Evaluation of weather forecasts

Gaining insight in the quality of weather forecasts for South Limburg

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Disclaimer

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1 Introduction

Waterboard Limburg asked HKV to conduct a transboundary evaluation of weather forecasts.
The aim of this project is to provide advice on which weather forecast provides the best estimates of precipitation for South Limburg.

The catchments of the rivers Geul, Roer, Over and Jeker are transboundary, having their upstream origin in Germany and Belgium. Therefore, it is important for the waterboard to have insight in the accuracy of weather forecasts in Germany and Belgium to take timely action.

For rainfall estimates the short- and long-term forecasts are relevant. Short-term forecasts are defined as forecast for the next 48 hours, whereas long-term forecasts are defined by the waterboard as futher than 48 hours ahead.

Currently the waterboard uses Harmonie (published by KNMI) for forecasts up to 48 hours and ECMWF for forecasts further than 48 hours ahead. Next to these forecasts also other forecasts exist. Among others these are COSMO and ICON (provided by the Deutsche Wetter Dienst – abbreviated by DWD), Arome (provided by Meteo France) or ALARO (provided by the Belgium Konijklijk Meteorologisch Instituut – abbreviated by KMI).

In the following paragraphs we first provide an overview of the (technical) backgrounds of weather forecasts (Chapter 2). In Chapter 3 we present the available forecasts for the South Limburg region and in Chapter 4 we assess the quality of forecasts. The conclusions and recommendations are given in Chapter 5.

2 Introduction to weather forecasts

2.1 Theoretical background on weather forecasts

Weather forecasts are based on numerical weather prediction models (NWP). NWP-models exists out of different steps and are applied in different settings. In this paragraph we provide an overview of the relevant steps and setting for the application in water management purposes. The first paragraph describes the different applications of weather forecasts in time, the second provides insight in the various technical steps which are applied to NWP-models. Finally, an overview of ongoing developments is described.

In this section the different steps are generalized on NWP-models. This means that there might be differences between different NWP-models provided by different organizations. These differences will be highlighted in the third chapter.

2.2 Types of weather forecasts

Weather forecasts cover a certain forecast horizon. The different forecast horizons are described as follows:

- **Nowcasts**: At the time interval between now and approximately 6 hours ahead the best prediction is based on the current (radar-)measurements and a forecasts based on extrapolation.
- **Forecast:** Between 6 hours ahead and approximately 2 – 10 days ahead numerical weather predictions are applied. This can be deterministic forecasts or ensemble forecasts.
- **Extended forecast:** On sub-seasonal scale forecasts are available for approximately 3 months ahead. These are generally ensemble forecasts.
- **Seasonal forecast**: Seasonal forecasts focus on the long-term development of weather patterns based on numerical weather predictions. The timespan of seasonal forecasts is up to half a year.

This research focuses on forecasts (between 6 hours ahead up to 2-10 days) as these are most relevant for operational water management in wet situations. Nowcasts, extended forecasts and seasonal forecasts are not taken into consideration.

2.3 Technical steps in weather forecasting

Three important elements can be distinguished in numerical weather predictions:

- The model itself
- Data assimilation
- Ensemble definition

Numerical weather models: Global versus Regional

Figure 1 shows a scheme of a numerical weather model. A numerical weather model covers the whole globe and the atmosphere. As complex 3-dimensional problems must be solved, these models require large amounts of computational power and storage. In order to do so, the spatial resolution of the global models is low.

In order to create an accurate forecast for a certain area, global models are downscaled and regionalized. The downscaled models receive their boundary conditions based on the global model and can only provide output for a limited area (for example west Europe).

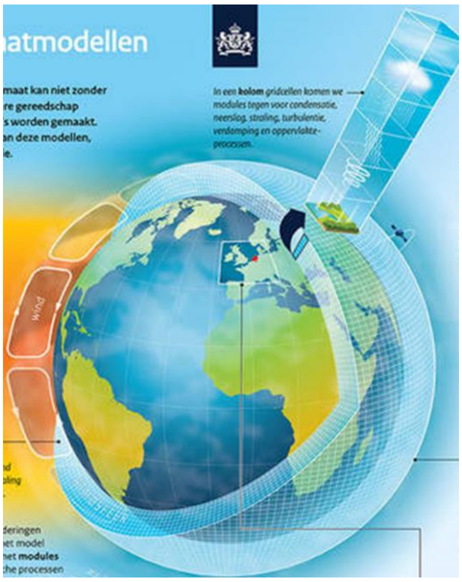


Figure 1: Scheme of a Numerical weather model (source: KNMI)

Data assimilation

Data assimilation is applied to improve the NWP's initial condition, at the beginning of the forecast, based on measured data sources. These data sources can be of various origins: weather stations on the ground, precipitation radar measurements, weather balloons or satellite measurements. Figure 2 shows the concept of data assimilation (source: ECMWF). Based on the previous forecast (blue line) and observations (green dots) the model results are assimilated to a 'corrected' forecast (red line in the chart). In this way the outcome of the regionalized NWP-models are matched to historical forecasts and observations.

