPS) at the European Centre for Medium-Range Weather Forecasts (ECMWF) takes into account that the models are not perfect by stochastically perturbing the tendencies calculated by the model physics (Buizza et al. 1999). For limited area ensemble prediction systems it is also necessary to perturb the lateral boundary conditions (Frogner and Iversen, 2002).

The limited area ensemble prediction system (LAMEPS) described here uses a version of ECMWF EPS to perturb both the initial conditions as well as the lateral boundary conditions. A targeting procedure (Buizza, 1994) is applied to the global ensemble prediction system EPS resulting in a system that is designed to have maximum amplitude of the perturbations in a predefined area after the optimization time period. This system is called TEPS and it is described in Frogner and Iversen (2001). Hersbach et al (2000 and 2003) describes a similar system for the European area.

Earlier studies with LAMEPS at the Norwegian Meteorological Institute (met.no) has showed promising results when focusing on extreme precipitation events, although the system has been run for only a few cases chosen because of their large precipitation rates. In this paper a more extensive test of the system is performed. 54 cases distributed in all four seasons in 2002/2003 have been tested. The periods have all except one, been chosen randomly during the year, although completely dry periods have been excluded.

The paper is organized in 5 sections. In section 2 the set-up for the experiments and the different ensemble prediction systems are briefly described. The results are presented in section 3, both aggregated over all 4 seasons, each season by itself and a case study with extreme precipitation. A discussion and some conclusions are presented in section 4. The possibility of making LAMEPS operational at met.no is discussed in section 5.

Section 2: The set-up for the experiments

The EPS technique consists of adding small dynamically active perturbations to the operational analysis for the day. The perturbations used here are based on singular vectors (SV) (Buzzia and Palmer, 1995, Barkmeijer et al. 1998 and 2001), focusing on the unstable subspace. The singular vector analysis tries to identify the dynamically most unstable regions of the atmosphere by calculating where small initial uncertainties would affect a 48 hour forecast most rapidly, either increasing or damping the forecast amplification of different weather states.

In this study we have compared our experiment LAMEPS with other ensemble prediction systems, one operational and some experimental systems. 54 cases are studied, distributed among 4 time-periods (see table 1). The focus has been on total precipitation rates. It has further been drawn conclusions about which system is favourable to be used in an operational setting when forecasting total precipitation in our area of interest, i.e. Northern Europe and adjacent sea areas (see figure 1). The different ensemble prediction systems are described here. (In table 2 the different systems are listed for clarification.)

EPS

EPS is an abbreviation for ECMWF's global operational ensemble prediction system. EPS has been operationally since 1992. The resolution at the moment of our experiments is $T_l255L40$ (approximately 80 km horizontal resolution and 40 vertical levels). The system consists of 50 perturbations, which give 50 alternative forecasts, plus a control run without perturbed analysis. (The control run has horizontal resolution ~40km and 60 vertical levels.) EPS has the Northern Hemisphere (NH) north of 30° as target area and is perturbed with both regular singular vectors and evolved singular vectors. The EPS optimization time is 48 hours and the forecast length is 10 days (see also table 2).

EPS20

EPS20 is a subset of EPS consisting of the 20 first EPS ensemble members plus the EPS control integration (see table 2). These 20 ensemble members have the largest growth over the optimization time for the chosen area (NH north of 30°) compared to the last 30 ensemble members of the EPS.

TEPS

In this study TEPS is a re-run of EPS (Frogner and Iversen, 2001) with Northern Europe as target area (see figure 1). The TEPS integrations are done at ECMWF's supercomputer. TEPS consists of 20 ensemble members plus the control which is the unperturbed forecast. The horizontal and vertical resolutions are the same as for the EPS. The TEPS optimization time is also the same as for the EPS, i.e. 48 hours. The forecast length is 66 hours for most of the cases. (See table 2).

TEPS_ESV

TEPS_ESV is also a re-run of EPS with the same target area as EPS (see table 2). TEPS_ESV uses evolved singular vectors as perturbations in addition to the regular singular vectors. Perturbations are created 48 hours before the prognosis start. A scaled combination of the 48 hour old perturbations and the current perturbations are added to the analysis. Hence the model includes perturbations with significant growth already at the starting time. (Evolved singular vectors are also included in EPS and EPS20, but it has not been tried used in computing perturbations for the limited area ensemble system developed at met.no before.) TEPS_ESV uses the same resolution as EPS and TEPS and the same forecast length as TEPS. Using evolved SV result in out-stretching of the perturbations over a larger area since the perturbations are of significant order already at starting time.

LAMEPS

LAMEPS is the abbreviation for high resolution limited area ensemble prediction system with HIRLAM (see table 2). The method consists of using the perturbations, TEPS, to perturb both the initial and boundary conditions in the HIRLAM runs (Frogner and Iversen, 2002). This results in 20 different forecasts besides the control run. The horizontal resolution is approximately 28 km and vertically the model has 31 levels. Initially LAMEPS has very small or no perturbations inside the target area, since they are optimized to be in the target area after 48 hours.

LAMEPS_ESV

LAMEPS_ESV is also a high resolution limited area ensemble prediction system, but instead of using TEPS, LAMEPS_ESV uses TEPS_ESV to perturb the initial and boundary condition in the HIRLAM runs. Evolved SV is introduced to get perturbations in our area of interests also at the starting time. (See also table 2.)

CLAMEPS_ESV

CLAMEPS_ESV is a combination-result of TEPS_ESV and LAMEPS_ESV (a “poor-mans”-limited area ensemble) (see table 2). The total number of ensemble members is therefore 41 plus the control run (LAMEPS_ESV-control). The reason why the CLAMEPS_ESV has been introduced is firstly that it gives an increase in ensemble members without further cost since we already have TEPS_ESV to compute LAMEPS_ESV. Both systems are also designed to be optimal for our area of interest. It is also fairer to compare 41 ensemble members against EPS’s 50 ensemble members than to only use 20 ensemble members against the 50 which is the case for the other LAMEPS-systems.

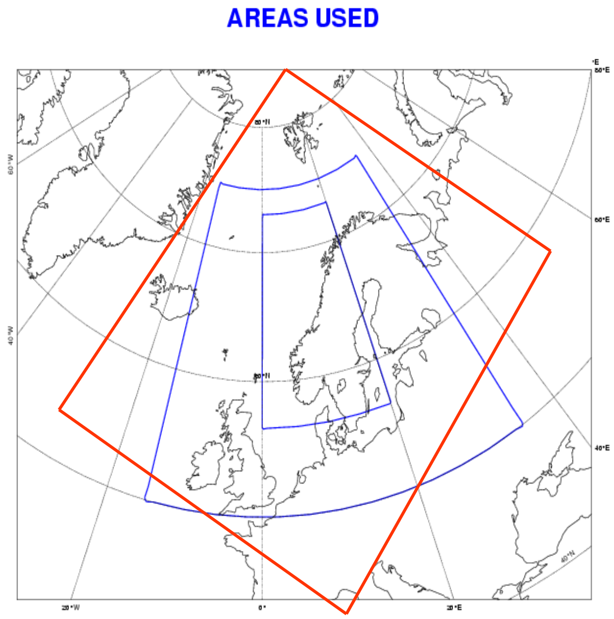

Figure 1. The figure shows the areas used in the experiments. The outermost area is the HIRLAM integration area. The outermost blue area is the target area, and the innermost blue area is the verification area.

Period	Start date	End date	Number of cases	Missing dates
Autumn1	20021018	20021026	9	none
Autumn2	20021027	20021031	5	none
Winter	20030110	20030131	21	20030116
Spring	20030504	20030521	15	20030507,09,10
Summer	20030811	20030814	4	none

Table 1. The table shows the experiment periods.

Table 2. The table shows the different experiments and gives a short description of each. The descriptions consist of model type, horizontal and vertical resolution, number of ensemble members, optimization time, forecast length and the periods for which each system has been studied.

Experiment	**Description**
EPS	ECMWF EPS model, hemispheric, targeted to NH>30°, ~80 km h.resolution 40 levels, 50 ens members+1 ctrl, 96 h optimization.t (-48h to +48h), +10 d forecast length, **operational**
EPS20	ECMWF EPS model hemispheric, targeted to NH>30°, ~80 km h. resolution, 40 levels, subset of EPS (consisting of the first 20 ens members + 1 ctrl), +48 h optimization t, +10 d forecast length, used for all 5 experiment periods
TEPS	ECMWF EPS model, hemispheric, perturbed with only regular singular vectors, target area: Northern Europe and adjacent sea areas (see fig.1), ~80 km h. resolution, 40 levels, 20 ens members+1 ctrl, +48 h optimization time, 66 hour forecast length, only used in "autumn1" (see table 1)
TEPS_ESV	ECMWF EPS model, hemispheric, perturbed with both regular singular vectors and evolved singular vectors, targeted to Northern Europe and adjacent sea areas, see fig. 1), ~80 km h. resolution, 40 levels, 20 ens members+1 ctrl, +96 h optimization t (-48h to +48h), 66 h forecast length, used for all 5 periods
LAMEPS	HIRLAM-EPS model (area; see fig. 1), perturbed with TEPS, ~28 km horizontal resolution, 31 levels, 20 ens members+1 ctrl, +66 h forecast length, only used in "autumn1"
LAMEPS_ESV	HIRLAM-EPS model, perturbed with TEPS_ESV, (area; see fig.1), ~28 km h resolution, 31 levels, 20 ens + 1 control, +66h forecast length, used for all 5 periods
CLAMEPS_ESV	Combination of TEPS_ESV and LAMEPS_ESV (area; see fig.1), 41 ens members+1 ctrl, optimization time, forecast length and run-periods are defined by LAMEPS_ESV and TEPS_ESV

Section 3: Results

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The results are described in terms of the spread of the ensembles and also graphically represented as Relative Operating Characteristic curves (ROC) (Mason, 1982) and Cost/Loss-diagrams (Katz and Murphy, 1997; Richardson, 1998). These diagrams do not only compare the ensembles against the control run, but also take into account if the event in fact occurred or not. Since precipitation is only observed at 0600 UTC, the results of interest occur at forecast time +42 hours and +66 hours. The results are compared to observations where all the available precipitation stations are included.

Given a probability threshold-value, the ROC-curves categorize the results into probability ranges depending on how many members predicted the event. The hit rate is defined as the proportion of correct forecasts when the weather-event occurs. The false alarm rate is the number of times the event was incorrectly forecasted divided by the number of times the event was not observed. Hit rate and false alarm rate are plotted against each other for the different probability ranges. It is defined as many probability ranges as it is ensemble members. The space enclosed by the curve and the y-axis and the top level indicate the skill of the experiment. The experiment becomes better with less area[1]. Many points in the upper left corner indicate very good results. A useless forecast is represented by a curve that lies along the diagonal as this forecast system will predict false alarms at the same rate as hits.

The cost/loss-diagram defines a value, V, based on mean expense values when using different systems (a perfect forecasting system, a climate system or the ensemble forecasting system). The value depends on the forecast quality (hit rate and false alarm rate), the user cost/loss-ratio and the weather event together with the probability threshold. The higher the value of the ensemble system, the more benefit it is for the user to use this ensemble system.

3.1 Spread of the ensembles

The spread of the ensemble members around the control run should ideally reflect the uncertainty in the particular weather situation. The ensembles should describe as much as possible of the probability distribution for weather-development caused by initial state uncertainty. This is important in order to detect rare and possibly extreme weather events (Frogner and Iversen, 2001).

The spread is defined as the root mean square of the difference between the ensemble member and the control averaged over all the cases and all the ensemble members. The root mean square is also averaged over all the grid-points in the specified area (see figure 1) and can mathematically be written as follow:

[1] (The ROC-curves can also be represented turned upside-down focusing on the area under the curves. The ROC-curves represented this way will not be used in this study.)

$$S=\frac{1}{I}\sum_{i=1}^{I}\sqrt{\frac{1}{N\cdot D}\sum_{n=1}^{N}\sum_{d=1}^{D}\left(e_{ind}-p_{id}\right)^{2}} \qquad (1)$$

where I is the number of points inside the verification area, N is the number of ensemble members, D is the number of cases. e_{ind} is the ensemble member value for the member n, in the case d and in the specific point i. p is the control value for the same case and in the same point.

Forecast time (hours)	EPS	EPS20	TEPS_ESV	LAMEPS_ESV	CLAMEPS_ESV
42	2.73	2.62	3.27	2.82	3.69
66	1.68	1.69	2.11	2.12	2.78

Table 3. Spread in total precipitation for the different systems.

The spread in total precipitation (Large Scale Precipitation plus Convective Precipitation) is shown in table 3. The spread at forecast time 42 hour is based on all the experiment sets, whilst the spread in total precipitation at 66 hour is only based on the winter, spring and summer sets due to +66 hour missing for the autumn set.

Comparing the spread in the different systems shows that TEPS_ESV, LAMEPS_ESV and CLAMEPS_ESV have larger spread than EPS and EPS20 for both forecast times. These systems include more diverging cases from the control than the EPS and EPS20 and can hence include the more extreme cases which the large scale EPS may not incorporate. CLAMEPS_ESV has the highest spread of the five different systems compared.

The spread is expected to grow in time, but this seems not to be the case here. Why the 42 hour total precipitation spread is larger than the 66 hour total precipitation spread is probably explained by the fact that the two hour-groups include different cases (the autumn set missing for +66 h). The autumn set had some cases with extreme precipitation rates (Bremnes and Homleid, 2003 a).

3.2 Comparing systems run with and without evolved singular vectors.

The comparison of the system run with evolved singular vectors (LAMEPS_ESV) and the system run with only regular singular vectors (LAMEPS) is based on 9 autumn-cases in 2002 (set 1 in table 1). The results are averaged over these 9 cases.

Both LAMEPS and LAMEPS_ESV show useful skill as the curves are well above the diagonal for all total precipitation rates (see upper panel of figure 2). The figure shows the results at threshold values 2.5 mm/24 hour and 25 mm/24 hour. (A larger sample of threshold values is shown in appendix A.1.1.) LAMEPS and LAMEPS_ESV are quite similar for small precipitation rates, but LAMEPS_ESV gets clearly much better with increasing precipitation rates.

LAMEPS_ESV has larger cost/loss-values than LAMEPS for medium to large precipitation rates (see the lower panel of figure 2 b and appendix A.1.1). At smaller precipitation rates, the top point and the right hand of the curves are equal, but LAMEPS_ESV has higher values to the left, and are therefore better also for lower precipitation rates (see lower panel of figure 2 a).

LAMEPS_ESV is the most skilful experiment of the two in set 1. It was therefore decided to include evolved singular vectors in perturbing the HIRLAM ensembles for the remainder of the test cases.