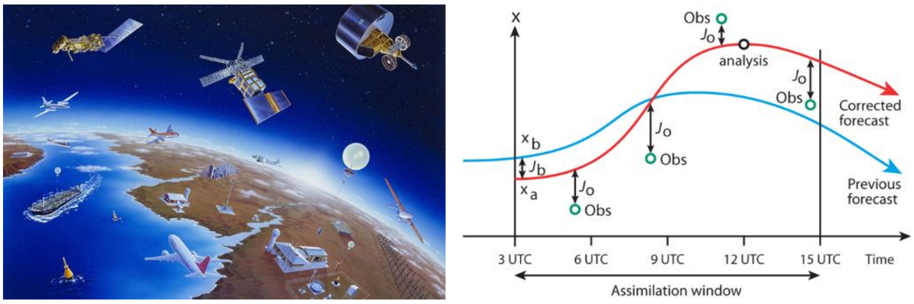


Figure 2: Schema of data assimilation (source: https://www.ecmwf.int/en/about/media-centre/news/2017/20-years-4d-var-better-forecasts-through-better-use-observations)

Ensemble definition

The nature of forecasts is that they are uncertain. In order to provide insight into the uncertainty, ensemble definitions are used. There are various ways of creating ensembles. In one of these, an ensemble is created by changing the initial conditions of the regionalized NWP within the limits of the certainty of the initial conditions. *Figure 3* shows an ensemble schematically. By changing the initial conditions different model results are generated (colourful lines in the scheme).
These variations of the model results represent the uncertainty of the forecast given by the uncertainty in the initial conditions. The uncertainty is relatively small at the beginning of the forecast run (indicated by the left, small circle), at the end of the run the uncertainty is largest (indicated by the right circle).
In other words: An ensemble represents the possible solutions of a forecast, given (small) changes in the initial model conditions.

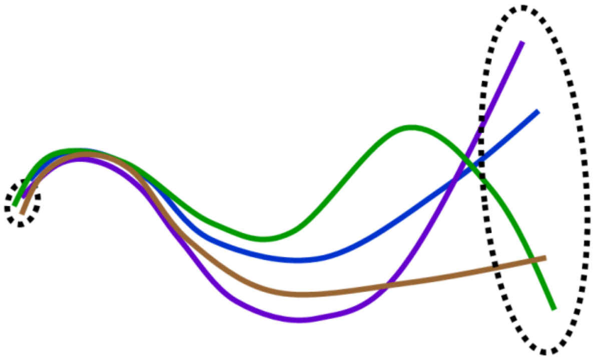


Figure 3: Scheme of an ensemble

Other examples of ensembles are those existing of members with variations in model parameters, reflecting the uncertainty resulting from uncertainty in those parameters, or those existing of various models, reflecting the uncertainty resulting from a choice of model.

2.4 Developments

Numerical Weather Predictions are constantly in development. We acknowledge that in this assignment the current models are analysed. Future model improvements are not taken into consideration.

For example, one the major developments of the Dutch Harmonie model is, to upgrade to a new calculation domain (UWC-West). *Figure 4* provides a sketch on the transformation of Harmonie (Harmonie40) into two new calculation domains. This development will have significant influence on the performance of the new Harmonie model (Harmonie43). For further details and description of the impacts of this development we refer to HKV (2023).