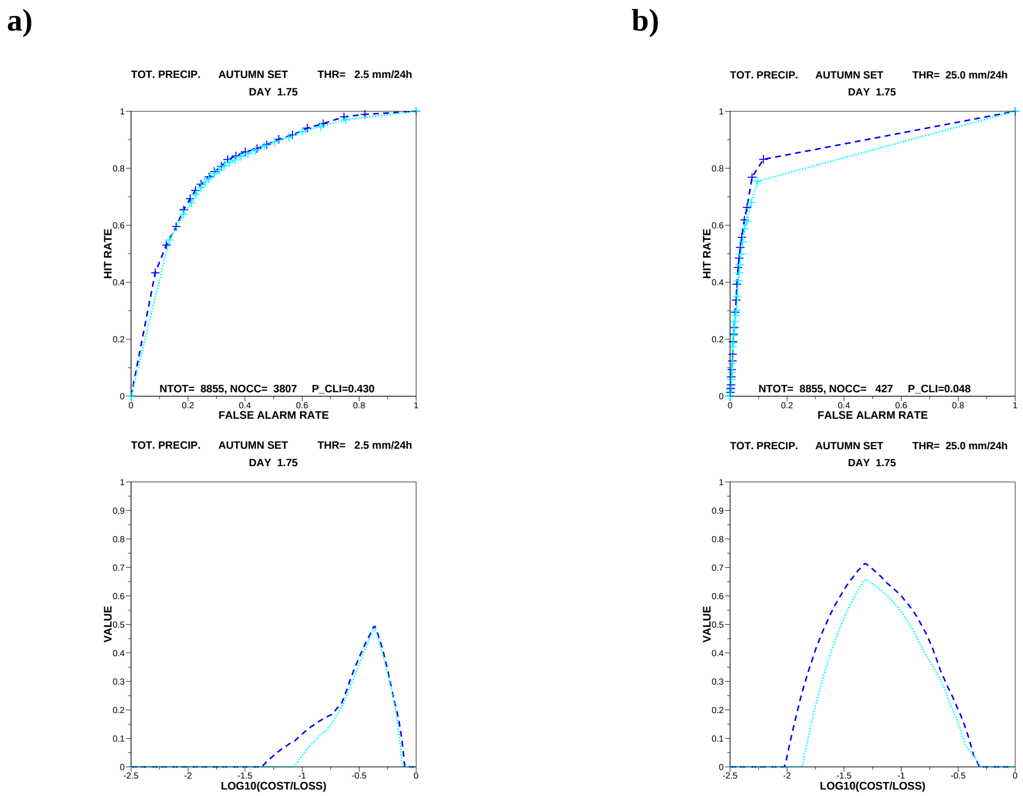


Figure 2. The figure shows the ROC-diagram (upper panel) and cost/loss-diagram (lower panel) for LAMEPS_ESV (blue) and LAMEPS (cyan) computed for the verification area and all 9 cases in the first set (autumn1 in table 1) at forecast time +42 hours. The threshold values are a) 2.5mm/24hour and b) 25mm/24hour. NTOT is the total possible number the event could occur (the number of points in the target area multiplied by the number of cases) while NOCC is the number of times the event occurred in the sample. P_CLI is the total precipitation frequency in the experiment period.

3.3 Verification over all four seasons

In this section we look at a total verification over all four seasons, i.e. all 54 cases. Seasonal verification will be discussed later. The results are given in form of total precipitation in ROC-diagrams and cost/loss-curves. The results from the systems LAMEPS_ESV and CLAMEPS_ESV compared to respectively EPS20 and EPS are shown in the diagrams together with the results from the system TEPS_ESV. Plots showing several threshold values of total precipitation rates are given in the appendix, while the most interesting curves are shown in the text.

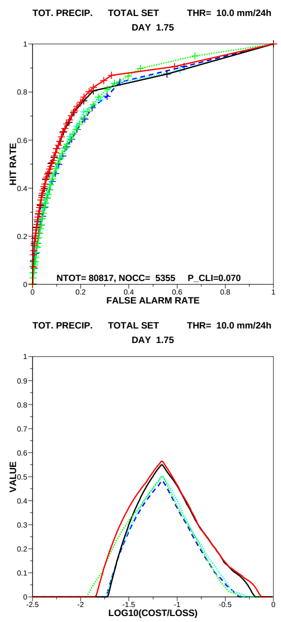
Results at forecast time +42 hours (day 1.75):
EPS and EPS20 show best results at low precipitation rates (see appendix A.2.1.). The LAMEPS_ESV and CLAMEPS_ESV improve fast with rising precipitation amounts.
At total precipitation rate 10 mm/24h, CLAMEPS_ESV verifies slightly better than EPS and LAMEPS_ESV verify slightly better than EPS20 (see upper panel of figure 3.a). At total precipitation rate 15 mm/24h both CLAMEPS_ESV and LAMEPS_ESV verify better than EPS (see upper panel of figure 3.b). The difference between CLAMEPS_ESV and EPS increase with higher precipitation rates (see upper panel of figure 3. c, d). This is also the case when LAMEPS_ESV is compared to EPS20. High precipitation amounts happen however rarely and in the ROC-diagram the false alarm rates become low because the number of non-events is the denominator of the false-alarm-rate. This is indicated by all the crosses close to the y-axis (see figure 3.d). When the precipitation amounts are lower, the events are more uniformly distributed and the curves can be more credible.

The cost/loss-curves show that the value is largest for EPS and EPS20 for precipitation amounts up to 10 mm/24 hour (see lower panel of figure 3 and appendix A.2.1). Thereafter CLAMEPS_ESV and LAMEPS_ESV are best (see lower panel of figure 3, b-d). The maximum value for the larger precipitation rates change between LAMEPS_ESV and CLAMEPS_ESV and it is the user's cost/loss-ratio that determines which of the systems is best. Users who have small cost/loss-ratio will benefit the most from using CLAMEPS_ESV, while users with higher cost/loss-ratio will have benefit using LAMEPS_ESV (see figure 3. b, c).

Results at forecast time +66 hours (day 2.75):
(The results include the winter, spring and summer sets. The autumn set misses the +66 hour forecast time.)

EPS, EPS20, TEPS_ESV and CLAMEPS_ESV generally show some better results than at 42 hours. The improvement is best seen at total precipitation rate15 mm/24h (see the upper panel of figure 4.a). CLAMEPS_ESV is the best system or approximately equal to EPS for medium and large precipitation rates. All the curves are more clustered than at 42 hour and indicate a larger agreement in the results. LAMEPS_ESV is better than EPS20 at a few precipitation rates (15 mm/24h and 30 mm/24h, see upper panel of figure 4.a, b). The cost/loss diagram (see lower panel of figure 4 and figure 3) shows that CLAMEPS_ESV together with EPS, EPS20 and TEPS_ESV have got larger cost/loss-values compared to the cost/loss-values at +42 hours.

a)



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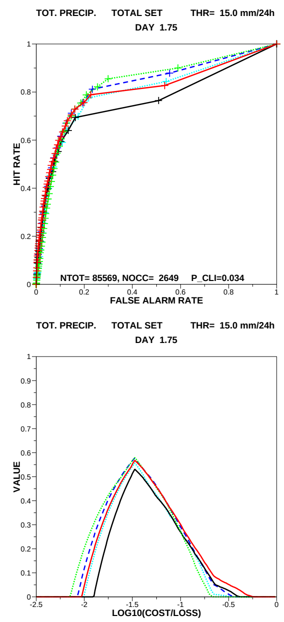

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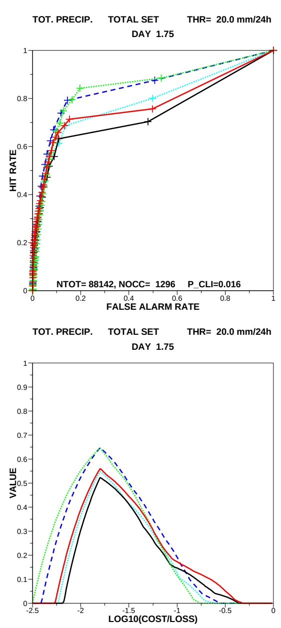

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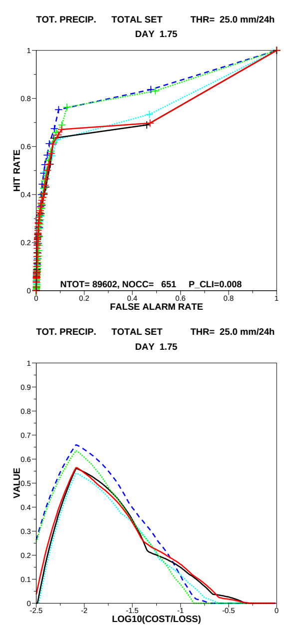


Figure 3 a-d) The figure shows the ROC-diagram (upper panel) and cost/loss-diagram (lower panel) for different threshold values of total precipitation rates where all the experiment sets are included; The different threshold values are a) 10mm/24h, b) 15mm/24h, c) 20 mm/24h and d) 25 mm/24h. The different curves are EPS(red), EPS20(black), TEPS_ESV(light blue), LAMEPS_ESV(blue) and CLAMEPS_ESV(green).

a) b)

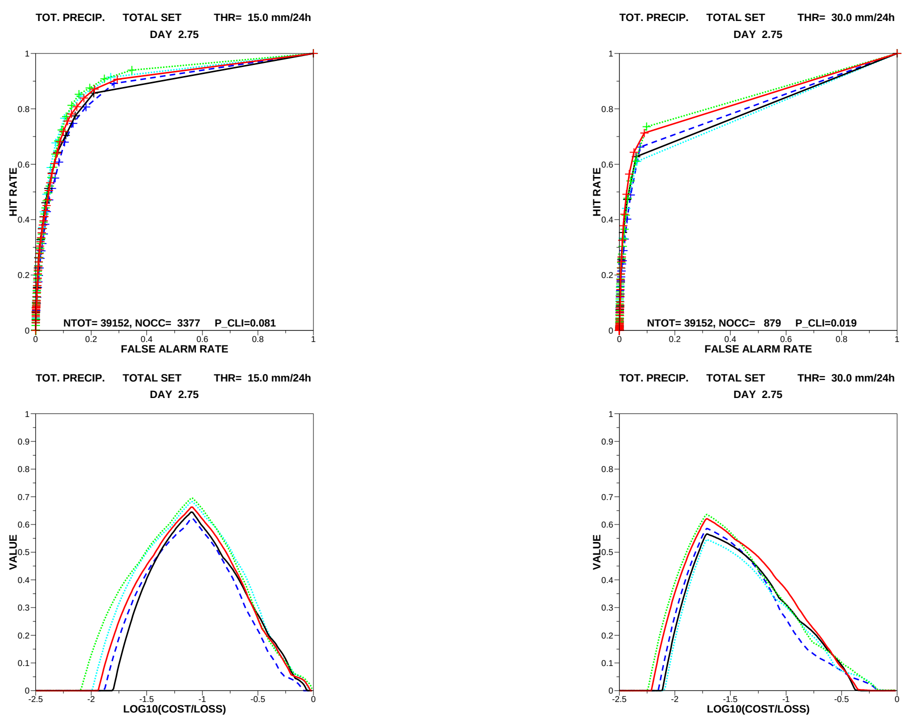


Figure 4 a, b) The figure shows the ROC-diagram (upper panel) and cost/loss-diagram (lower panel) for different threshold values of total precipitation rates looking at all the cases in the winter, spring and summer sets at forecast time +66 hours. The different curves are EPS(red), EPS20(black), TEPS_ESV(light blue), LAMEPS_ESV(blue) and CLAMEPS_ESV(green). The threshold values are a) 15 mm/24h, b) 30mm/24h.

LAMEPS_ESV is better than TEPS_ESV and EPS20 at 30 mm/24hour (see lower panel of figure 4.b). This can probably indicate the importance of including finer orography and other mesoscale structures to predict large total precipitation rates.

3.4 A seasonal comparison of the ensemble systems

The ROC-diagrams and the cost/loss-curves for the seasonal study include the systems EPS, EPS20, TEPS_ESV, LAMEPS_ESV and CLAMEPS_ESV. LAMEPS_ESV is mainly compared to EPS20 and CLAMEPS_ESV is mainly compared to EPS. The plots for all total precipitation rates are shown in the appendix, while the most interesting curves are shown and discussed in the text. Observed total precipitation rates in the experiment periods are represented in table 4 by the mean of the frequencies of the threshold values inside the 3 precipitation groups. The table shows that highest frequencies of large and medium total precipitation rates were observed in the summer set, whilst small total precipitation rates were observed in the spring set. The autumn and winter periods had something in between.

	0-10mm/24h	10-20mm/24h	20-30mm/24h
Autumn	0.404	0.096	0.065
Winter	0.566	0.090	0.057
Spring	0.391	0.040	0.013
Summer	0.287	0.117	0.146

Table 4. The mean of the frequency of the different threshold values of total precipitation inside the precipitation groups. In other words; the numbers represent observed total precipitation in the different experiment periods.

3.4.1 Autumn

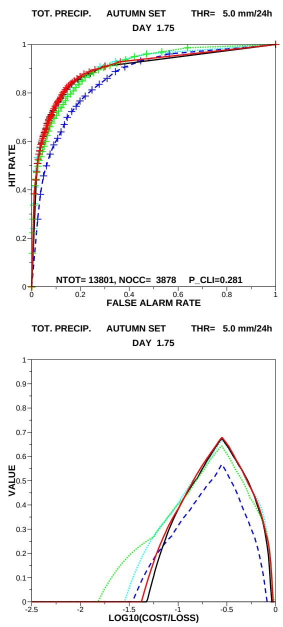
The autumn set consist of 14 cases where each case is running for 60 hours. (The forecast time include only one observation time of total precipitation rate, i.e. +42 hours.) Table 4 shows that this set had generally high amounts of small to large total precipitation rates.
Several of the 14 cases include observations of high precipitation rates (Bremnes and Homleid, 2003 a).

The ROC-diagrams show that all the curves lie well above the diagonal for all threshold values of total precipitation rates (see upper panels of figure 5 and appendix A.3.1.). EPS is the system with the highest skill for very small total precipitation rates. CLAMEPS_ESV is the system with the best curve at total precipitation rates 5 mm/24 hour, but only for large false alarm rates (see upper panel of figure 5.a). The high hit rate occurs in other words on cost of a high false alarm rate. The improvement in the skill of the CLAMEPS_ESV compared to the other systems increases with raising precipitation rates. At precipitation rates 15 mm/24 hour and more CLAMEPS_ESV is the experiment with highest skill also at small false alarm rates (see upper panel of figure 5. b, c and d).

The space enclosed by the different curves, the y-axis and the top level indicates the credibility of the experiment. EPS and EPS20 are most credible for precipitation rates 15 mm/24hours and smaller (see upper panel of figure 5.b). CLAMEPS_ESV is also most credible at low to middle precipitation rates, but does not loose information in the same degree as EPS and EPS20 for greater precipitation rates (see upper panel of figure 5 d).