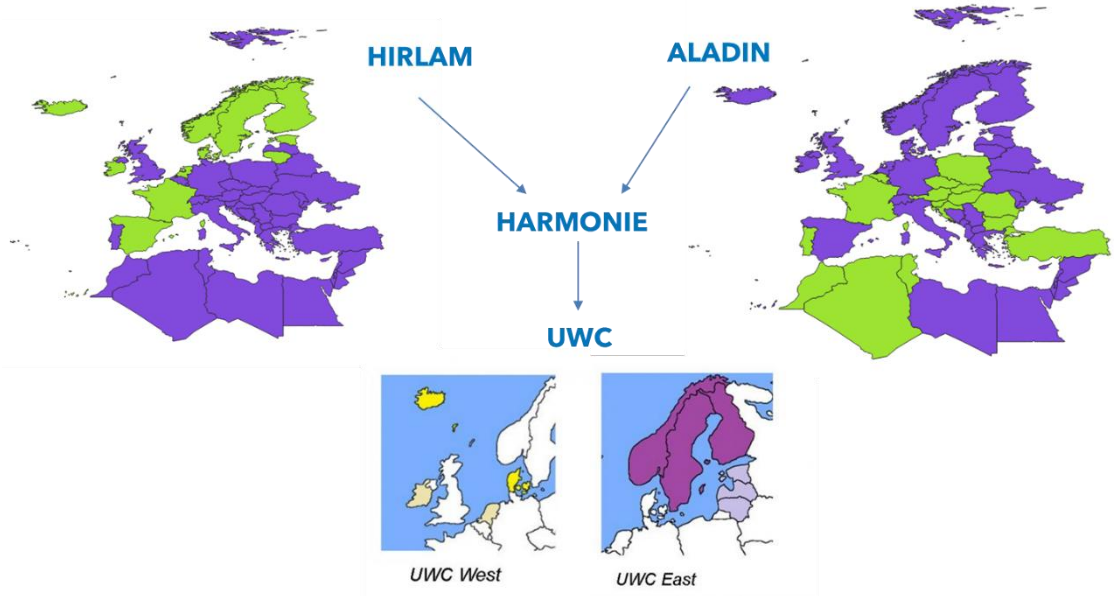


Figure 4: Development of Numerical weather model in Europe.

Another example of continuous development is the ongoing innovation and development in the field of nowcasting in which rainfall between now up to approximately 6 hours ahead is forecasted. With these developments also 'blending' approaches are developed, to provide seamless transition between the forecast models (nowcast into forecast).
As this development is at a short timescale (now up to the coming 6 hours) this is very interesting and promising for the application in water management in South Limburg. We recommend for the Waterboard Limburg to follow the developments closely.

3 Available forecasts for South Limburg

In this section we present the available rainfall forecast for the South Limburg region. First, we present an overview of the available forecasts, in the second part of this chapter we summarize the outcomes of the overview.
Figure 6 indicates the South Limburg region for this study on the map.

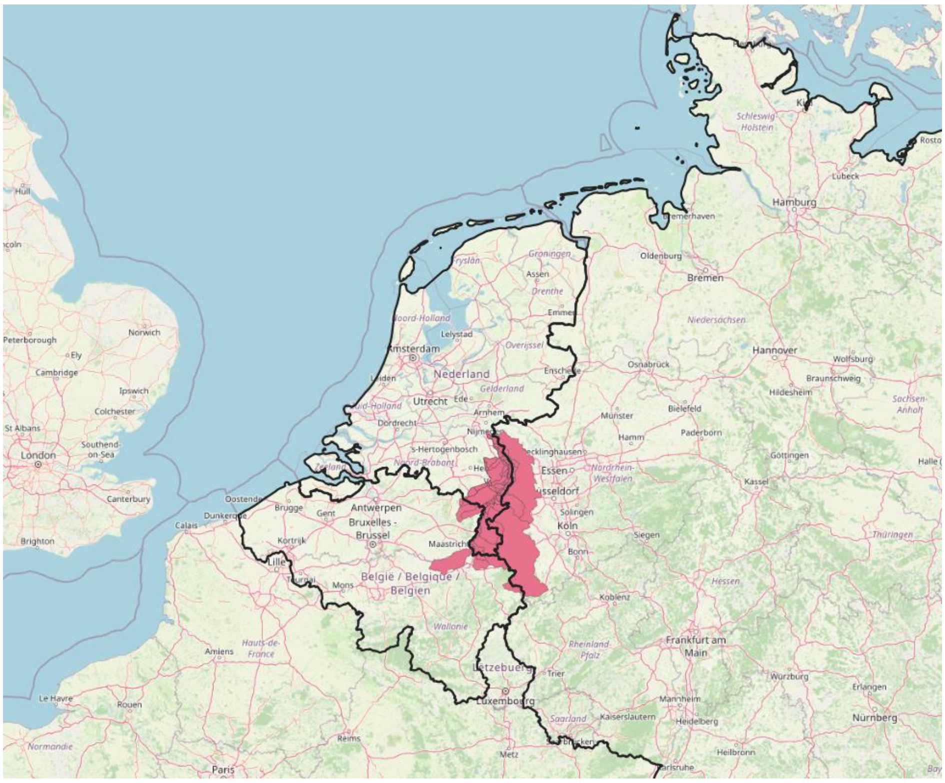


Figure 5: Map showing the South Limburg region (red indication).