The maximum value in the cost/loss-diagrams occurs at total precipitation rate 20 mm/24hour (see lower panel of figure 5 c). It is the CLAMEPS_ESV experiment that has this maximum value which shows high quality of the experiment for this threshold value. The maximum in the different cost/loss-curves moves from right at small precipitation rates toward the centre of the diagram with higher precipitation rates. This means a larger quality in the systems for lower

a)



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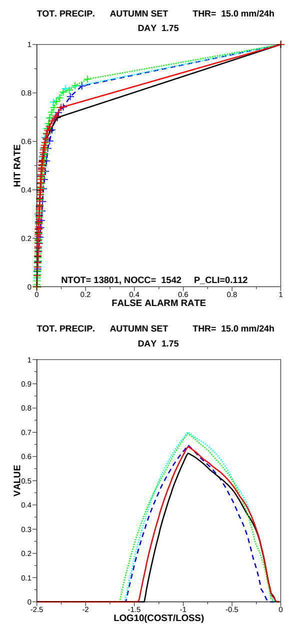

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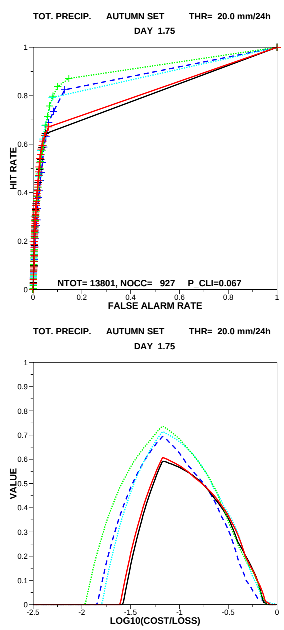

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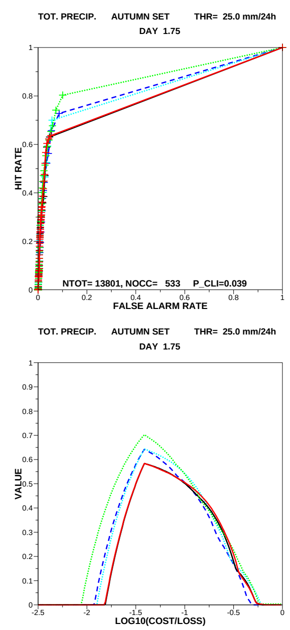


Figure 5 a-d) The figure shows the ROC-diagram (upper panel) and cost/loss-diagram (lower panel) for different threshold values of total precipitation rates looking at the cases in the autumn set at forecast time +42 hours. The different curves are EPS(red), EPS20(black), TEPS_ESV(light blue), LAMEPS_ESV(blue) and CLAMEPS_ESV(green). The threshold values are a) 5 mm/24h, b) 15 mm/24h, c) 20 mm/24h and d) 25mm/24h.

cost/loss-ratios when the precipitation threshold value increase. At precipitation rates 15, 20 and 25 mm/24hours, CLAMEPS_ESV and LAMEPS_ESV have the largest values (se lower panel of figure 5 b-d), and the user will have benefit of using these systems rather than EPS or EPS20.

3.4.2 Winter

The winter set consist of 21 cases. The systems TEPS_ESV and LAMEPS_ESV have been run for 66 hours for each case and include both observation times of the total precipitation rate; one at 42 hours and one at 66 hours. The frequency of medium precipitation rates is approximately equal to the autumn set. The frequency of large precipitation rates is somewhat lower and the frequency of small precipitation rates is somewhat higher (see table 4).

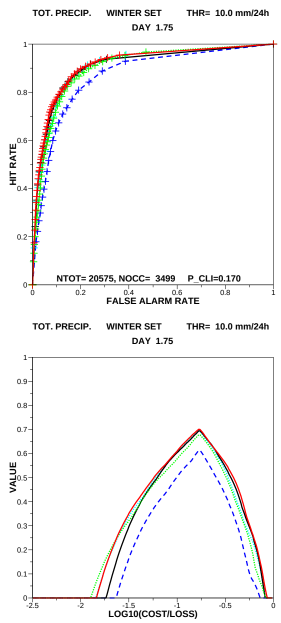
<u>The results at forecast-time 42 hours:</u>
The CLAMEPS_ESV and EPS-curves are almost equal in the ROC-diagram and show good results up to total precipitation rates of 25 mm/24h (see upper panel of figure 6 a-c). At the threshold value of 30 mm/24h CLAMEPS_ESV is a little bit better than EPS (see upper panel of figure 6 d), but since these high total precipitation rates do happen rarely, all the curves show not as credible results as at lower precipitation rates. The most credible results (the diagram with most of the points clustered in the upper left corner) take place at 10 mm/24hour (see upper panel of figure 6 a). At this threshold value CLAMEPS_ESV has slightly better skill than EPS for large hit rates, but the high skill occurs on cost of a high false alarm rate. The LAMEPS_ESV-curve passes EPS20 at the highest total precipitation rates (see upper panel of figure 6 c, d).

The cost/loss-curves move to the left with rising precipitation rates (see lower panels of figure 6). The movement toward left is according to a transfer of the quality in the systems toward lower cost/loss-ratios when the precipitation rates increase. The threshold value with highest system-quality take place at precipitation rates 10-15 mm/24 hours. Here EPS, EPS20, TEPS_ESV and CLAMEPS_ESV have almost the same top point and hence the systems are of almost equal quality. At threshold value 30 mm/24 hours CLAMEPS_ESV has slightly better quality than the EPS, the quality in all the systems are however not so good compared to the quality at lower precipitation rates.

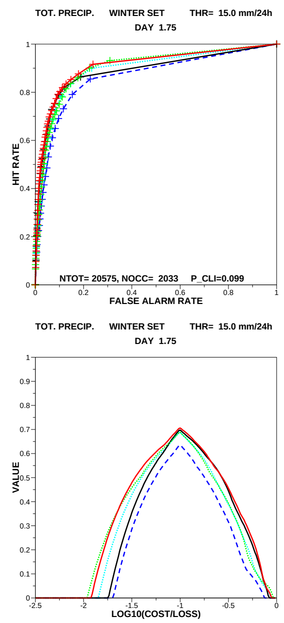
<u>The results at forecast-time 66 hours:</u>
LAMEPS_ESV shows better results at all precipitation rates at +66 hours compared to the LAMEPS_ESV results at +42 hours. At 30 mm/24 hours LAMEPS_ESV shows higher skill than EPS20 (see upper panel of figure 7 d). CLAMEPS_ESV shows better results than EPS not only at 30 mm/24 hours which was the case at +42 hours, but also at 10, 15 and 20 mm/24 hours (see upper panel of figure 7 a-c). In addition to this, all the systems have increased it’s skill at middle and large total precipitation rates, since the curves lie higher in the ROC-diagrams.

Looking at the cost/loss-curves, the systems top points lie higher at middle and large precipitation rates (see lower panel of figure 7) and indicate a higher quality in the systems for these precipitation rates compared to the results at +42 hours. The curves are also moved a little more

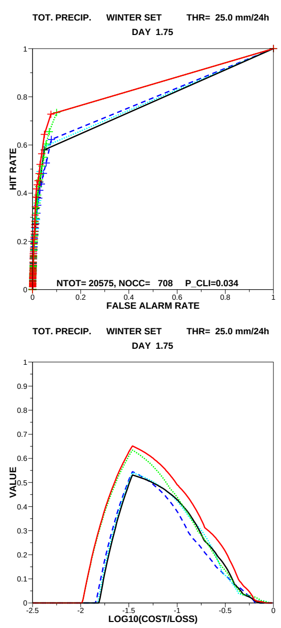
a)



b)



c)



d)

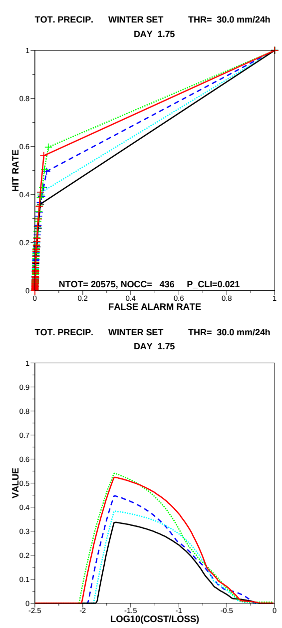
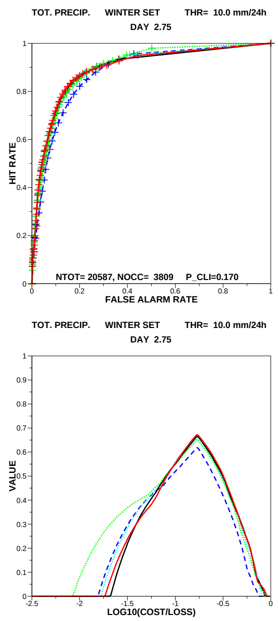
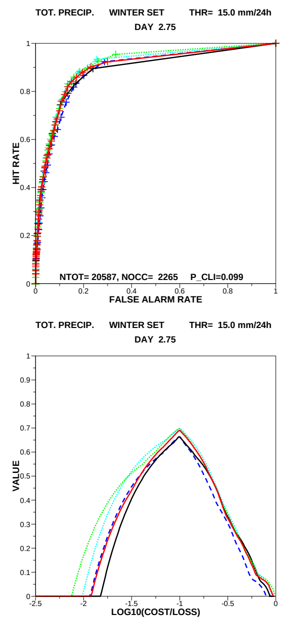


Figure 6 a-d) The figure shows the ROC-diagram (upper panel) and cost/loss-diagram (lower panel) for different threshold values of total precipitation rates looking at the cases in the winter set at forecast time +42 hours. The different curves are EPS(red), EPS20(black), TEPS_ESV(light blue), LAMEPS_ESV(blue) and CLAMEPS_ESV(green). The threshold values are a) 10 mm/24h, b) 15 mm/24h, c) 25 mm/24h and d) 30mm/24h.

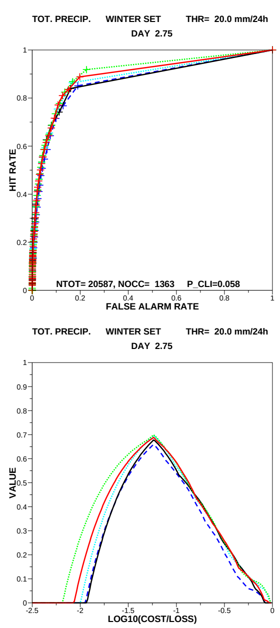
a)



b)



c)



d)

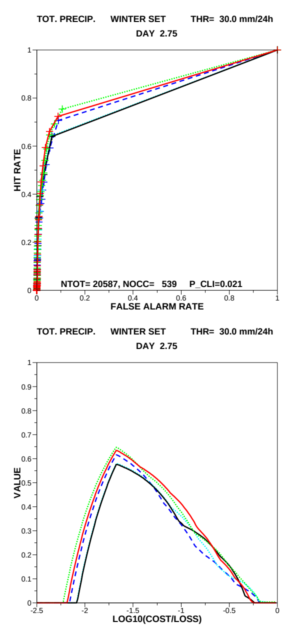


Figure 7 a-d) The figure shows the ROC-diagram (upper panel) and cost/loss-diagram (lower panel) for different threshold values of total precipitation rates looking at the cases in the winter set at forecast time +66 hours. The different curves are EPS(red), EPS20(black), TEPS_ESV(light blue), LAMEPS_ESV(blue) and CLAMEPS_ESV(green). The threshold values are a) 10 mm/24h, b) 15 mm/24h, c) 20 mm/24h and d) 30mm/24h left compared to the curves at +42 hours. LAMEPS_ESV has increased for all precipitation rates and show higher quality than EPS20 at the threshold value 30 mm/24 hour. CLAMEPS_ESV shows however still the best results together with EPS at all total precipitation rates.

3.4.3 Spring

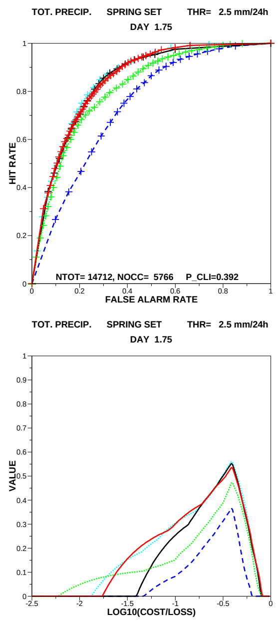
The spring set consists of 15 cases. The systems TEPS_ESV and LAMEPS_ESV have been running for 66 hours and hence both observation times are included. The spring set had the smallest observed precipitation rates compared to the other 3 experiment periods. The cases include firstly small to medium range precipitation rates. The highest measured precipitation rate at Gardermoen was approximately 14 mm/24 hours (Bremnes and Homleid, 2003 b). The frequencies of medium and large precipitation rates are low (see table 4).

<u>The results at +42 hours:</u>
CLAMEPS_ESV becomes just the uppermost curve at precipitation rates 5.0 mm/24 hours, but on cost of large false alarm rates (see upper panel of figure 8 b). EPS is best for low false alarm rates. At precipitation rates 7.5 to 15 mm/24 hours CLAMEPS_ESV is marginally the best system (see upper panel of figure 8 c) while EPS is best both for smaller and larger precipitation rates (see figure 8 a, d). The cost/loss-curves show that the CLAMEPS_ESV does not reach the top-point of the EPS curve at any precipitation rate (lower panels of figure 8). The curve is on the other hand stretched out over more cost/loss-values. Users with low cost/loss-values can have benefit of using the CLAMEPS_ESV (see lower panel of figure 8 a-c).

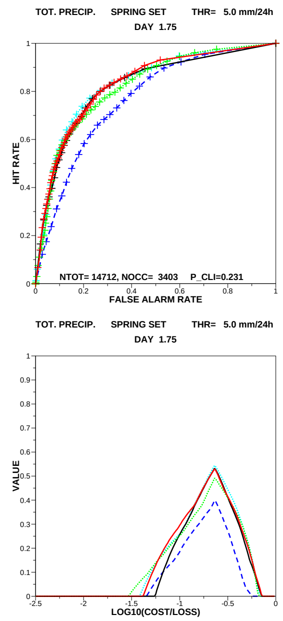
<u>The results at +66 hours:</u>
LAMEPS_ESV and CLAMEPS_ESV show better results compared to the results at forecast time +42 hours for medium precipitation rates (5-15 mm/24h) (see upper panels of figure 9 a-c). At 10 mm/24hours CLAMEPS_ESV has higher skill than EPS and LAMEPS_ESV has higher skill than EPS20 (see upper panel of figure 9 b). At 15 mm/24hour CLAMEPS_ESV is the system with the highest skill (see upper panel of figure 9 c).

CLAMEPS_ESV is the highest curve in the cost/loss-diagram at precipitation rate 15 mm/24hour (see figure 9 c), and the user will have benefit of using the CLAMEPS_ESV compared to the other systems for this precipitation rate. This is, however, not the case for the other precipitation rates.

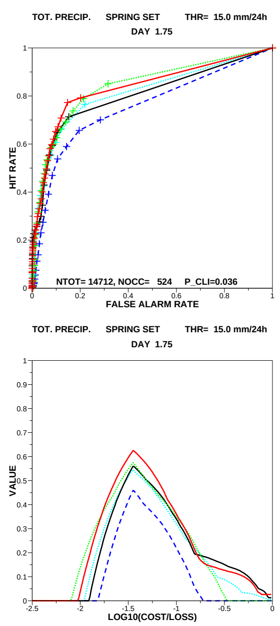
a)



b)



c)



d)

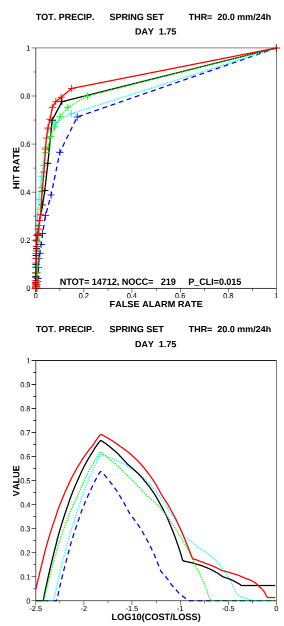
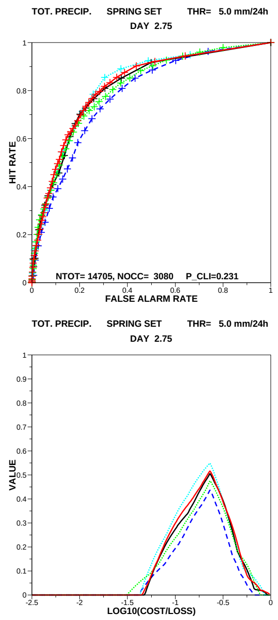
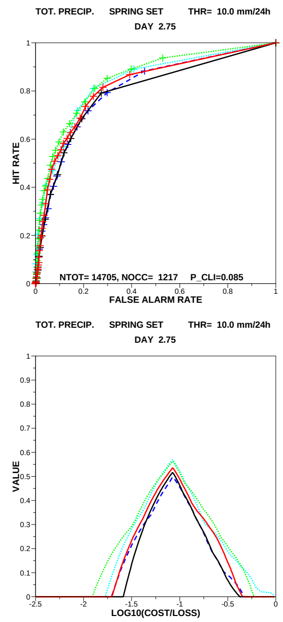


Figure 8 a-d) The figure shows the ROC-diagram (upper panel) and cost/loss-diagram (lower panel) for different threshold values of total precipitation rates looking at the cases in the spring set at forecast time +42 hours. The different curves are EPS(red), EPS20(black), TEPS_ESV(light blue), LAMEPS_ESV(blue) and CLAMEPS_ESV(green). The threshold values are a) 2.5 mm/24h, b) 5 mm/24h, c) 15 mm/24h and d) 20mm/24h.

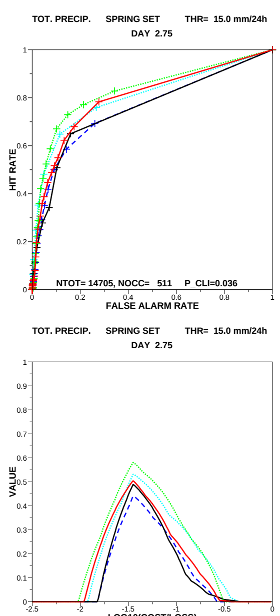
a)



b)



c)



d)

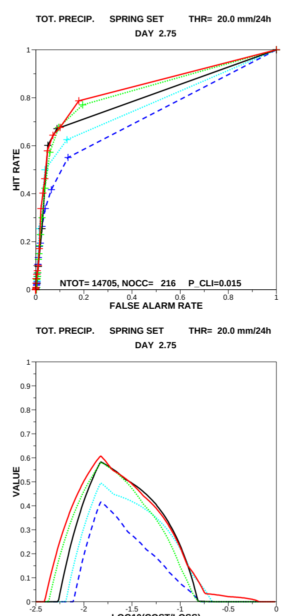


Figure 9 a-d) The figure shows the ROC-diagram (upper panel) and cost/loss-diagram (lower panel) for different threshold values of total precipitation rates looking at the cases in the spring set at forecast time +66 hours. The different curves are EPS(red), EPS20(black), TEPS_ESV(light blue), LAMEPS_ESV(blue) and CLAMEPS_ESV(green). The threshold values are a) 5 mm/24h, b) 10 mm/24h, c) 15 mm/24h and d) 20mm/24h.

3.4.4 Summer

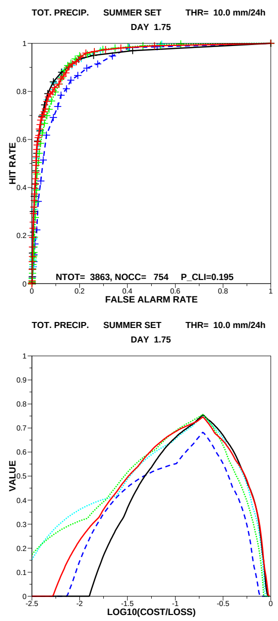
The summer set was chosen because a very rare precipitation event occurred. The summer set is hence the only experiment period chosen because of it's extreme precipitation rates. The precipitation rates at some stations were as large as what take place statistically once each century. The set consists of only 4 cases. The systems TEPS_ESV and LAMEPS_ESV are run for 66 hours for each case and include the 2 observation times at +42 hours and +66 hours.

<u>The results at +42 hours:</u>
The CLAMEPS_ESV-curve is generally the best curve in the ROC-diagrams (although CLAMEPS_ESV alternates with the other systems at low false alarm rates. See upper panel of figure 10 a-d). CLAMEPS_ESV has also the maximum cost/loss-value at almost all the total precipitation rates. The results at the threshold value 10 mm/24hour total precipitation shows very good results with high density of crosses in the upper left corner of the ROC-diagram (see figure 10 a). The cost/loss-curves for this total precipitation rate show maximum values of approximately 0.77 for all the systems without LAMEPS_ESV which shows a lower maximum value (0.69) (see lower panel of figure 10 a). The maximum takes place at the right hand side of the cost/loss-diagram. The LAMEPS_ESV-curve crosses the EPS20-curve in the ROC-diagrams (see upper panel of figure 10 a-d) and shows higher hit rates when the false alarm rates are high. At large total precipitation rates (20 mm/24 hours and more), LAMEPS_ESV becomes higher hit rates than EPS20, but this happen for relatively large false alarm rates, and EPS20 has therefore still the highest cost/loss-value.

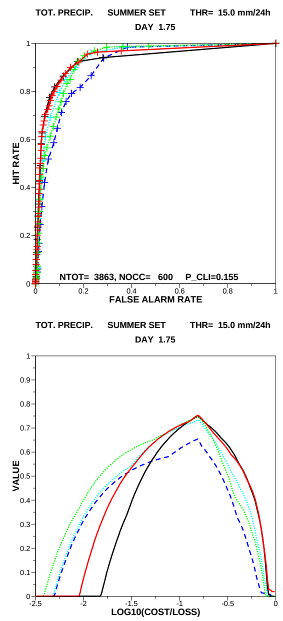
<u>The results at +66 hours:</u>
CLAMEPS_ESV has also here generally the best curve in the ROC-diagrams and the largest value in the cost/loss diagrams (see figure 11). Only at total precipitation rate 10 mm/24 hour the CLAMEPS_ESV curve is passes by EPS.

The summer set includes only 4 days, all with heavy precipitation. This leads to good results for all the systems. It seems that the forecast hour +42 is somewhat better than the forecast time +66 hours.

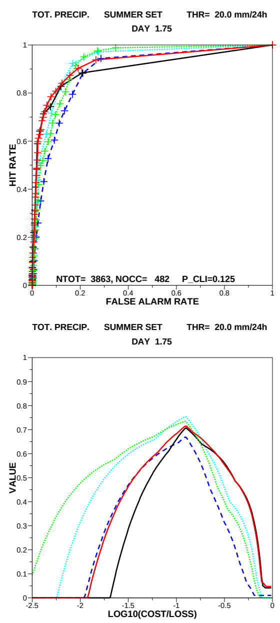
a)



b)



c)



d)

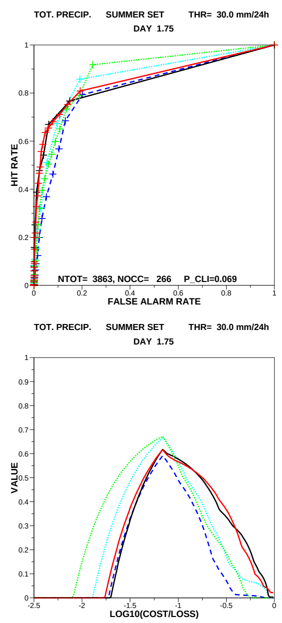
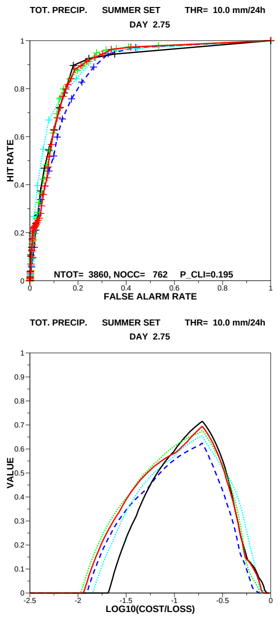
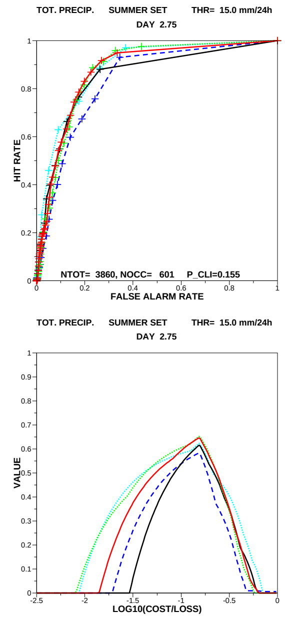


Figure 10 a-d) The figure shows the ROC-diagram (upper panel) and cost/loss-diagram (lower panel) for different threshold values of total precipitation rates looking at the cases in the summer set at forecast time +42 hours. The different curves are EPS(red), EPS20(black), TEPS_ESV(light blue), LAMEPS_ESV(blue) and CLAMEPS_ESV(green). The threshold values are a) 10 mm/24h, b) 15 mm/24h, c) 20 mm/24h and d) 30mm/24h.

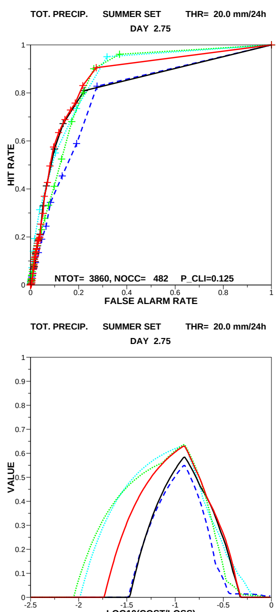
a)



b)



c)



d)

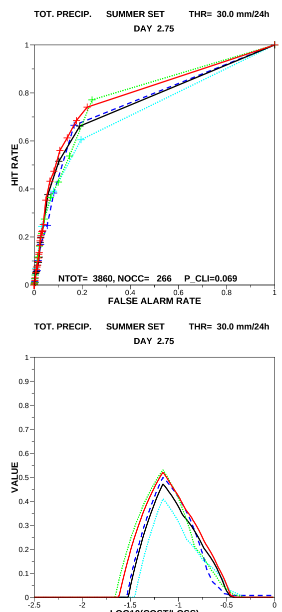


Figure 11 a-d) The figure shows the ROC-diagram (upper panel) and cost/loss-diagram (lower panel) for different threshold values of total precipitation rates looking at the cases in the summer set at forecast time +66 hours. The different curves are EPS(red), EPS20(black), TEPS_ESV(light blue), LAMEPS_ESV(blue) and CLAMEPS_ESV(green). The threshold values are a) 10 mm/24h, b) 15 mm/24h, c) 20 mm/24h and d) 30mm/24h.

3. 3.5 Case-study

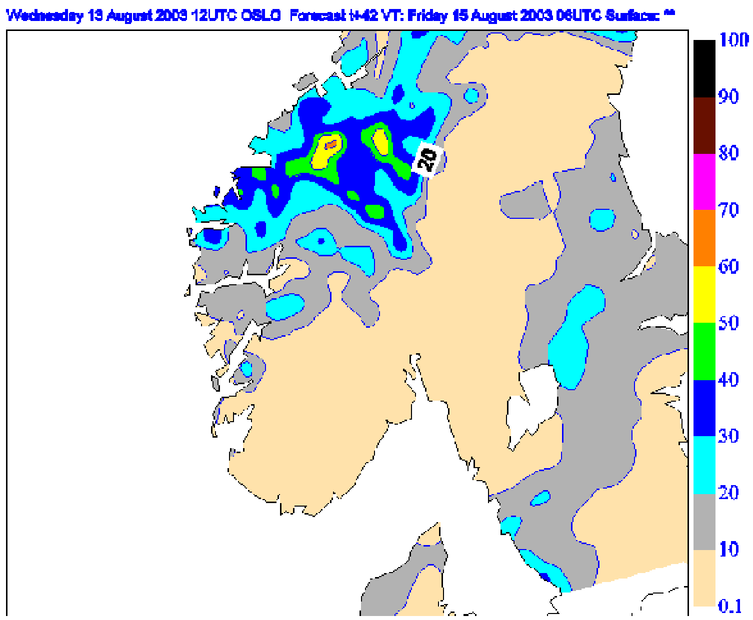
At the 14-15 August 2003 it was measured extreme precipitation rates in the middle of Norway, e.g.116.5 mm during 24 hours and 156,2 mm during 48 hours at the precipitation station Atnadalen in Hedmark. At Sunndalsøra in Møre and Romsdal it was measured 102.5 mm during 24 hours and 171,9 mm during 48 hours. This precipitation amounts are statistically measured more rarely than once each century.

The figure 12 b shows the high precipitation rates that were observed. Neither the operational HIRLAM (20km) nor of the ECMWF's EPS ensemble members forecasted these high precipitation rates (see respectively figure 12 a and figure 13[2]). On the other hand some of the LAMEPS_ESV ensemble members forecasted it very accurately (see figure 14). The ensemble members 2 and 10 predicted more than 100 mm/24 hours at Western Norway. The ensemble members 7, 8, 15 and 20 show also good results at Western Norway (in Møre and Romsdal). This shows how valuable the limited area ensemble prediction system can be when extreme precipitation occurs.