3.1 Available forecasts

The following forecasts are taken into consideration within this assignment:

- Harmonie
- ECMWF
- COSMO
- ICON
- ALARO
- AROME
- Arpege
- UKMO
- HIRLAM

Next to these forecasts, the forecasts of Weather Research & Forecasting Model (WRF, US developed model), JMA (developed by Japan Meteorological Agency), GFS (the global weather forecast model of the US weather service), GEFS (Global Ensemble Forecast System created by the National Centers for Environmental Prediction;NCEP), GDPS (Global Deterministic Prediction System, developed by the Canadian Met Office), CMA (developed by the China Meteorological Administration) are available.

These are global weather forecasts which are known for their relatively poor performance on small spatial scales. For this reason, no further investigation on these forecasts have been done.

Table 1 provides an overview of the different characteristics of the forecasts. It becomes clear that the different European meteorological agencies develop a variety of forecasts which mainly differ in forecast horizon, temporal and spatial resolution, but also in the generation interval.

Furthermore, we acknowledge that the Harmonie forecasts of KNMI, the forecasts of the ICON-family (provided by DWD) and the forecast based on AROME (provided by MeteoFrance are freely available through the data portals of DWD and MeteoFrance. For DWD and MeteoFrance the free availability is limited to operational forecasts. Harmonie is for the waterboards in the Netherlands freely available through the WIWB (Weer Informatie Waterbeheer, *https://www.hetwaterschapshuis.nl/neerslag-weer-informatie-waterbeheer*) cooperation.

Another interesting aspect of the different regional forecast models is their dependency on the various large-scale (global) models. Figure 6 provides an overview of the model structure that is currently in operational use in the different countries. On the y-axis the spatial resolution of the models is indicated. Per country (the Netherlands and Belgium combined) the forecasts models are presented starting from the large scale down to the regionalized, small scale models.

This scheme clearly shows that for example the Dutch Harmonie-model and the Belgium Alaro-model are both downscaled from the ECMWF IFS model. This means that differences between Harmonie and ALARO will mainly be caused by regionalization of the model and less likely on the physical forcing of the model, as both receive their boundary conditions from the same global model.
Germany (ICON), France (ARPEGE) and the UK (UKMO-10) have all developed their own global scale models and the downscaled, regionalized model from the global models.

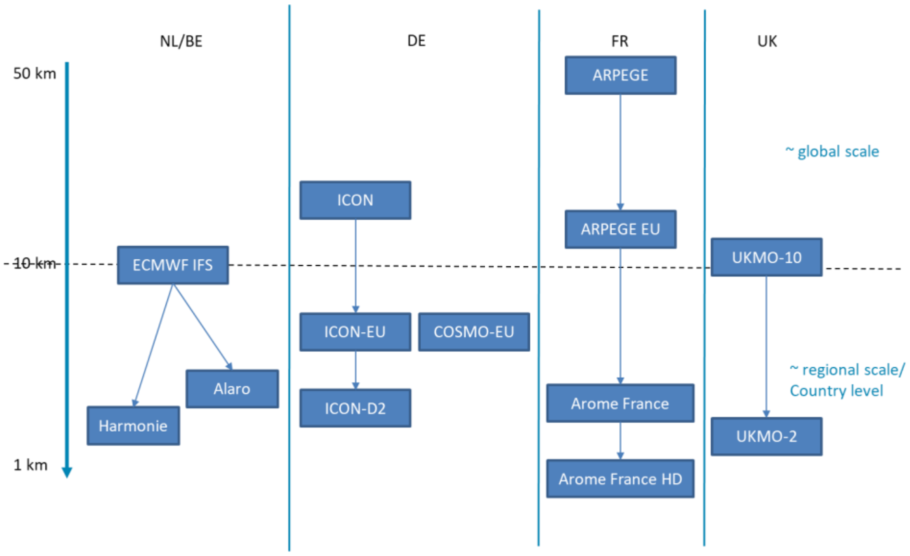


Figure 6 Overview of the dependencies of the forecast models.