The huge precipitation rates in Atnadalen are not likely good predicted by the LAMEPS_ESV ensemble system (see figure 12 b and figure 14). Some LAMEPS_ESV-ensemble members show high precipitation rates (ensemble nr. 4, 5, 11, 15 and 19) but not as high as was measured. These ensembles predict however higher precipitation rates than the operational forecasts and also higher than the EPS.

a)

[2] Only the first 20 ensemble members of the EPS are shown here, but the conclusion holds for all 50 members.



b)

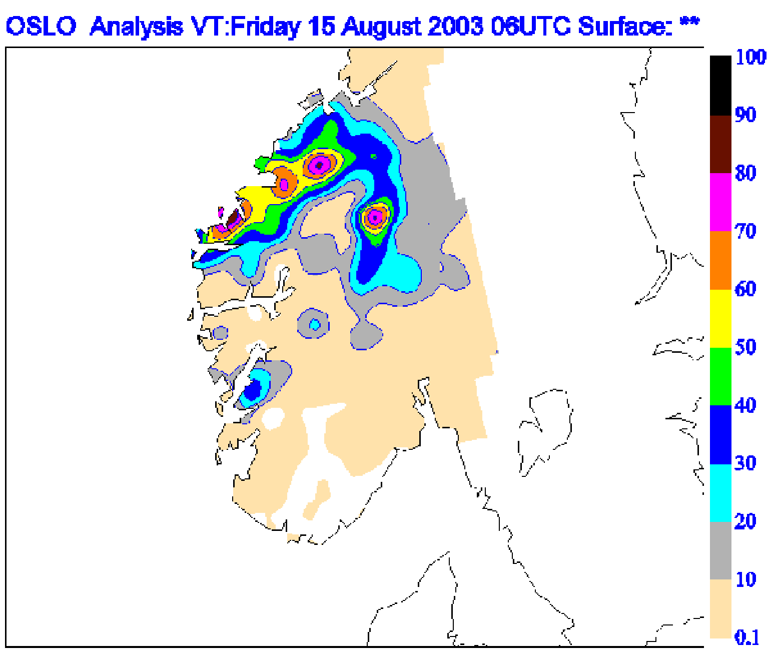


Figure 12. a) The figure shows the +42 hours predicted 24h total precipitation valid at 06UTC 15 August 2003**. b)** The figure shows the analysis of 24h total precipitation at 06UTC 15 August 2003.

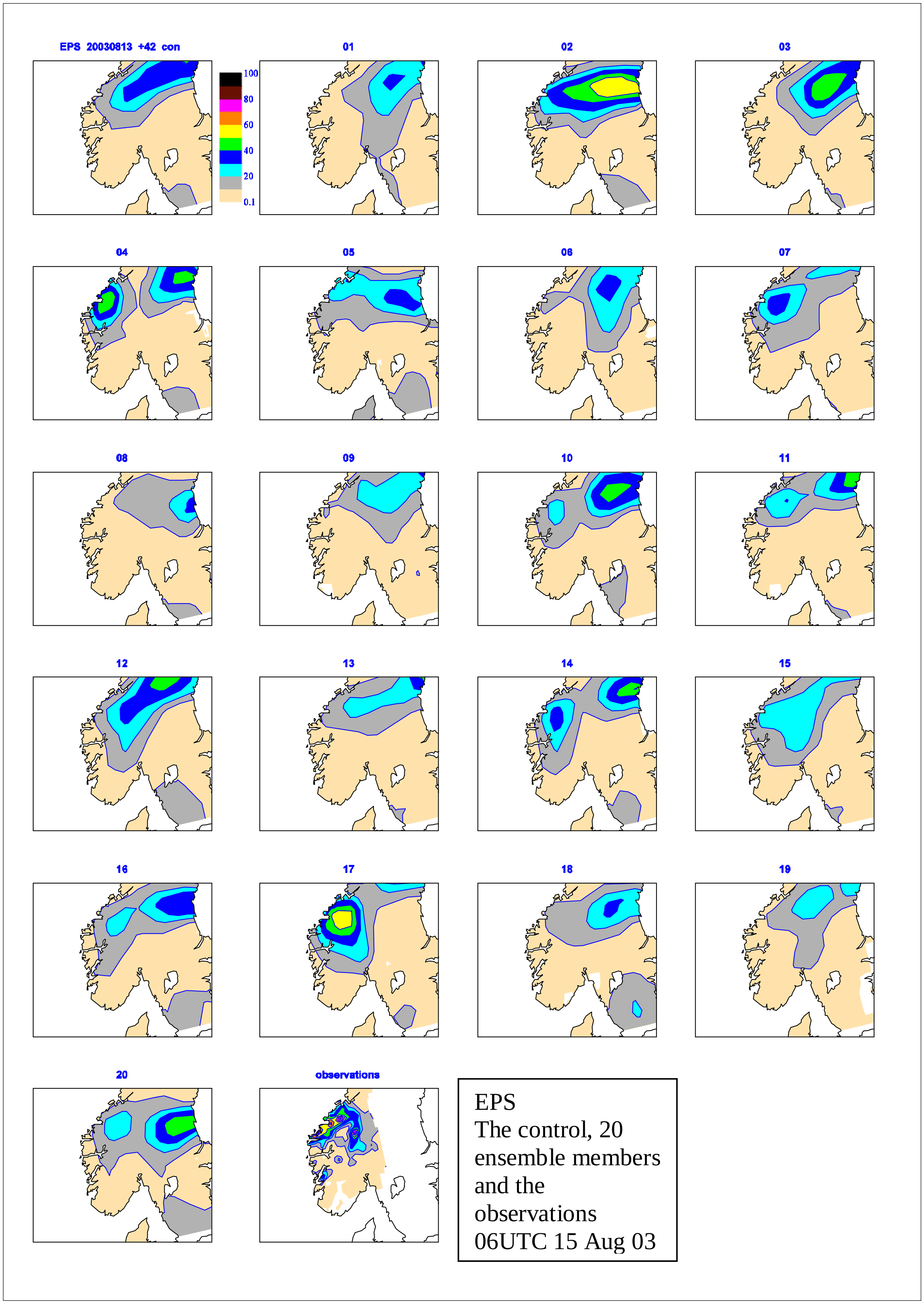


Figure 13. The figure shows the first 20 of the EPS ensemble members 06UTC 15 August 2003. The last figure is the observed precipitation at the same time.

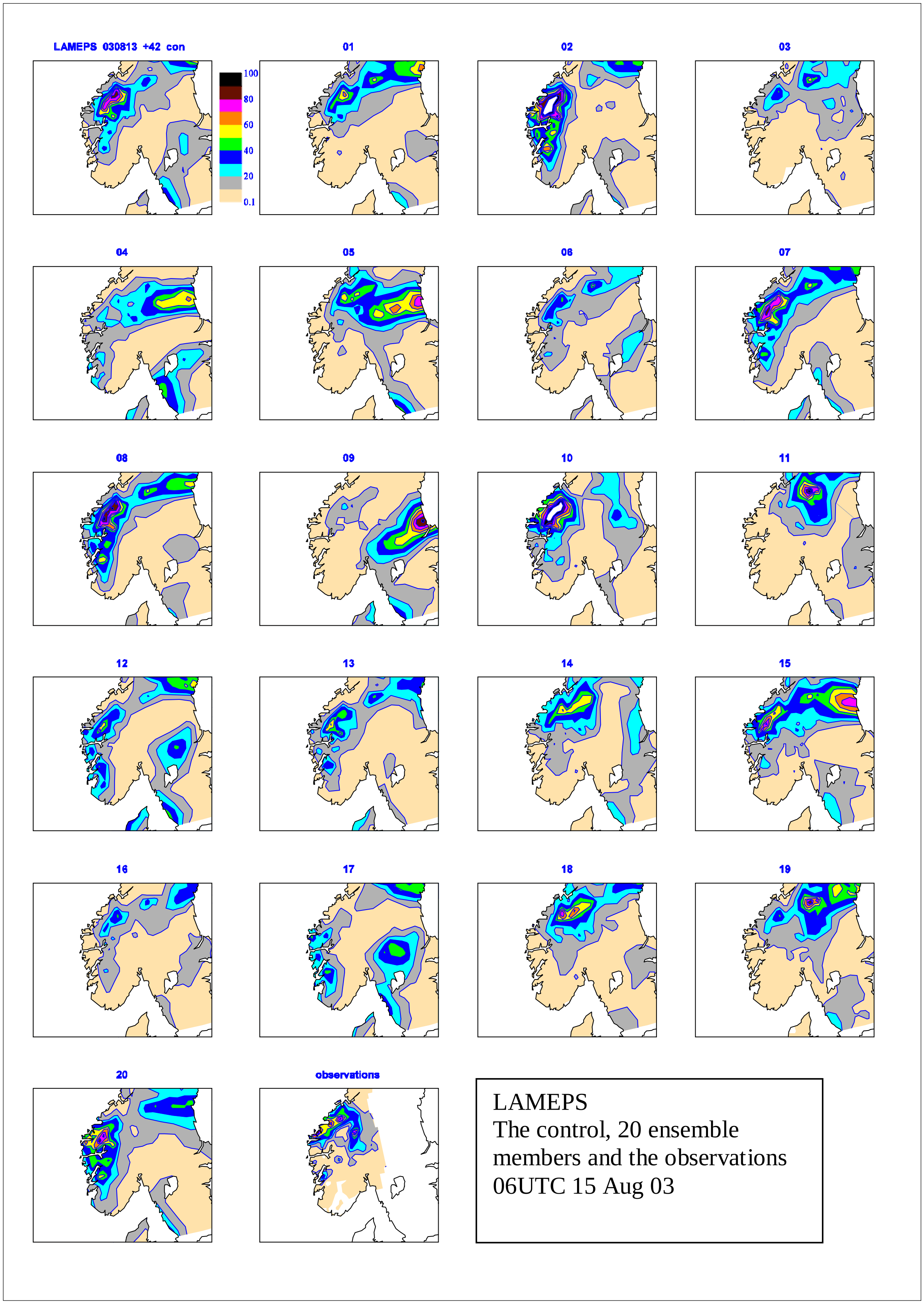


Figure 14. The figure shows the LAMEPS_ESV ensemble members 06UTC 15 August 2003. The last figure is the observed precipitation at the same time.

Section 4: Discussion and conclusions

In order to summarize the results, we have set up a table based on the results in the previous section. The systems with the best skill in different total precipitation groups are shown in table 5. The table shows that EPS has generally the highest skill when predicting small precipitation rates. CLAMEPS_ESV has generally the best skill when predicting medium precipitation rates and large precipitation rates (although it is not the case for the spring period.)

a)

+42 hours	**0-10 mm/24 hours**	**10-20 mm/24hours**	**20-30 mm/24 hours**
Autumn	EPS/20, CLAMEPS_ESV	CLAMEPS_ESV	CLAMEPS_ESV, TEPS_ESV
Winter	EPS/20	CLAMEPS_ESV, EPS	CLAMEPS_ESV, EPS
Spring	EPS/20	CLAMEPS_ESV, EPS	EPS
Summer	All systems	CLAMEPS_ESV, TEPS_ESV	CLAMEPS_ESV, TEPS_ESV
Total	EPS/20	CLAMEPS_ESV	CLAMEPS_ESV

b)

+66 hours	**0-10mm/24 hours**	**10-20mm/24 hours**	**20-30mm/24 hours**
Winter	EPS/20	CLAMEPS_ESV	CLAMEPS_ESV, EPS
Spring	EPS/20, TEPS_ESV, CLAMEPS_ESV	CLAMEPS_ESV	EPS
Summer	All systems	All systems	CLAMEPS_ESV
Total	EPS	CLAMEPS_ESV	CLAMEPS_ESV, EPS

Table 5. Table 5 shows the system/systems with the best skill in the different precipitation groups at forecast time a) +42 hours and b) +66 hours.

It is interesting to note that the good result of CLAMEPS_ESV at large precipitation rates (30 mm/24 hours) mainly comes from LAMEPS_ESV (LAMEPS_ESV performing better than TEPS_ESV), except maybe for the spring period. This holds for both verification times. For medium precipitation rates (15 mm/24 hours), however, TEPS_ESV is generally better than LAMEPS_ESV and hence contributing the most to the good results for CLAMEPS_ESV. By combining the two systems that both are designed for Northern Europe, we have been able to extend the precipitation interval for which the individual systems perform the best. The increase in ensemble members from 20+1 for the individual systems to 41+1 for CLAMEPS_ESV is also clearly favourable. The results are as expected, since systems with more members should be more capable of capturing extreme events.

The spring period is the only experiment period in which CLAMEPS_ESV does not have the highest skill at large precipitation rates. The results show that CLAMEPS_ESV doesn’t give good results at large precipitation rates when the observed total precipitation frequency is low (see figure 8d and 9d). When the frequency becomes higher, the experiment shows better results (see figure 5d).

The results from the winter and autumn periods are in accordance with the results Hersbach et.al. got in their study "A short to early-medium range Ensemble Prediction System for the European Area" (2000). Hersbach et.al. make out that TEPS had small impact with respect to EPS in winter cases, while the TEPS had significant impact for more extreme cases in the autumn set. We do however not see the same impact on the spring period in our results as what Hersbach et.al. did in their spring set, possibly because of the lack of extreme cases in our spring period.

An earlier study focusing on LAMEPS showed very promising results (Frogner, 2002) for high precipitation rates verified in the area of interest (se figure 1). The LAMEPS_ESV system does not to the same degree as in earlier studies outperform EPS. One reason can probably be that the EPS system which we compare our results against, has been improved since the last study. The horizontal resolution has increased from 120 km to 80 km and the vertical levels have increased from 31 to 40. The LAMEPS_ESV uses however not the latest operational version of HIRLAM at met.no which has horizontal resolution 20 km and 40 vertical levels, but the older version with 28 km horizontal resolution and 31 vertical levels. This also includes an older physics package. This older version was operational when the project started. In an eventual operational setting of LAMEPS_ESV, the latest operational version of HIRLAM at met.no will be used. The case study showed, however, that the LAMEPS_ESV results included a larger degree of details than the EPS and comes out with the best locally results. This is expected to be even better in a newer HIRLAM version. An improvement of LAMEPS_ESV would also have a positive impact on the combining of LAMEPS_ESV and TEPS_ESV as CLAMEPS_ESV.

Although the systems have been run for more extensive periods in this study, it is still too few to establish what the results yield beyond the experiment periods. Other choices of experiment periods could have given other results.

Section 5: Operationalizing

The plans for 2004 are to set up the ensemble system using HIRLAM on regional scale to run semi-operationally. The system has to be changed from a setup with only experiment-runs done for old periods to a setup which can run for the actual daily situation. The new setup will require EPS data from ECMWF on the form TEPS_ESV, to perturb the HIRLAM initial conditions and the lateral boundary conditions.