Name	Source	Forecast horizon	Temporal resolution	Generation interval	Latency	Spatial resolution	Ensemble	Availability / source	Historical availability
Harmonie	KNMI	48 hours	1 h	6 h	3 h	2.5 km	No *	Via WIWB	Since 10/2019
ECMWF HRES (Set I)	ECMWF	10 days	1 h – 3 h	6 h – 12 h		9 km (0.1°)	No		
ECMWF ENS (Set III)	ECMWF	15 days	1 h – 3 h	6 h – 12 h	8 h	18 km (0.2°)	Yes		Since 10/2019
ECMWF ENS extended (Set VI)	ECMWF	46 days		24 h		36 km (0.4°)	Yes		
COSMO-DE	DWD					2.8 km			
COSMO-LEPS (also: COSMO-EU)	DWD	5 days		12 h		7 km (0.1°)	Yes		
ICON-D2	DWD	45 hours *	1 h	3 h	1.5 h	2.2 km	No	Free via DWD	
ICON-D2 EPS	DWD	45 hours *	1 h	3 h		2.2 km	Yes	Free via DWD	
ICON-EU (ICON 7)	DWD	5 days	1 h – 3 h	3 h – 6 h	3.5 h	7 km (0.0625°)	No	Free via DWD	Since 21/07/2015
ICON global (ICON13)	DWD	7.5 days	1 h – 3 h	6 h – 12 h		13 km	No		Since 25/01/2015
ALARO	KMI	60 hours	1 h	6 h		4 – 50 km *			
AROME	Meteo France	42 hours	1 h	6 h – 12 h	4.5 h	1.25 km (0.01°)	No	Free via Meteo France	
Arpège EU	Meteo France	114 hours *	1 h – 3 h	6 h	4.5 h	5 km (0.1°)			
UKMO-2	UKMO	6 days				2 km			
UKMO-10 (global)	UKMO	6 days				10 km			
HIRLAM	EU institutes								

Table 1 Overview of the available forecasts.

Forecasting horizon

The forecasting horizon varies strongly between the forecast models. Table 2 shows the forecasting horizon of the models in comparison with each other. Most models are available for the upcoming 2 to 7 days. Only some models (e.g. ECMWF) have a longer forecasting horizon.
We acknowledge that for water management purposes in the Netherlands and South Limburg, a forecasting horizon up to 7 days is most promising.

Name	Forecast horizon	days 1–17
Harmonie	48 hours	
ECMWF HRES (Set I)	10 days	
ECMWF ENS (Set III)	15 days	
ECMWF ENS extended (Set VI)	46 days	--> longer (46 days)
COSMO-DE		
COSMO-LEPS (also: COSMO-EU)	5 days	
ICON-D2	27 hours (45 hours for the 03 UTC run)	
ICON-D2 EPS	27 hours (45 hours for the 03 UTC run)	
ICON-EU (ICON 7)	5 days (and 30 hours)	
ICON global (ICON13)	7.5 days (and 5 days)	
ALARO	60 hours	
AROME	42 hours	
Arpège EU	114 hours (max)	
UKMO-2	6 days	
UKMO-10 (global)	6 days	
HIRLAM (High Resolution Limited Area Model)		

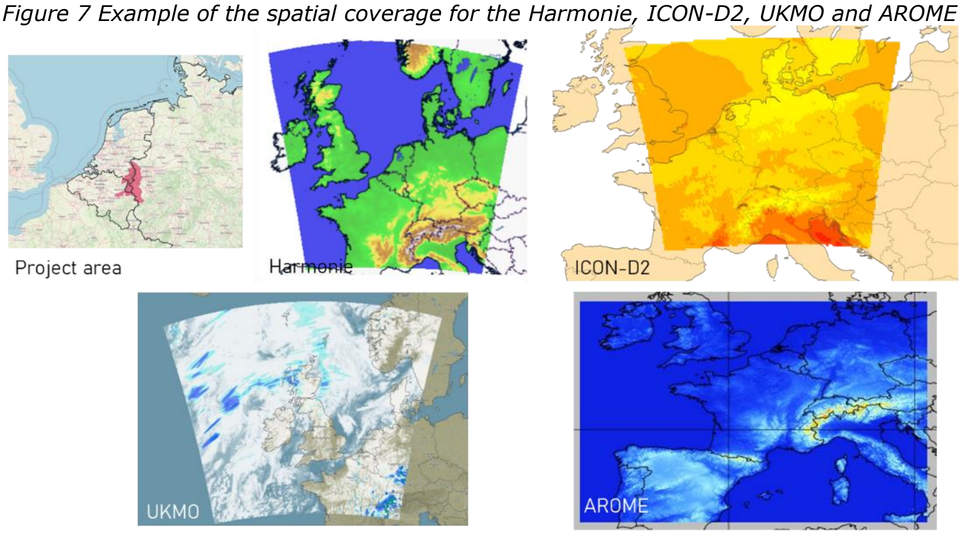
Table 2 Overview of forecasting horizon of forecasts.

Spatial coverage

For optimal performance of a regionalized forecast model, it is important that effects of boundary conditions are limited. For this reason, we investigate the spatial coverage of the forecast models for the South Limburg region.

Figure 7 present screenshots of the spatial coverage of the Harmonie (KNMI), ICON-D2 (DWD), UKMO-2 (UKMO) and AROME (MeteoFrance) model. These screenshots show that the project area (indicated in the upper left map) is represented well in all models, but in the UKMO-2 model the project area is on the boundary of the model.

Figure 7 Example of the spatial coverage for the Harmonie, ICON-D2, UKMO and AROME model.



3.2 Summary

This chapter shows that a variety of forecast model exist for the South Limburg region. In the list below we highlight the most important differences between the forecast models:

- The differences in the forecasts are in temporal and spatial resolution;
- Not all forecasts are freely available;
- Both the Dutch developed Harmonie-model and the Belgian developed ALARO model are based on the same global model (ECMWF IFS). Differences in the model are therefore caused by regionalization and not by physical forcing of the mode. We therefore expect a similar quality of the forecasts;
- The forecasting horizon of all investigated forecasts models is between 2 to 7 days ahead which is sufficient for water management purposes in South Limburg;
- Spatial coverage was analyzed for four models: This shows that the UKMO-2 model may be less suitable for the South Limburg region as the region is close to the model boundary.

To get good understanding of forecast quality in South Limburg the following forecast models are interesting for further investigation:

- Harmonie provided by KNMI,
- ICON-D2 provided by DWD,
- AROME provided by MeteoFrance.

4 Quality assessment

4.1 Methodology

The methodology for the quality assessment is based on the report 'Beoordeling kwaliteit weerverwachtingen - Meteo-onderzoek ten behoeve van het waterbeheer: Deelrapport 4' (HKV, 2023). In this assessment the Harmonie forecast and ECMWF IFS forecast are analysed for the Netherlands for precipitation and evapotranspiration.

For this research we focus on the performance of the Harmonie (Harmonie40-version) model on rainfall predictions. We focus on 4 accumulation intervals: 3 hours, 6 hours, 12 hours and 24 hours. These accumulation intervals are chosen to get a good understanding of rainfall amounts within short intervals and longer intervals.
Heavy, convective rainfalls in summer can cause floodings in the South Limburg catchments.
To capture the quality of these forecasts the short accumulation intervals (e.g. 3 hours and 6 hours) are interesting. Based on the accumulation intervals of 12 and 24 hours the forecast quality of larger rainfall fronts can be analyzed. Table 2 provides an overview of the accumulation periods and time steps chosen.

For each of the accumulation intervals, four forecasts time steps are analyzed, and a differentiation is made in the following seasons:

- *Winter*: The winter months are November, December, January and February (NDJF). During winter month stratiform precipitation is most common. This season provides insight in performance of the forecast for this kind of precipitation.
- *Summer*: The summer months are July and August (JA). In these two months high intensity, convective rainfalls are most likely to occur. This season provides therefore the most information on the performance of the forecast for convective rainfall events.
- *Growing season*: The growing season ranges from March up to October (MAMJJASO). Within this season stratiform and convective rainfalls can occur. The growing season provides good understanding of how rainfall predictions perform during most time of year.

Accumulation periode	Accumulation interval time steps [hours]	Seasons
Harmonie40		
3 uur	0-3, 3-6, 6-9, 9-12	Growing season, summer, winter
6 uur	0-6, 6-12, 12-18, 18-24	Growing season, summer, winter
12 uur	0-12, 12-24, 24-36, 36-48	Growing season, summer, winter
24 uur	0-24, 24-48	Growing season, summer, winter

Tabel 1: Overzicht van aggregaties en selecties waarop we verwachtingen en metingen vergelijken.

Figure 8 provides an overview of the used locations (black points) and shows in red the area of interest for South Limburg. The locations are:

- **KNMI**: Eindhoven, Ell, Arcen
- **Waterboard Limburg**: Noorbeek, Roermond, Vaals, Maastricht, Kaffeberg, Spaubeek, Mariahoop, Stein, Ransdaal
- **DWD**: Nettetal, Mönchengladbach, Achen

- **KMI**: Diepenbeek, Bierset, Spa, Mont Rigi
- **STW**: Gemmenich

We remark that KMI data of ground stations is only available for 6-hour intervals. Therefore, the analysis for the KMI stations can only be done for the 6, 12 and 24-hour accumulation period.