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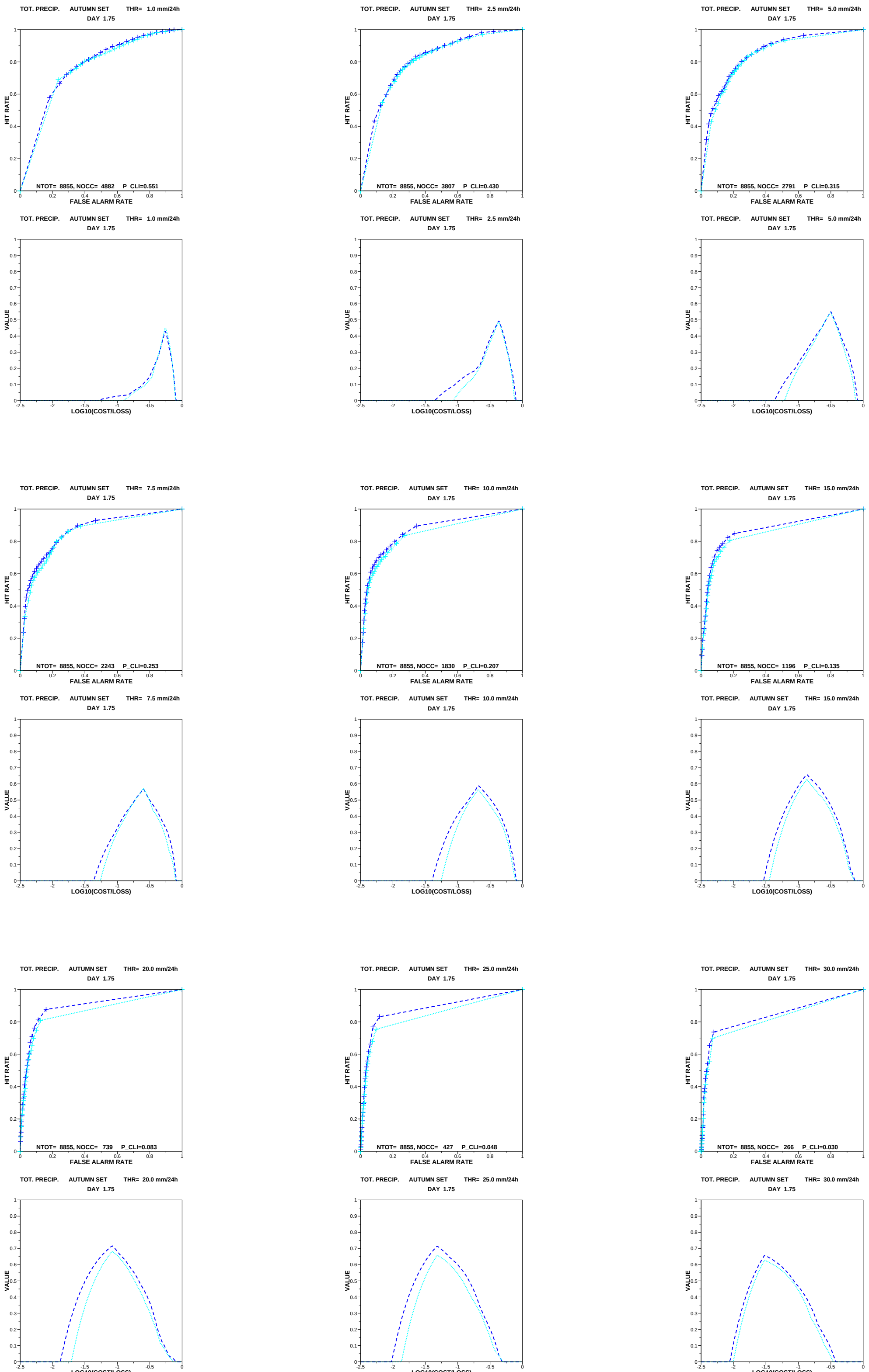
APPENDIX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DAY 1.75
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DAY 1.75
NTOT= 8855, NOCC= 2791 P_CLI=0.315
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DAY 1.75
VALUE
LOG10(COST/LOSS)
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DAY 1.75
TOT. PRECIP. AUTUMN SET THR= 5.0 mm/24h
DAY 1.75
TOT. PRECIP. AUTUMN SET THR= 7.5 mm/24h
DAY 1.75
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DAY 1.75
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DAY 1.75
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DAY 1.75
TOT. PRECIP. AUTUMN SET THR= 10.0 mm/24h
DAY 1.75
TOT. PRECIP. AUTUMN SET THR= 15.0 mm/24h
DAY 1.75
TOT. PRECIP. AUTUMN SET THR= 20.0 mm/24h
DAY 1.75
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DAY 1.75
NTOT= 8855, NOCC= 427 P_CLI=0.048
TOT. PRECIP. AUTUMN SET THR= 30.0 mm/24h
DAY 1.75
NTOT= 8855, NOCC= 266 P_CLI=0.030
TOT. PRECIP. AUTUMN SET THR= 20.0 mm/24h
DAY 1.75
TOT. PRECIP. AUTUMN SET THR= 25.0 mm/24h
DAY 1.75
TOT. PRECIP. AUTUMN SET THR= 30.0 mm/24h
DAY 1.75

Figure A.1.1. ROC-diagrams with belonging cost/loss-curves for different total precipitation rates, forecastday 1.75 (+42 hours) comparing LAMEPS(cyan) and LAMEPS_ESV(blue).

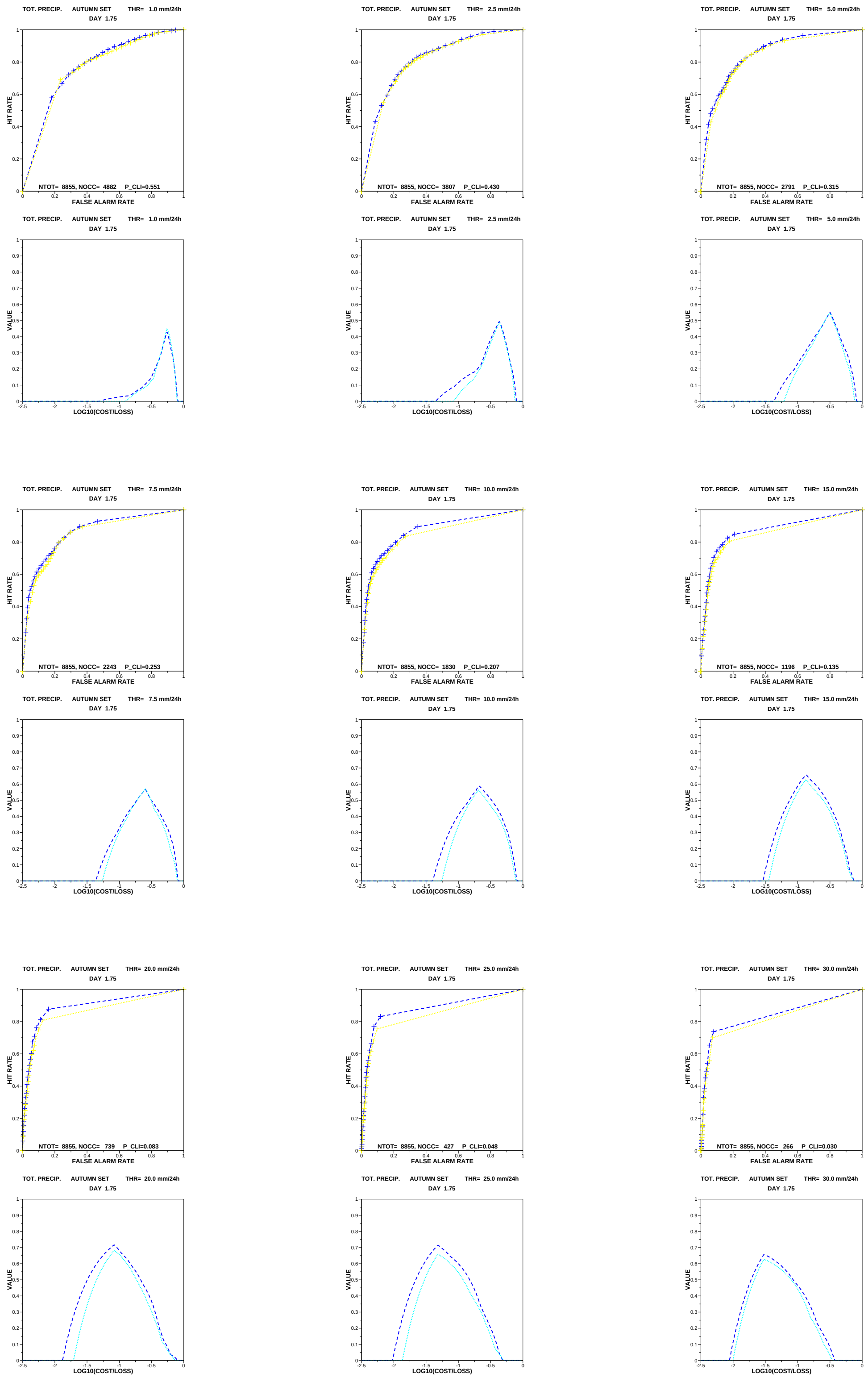


Figure A.1.1. ROC-diagrams with belonging cost/loss-curves for different total precipitation rates forecast-day 1.75 (+42 hours) comparing LAMEPS(yellow) and LAMEPS_ESV(blue).

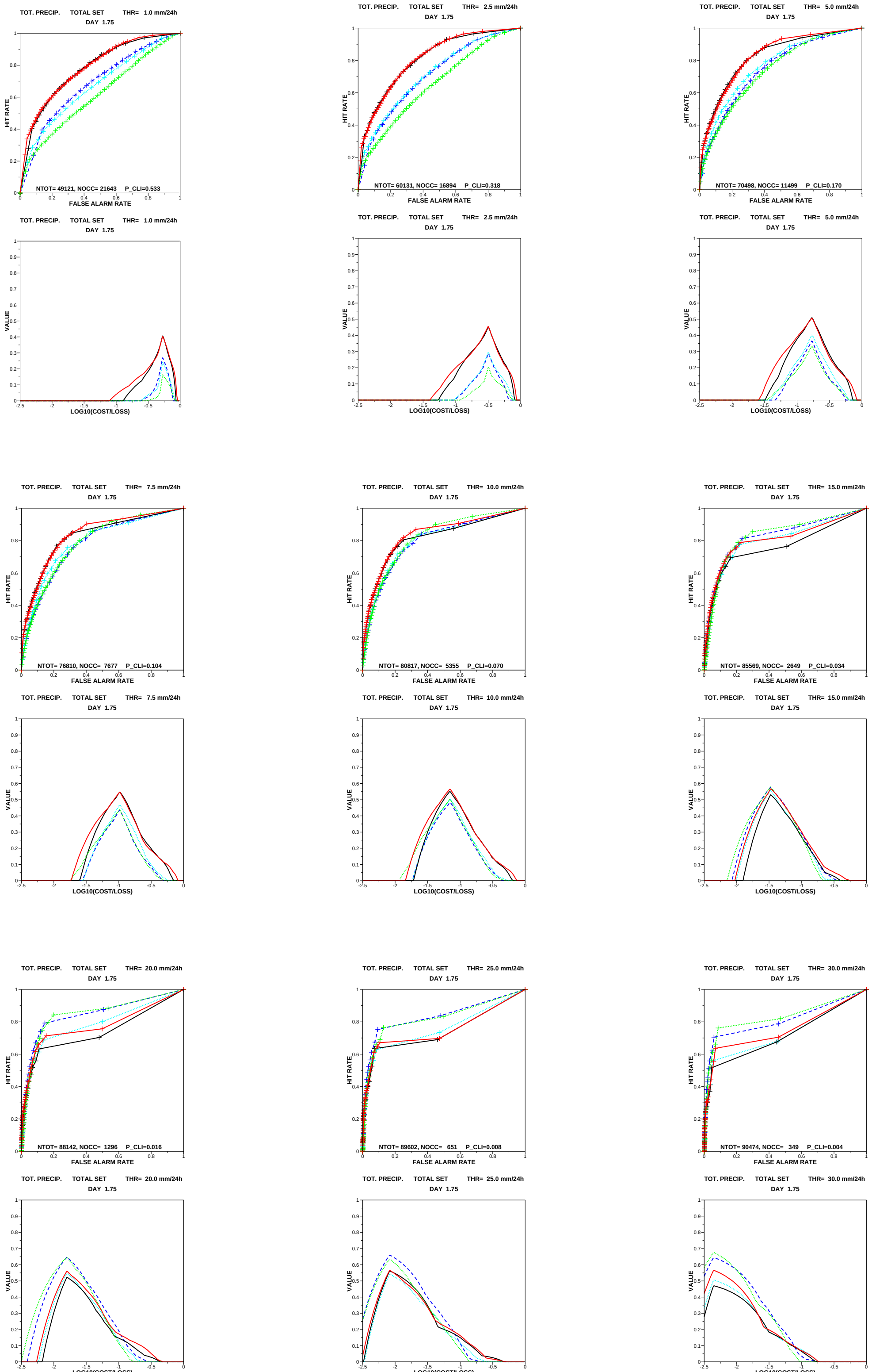


Figure A.2.1. ROC-diagrams with belonging cost/loss-curves for different total precipitation rates forecast-day 1.75 (+42 hours) for all four seasons.

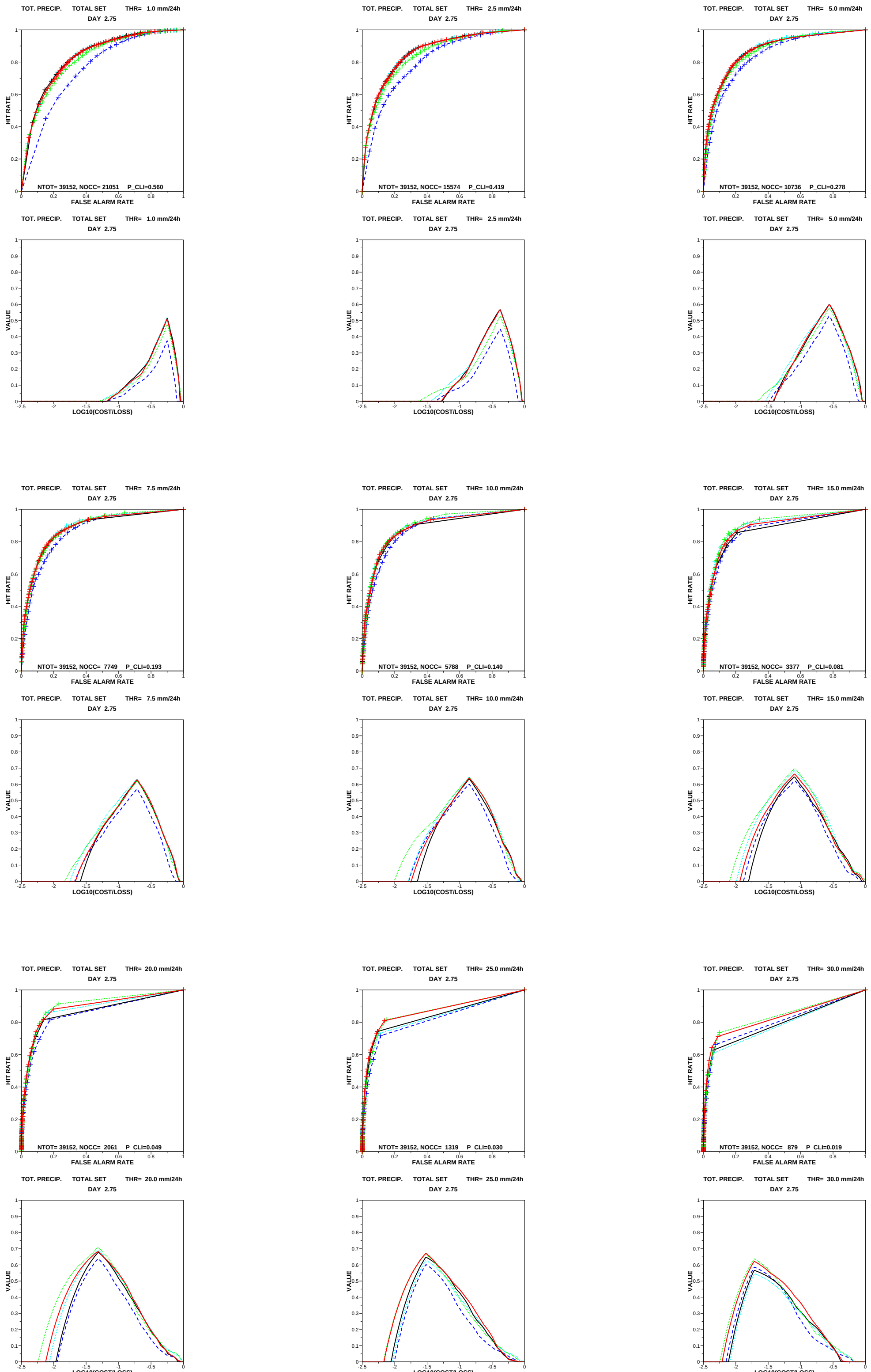


Figure A.2.2. ROC-diagrams with belonging cost/loss-curves for different total precipitation rates forecast-day 2.75 (+66 hours) for all four seasons.