For each of the rainfall locations the corresponding pixel from Harmonie forecasts is matched. Each Harmonie pixel has a size of about 2,5*2,5km.

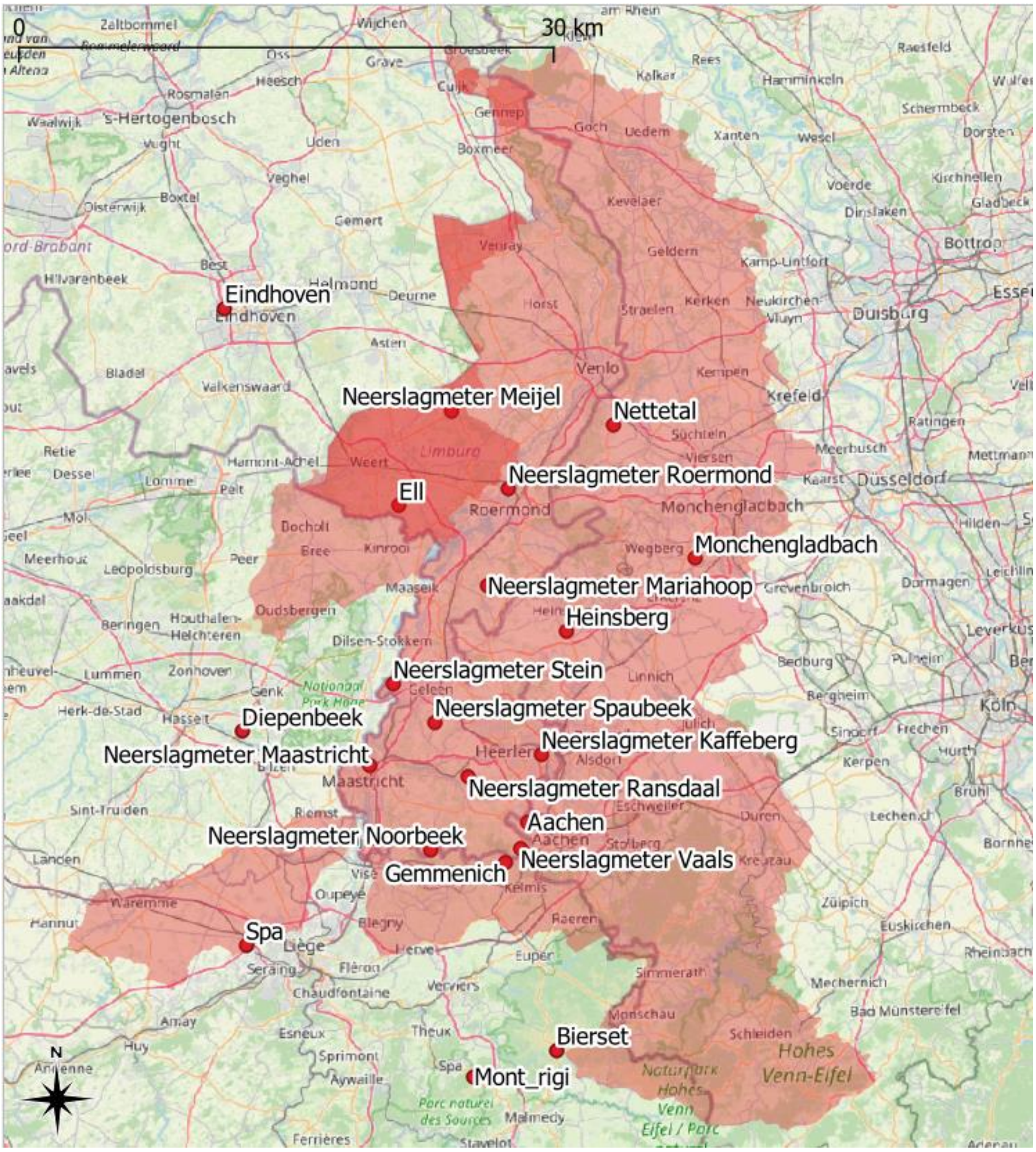


Figure 8 Overview of the used locations for the analysis.

Figure 9 shows an example of the analysis. All points in the chart represent the relation between measurement on a ground station (y-axis) and the forecasted rainfall from Harmonie (x-axis). The background color represents the intensity of the forecast. The blue range represents the forecasted rainfall amounts which represent the 95% percentile and above, the yellow range represents the forecasted rainfall amount between 75 and 95% percentile and the purple the 75% percentile and below. The color of the points (yellow to blue) represents the density (e.g. number of points) of the scatter. The title of each figure show the interval for which this figure is created.