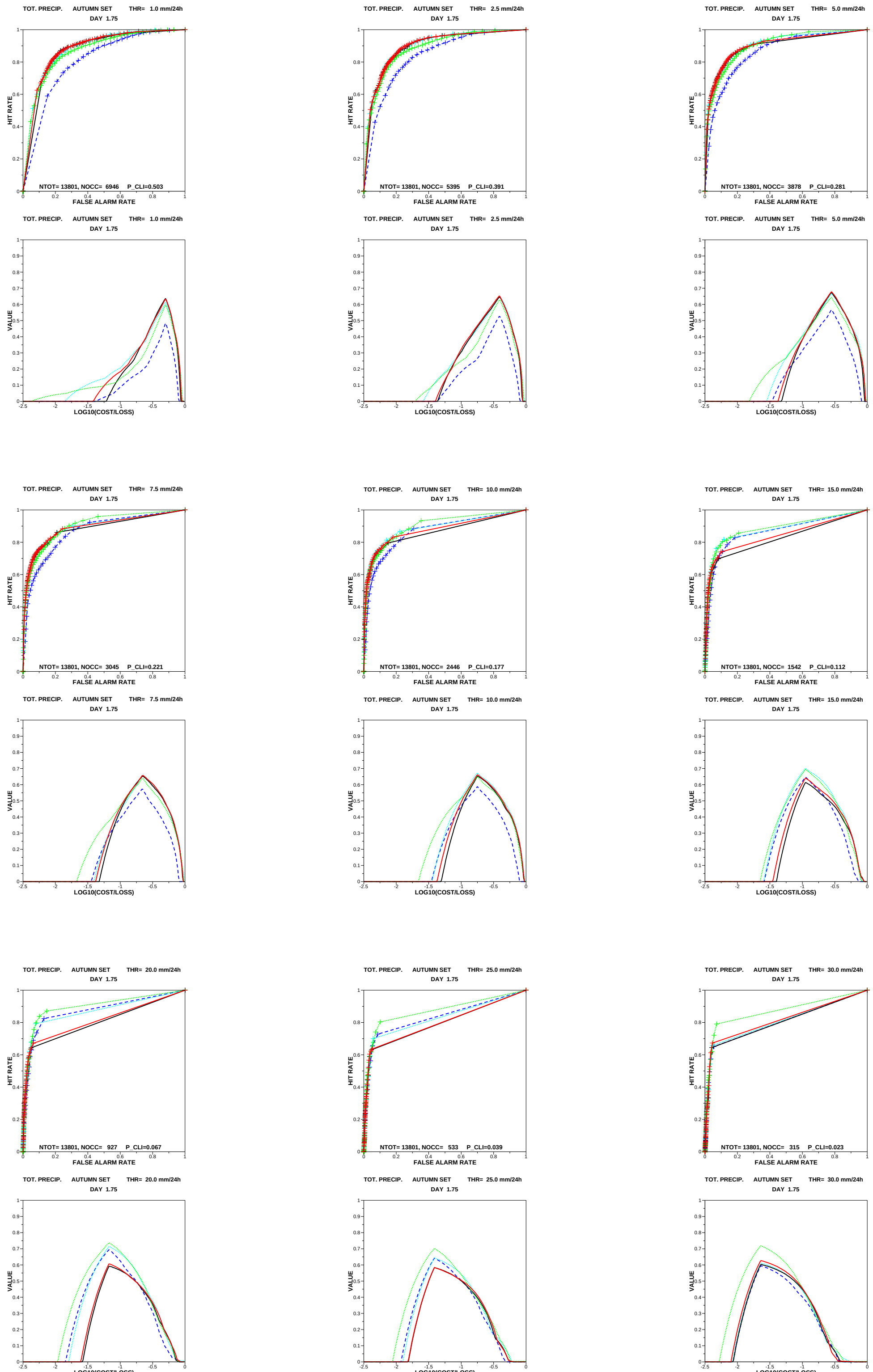


Figure A.3.1. The autumn-period results represented in ROC-diagrams with belonging cost/loss-curves for different total precipitation rates forecast-day 1.75 (+42 hours).

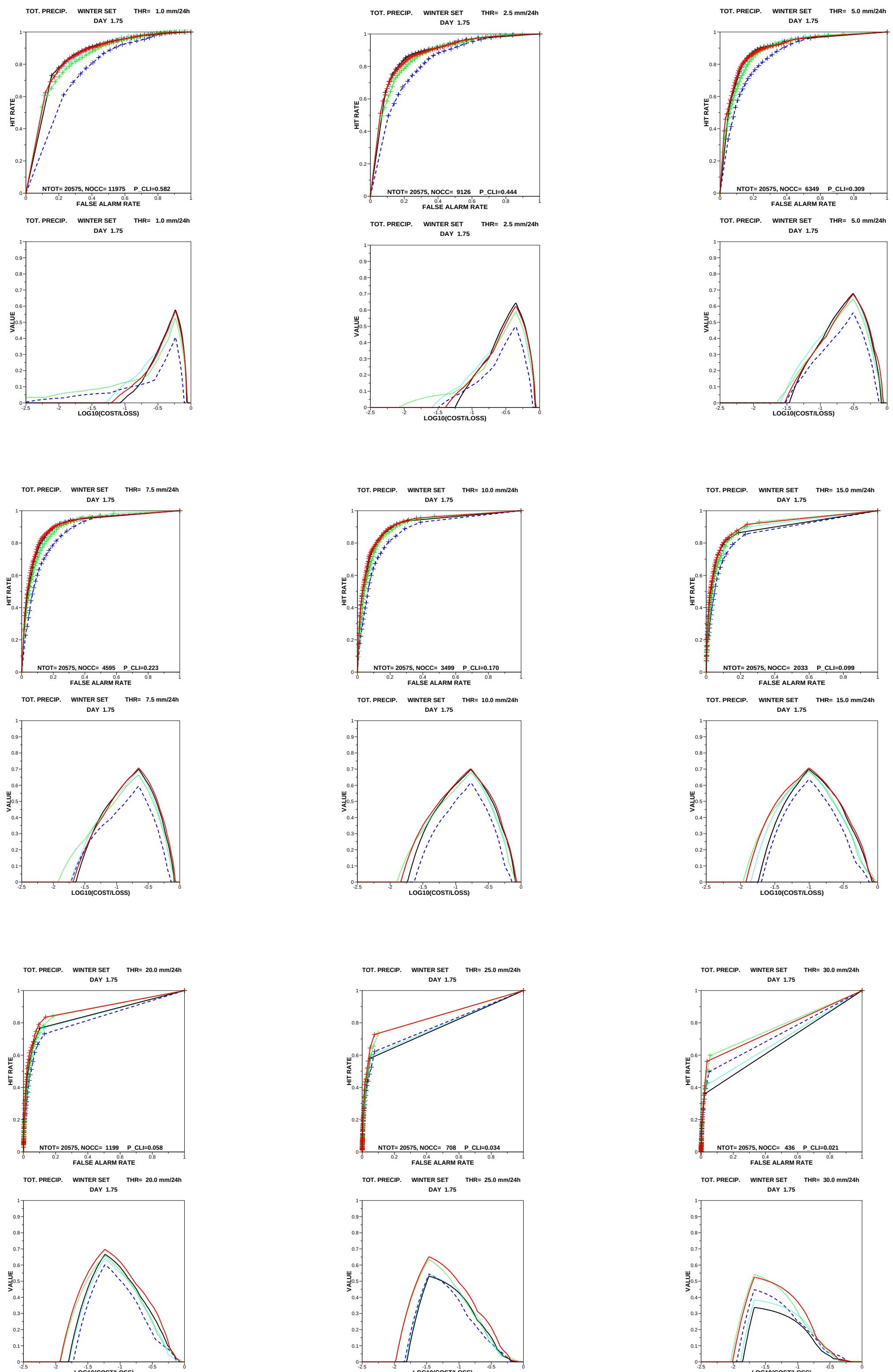


Figure A.4.1. The winter-period results represented in ROC-diagrams with belonging cost/loss-curves for different total precipitation rates forecast-day 1.75 (+42 hours).

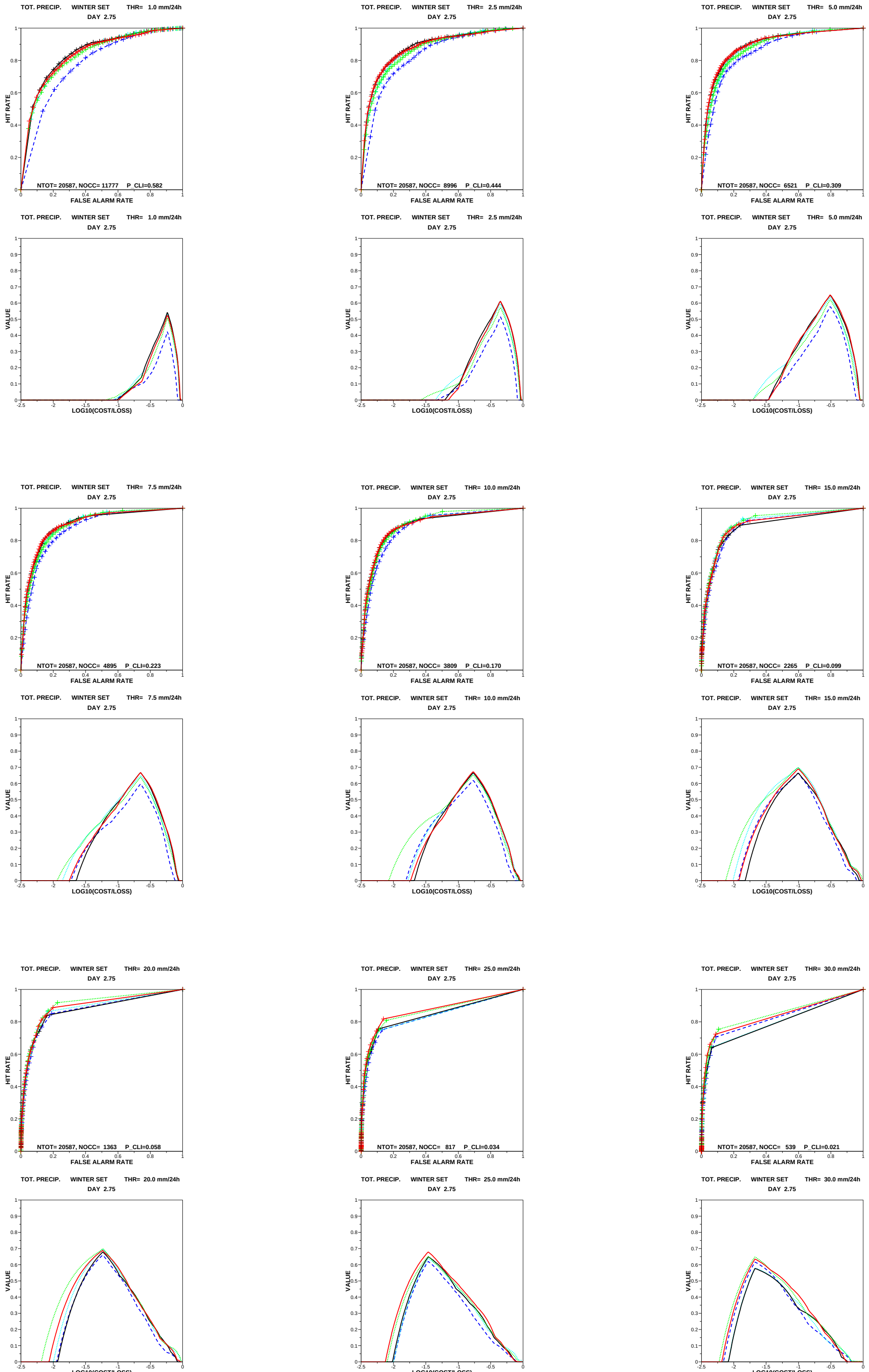


Figure A.4.2. The winter-period results represented in ROC-diagrams with belonging cost/loss-curves for different total precipitation rates forecast-day 2.75 (+66 hours).

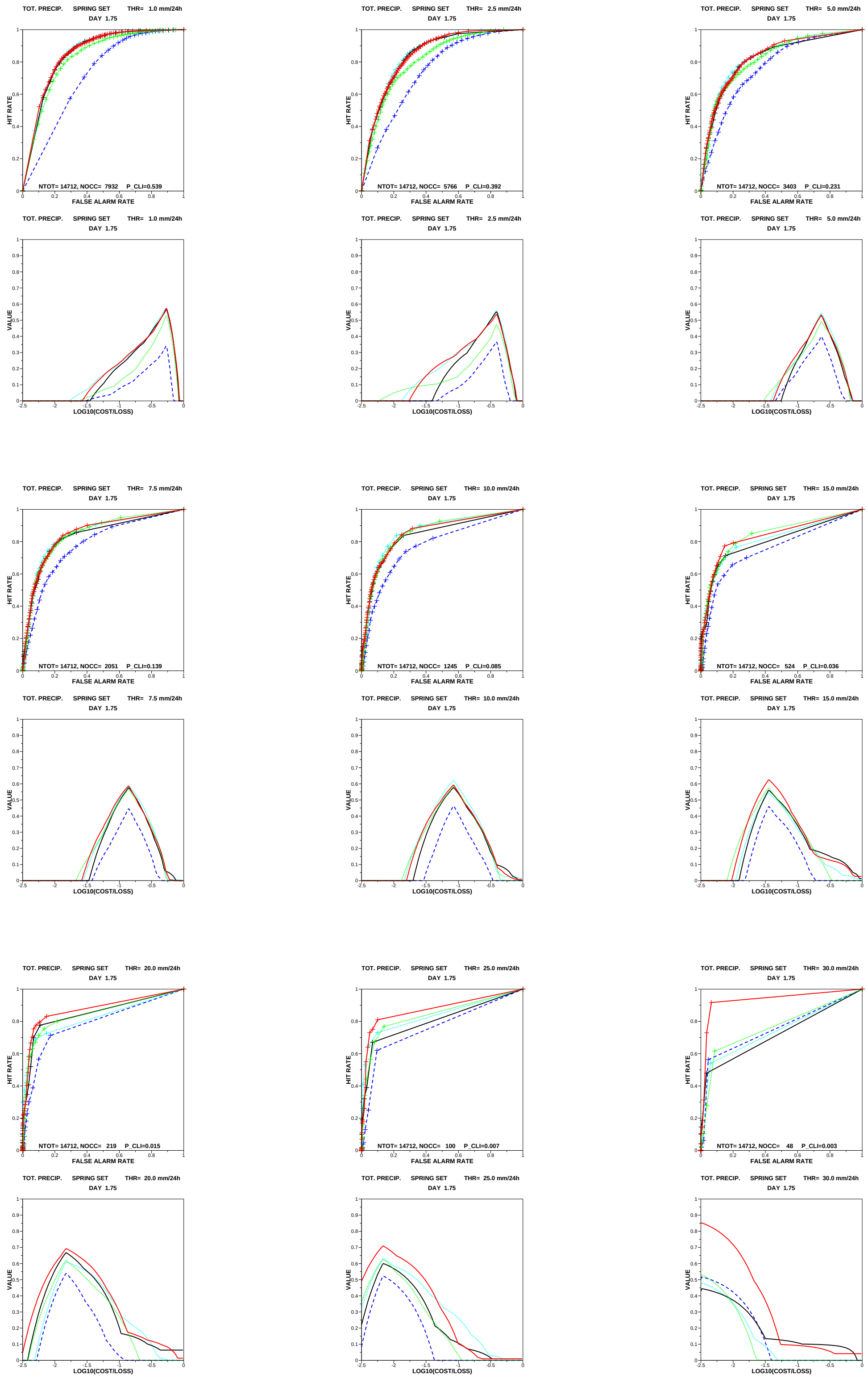


Figure A.5.1. The spring-period results represented in ROC-diagrams with belonging cost/loss-curves for different total precipitation rates forecast-day 1.75 (+42 hours).

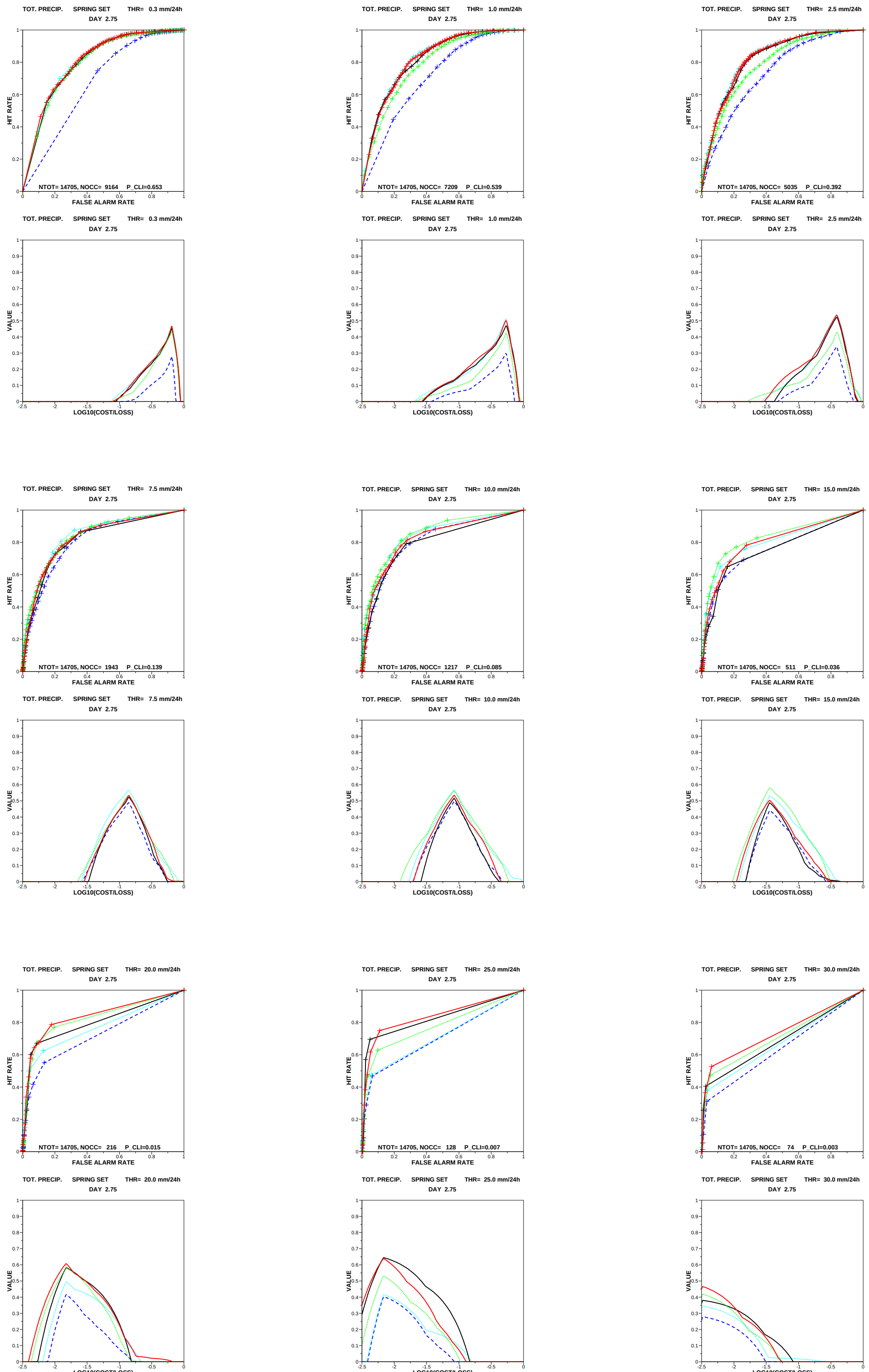
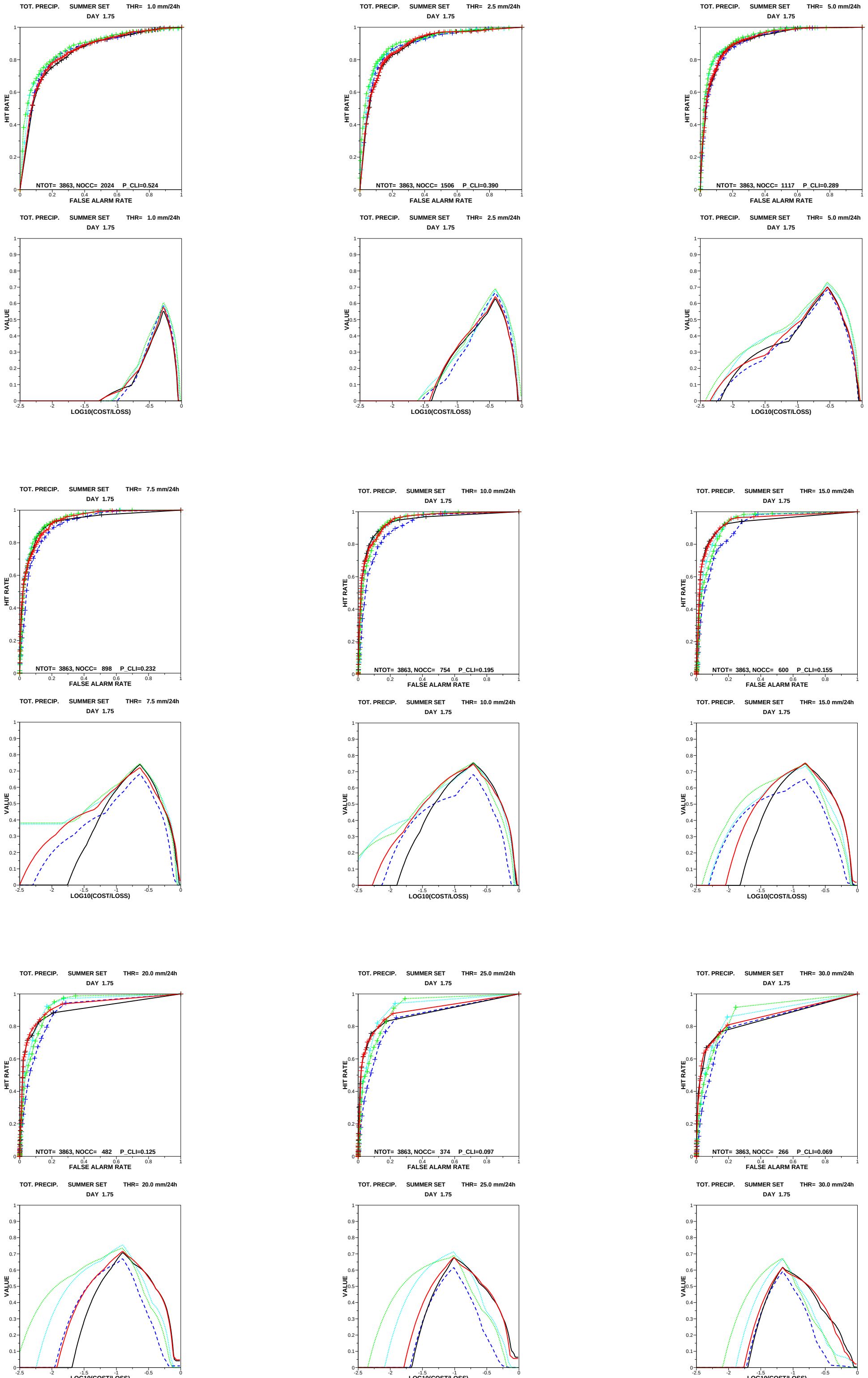


Figure A.5.2. The spring-period results represented in ROC-diagrams with belonging cost/loss-curves for different total precipitation rates forecast-day 2.75 (+66 hours).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DAY 1.75
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FALSE ALARM RATE
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TOT. PRECIP. SUMMER SET THR= 2.5 mm/24h
DAY 1.75
NTOT= 3863, NOCC= 1506 P_CLI=0.390
TOT. PRECIP. SUMMER SET THR= 5.0 mm/24h
DAY 1.75
NTOT= 3863, NOCC= 1117 P_CLI=0.289
VALUE
LOG10(COST/LOSS)
TOT. PRECIP. SUMMER SET THR= 7.5 mm/24h
DAY 1.75
NTOT= 3863, NOCC= 898 P_CLI=0.232
TOT. PRECIP. SUMMER SET THR= 10.0 mm/24h
DAY 1.75
NTOT= 3863, NOCC= 754 P_CLI=0.195
TOT. PRECIP. SUMMER SET THR= 15.0 mm/24h
DAY 1.75
NTOT= 3863, NOCC= 600 P_CLI=0.155
TOT. PRECIP. SUMMER SET THR= 20.0 mm/24h
DAY 1.75
NTOT= 3863, NOCC= 482 P_CLI=0.125
TOT. PRECIP. SUMMER SET THR= 25.0 mm/24h
DAY 1.75
NTOT= 3863, NOCC= 374 P_CLI=0.097
TOT. PRECIP. SUMMER SET THR= 30.0 mm/24h
DAY 1.75
NTOT= 3863, NOCC= 266 P_CLI=0.069

Figure A.6.1. The summer-period results represented in ROC-diagrams with belonging cost/loss-curves for different total precipitation rates forecast-day 1.75 (+42 hours).

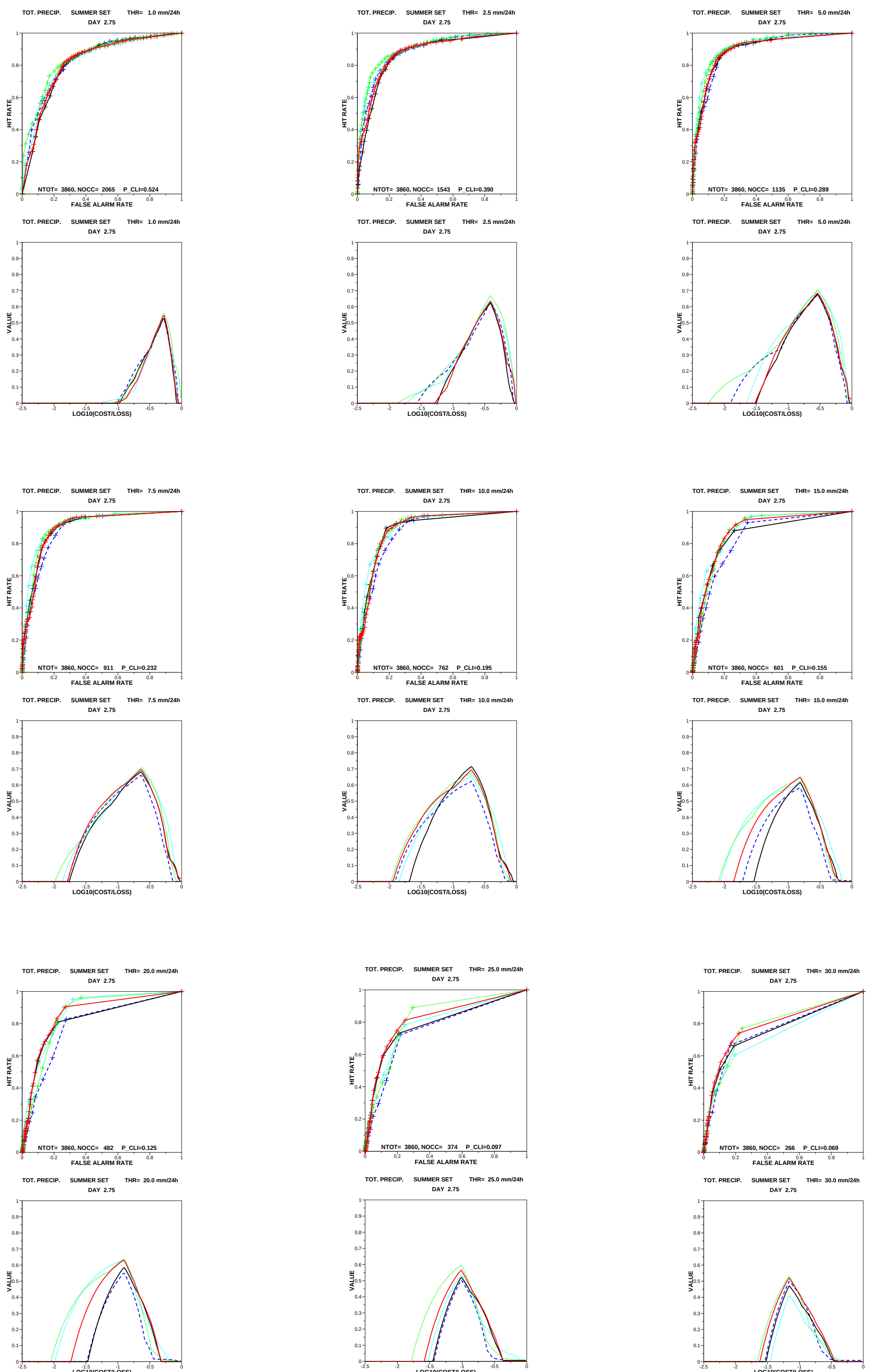

Figure A.6.2. The summer-period results represented in ROC-diagrams with belonging cost/loss-curves for different total precipitation rates forecast-day 2.75 (+66 hours).