For example: Figure 9 shows the analysis for the 12-hour accumulation interval and for the first timestep (e.g. 0-12 hours ahead).

This analysis will be carried out for the comparison for each ground station with the corresponding forecast pixel of Harmonie. Next to this we also analyse the spatial effects on the forecast quality. For this analysis we take a spatial average of a buffer of about 5 km (approximately 10 km^2) around each ground station and compare the spatial average rainfall forecast with the ground station observation. The results are discussed in section 4.4.

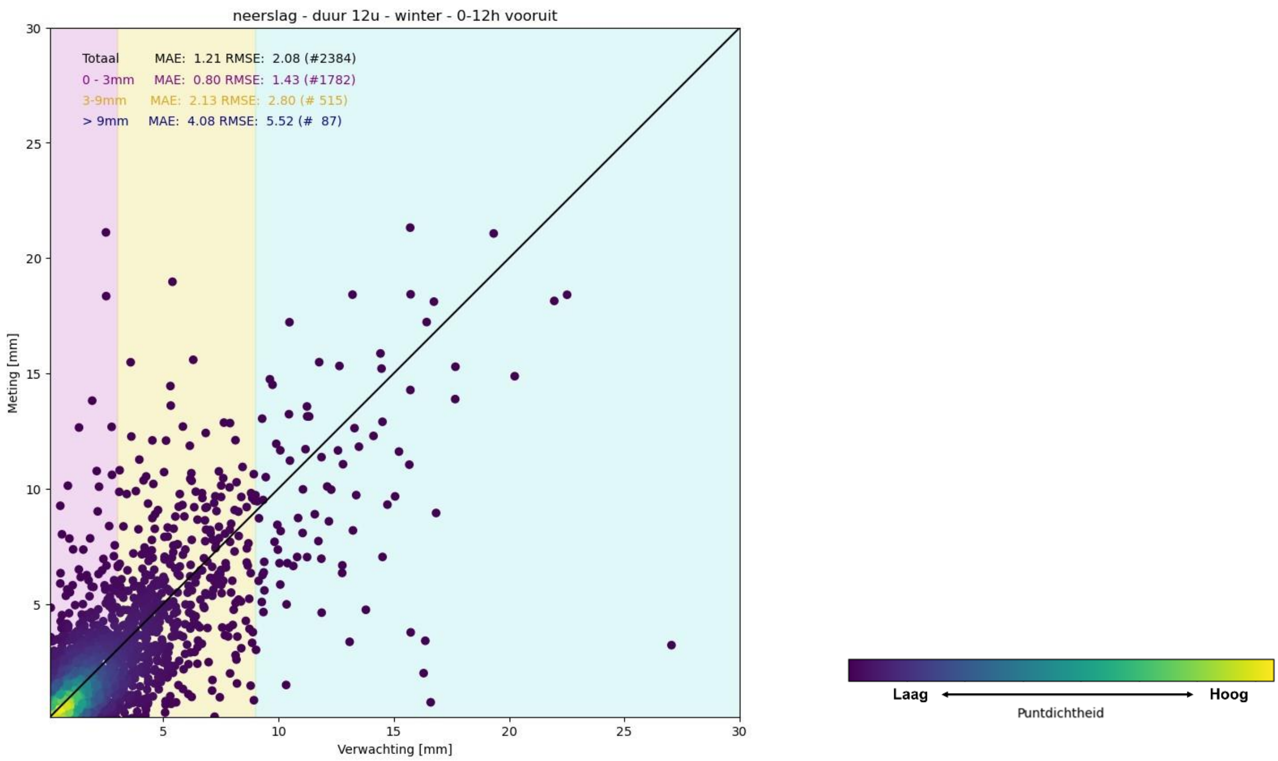


Figure 9: Example of the outcome of the analysis. Please not that the description of the figure is written in Dutch. For explaination we refer to the text.

4.2 Data requests

Measured Rainfall and Evapotranspiration on ground stations

The measured rainfall and evapotranspiration amount on the ground stations are requested from KNMI, KMI (Belgium) and DWD. These timeseries can be downloaded from the publica data portals of the meteorological agencies.

(Historical) Forecasts

For this analysis historical forecasts are needed and for this study it was chosen to apply for the data of DWD (ICON-D2) and MeteoFrance (AROME) The publicly available data portals only provide the forecasts for approximately the last 2 days. Historical forecasts are available through their secured data portals and a user account is needed.

Initially both (DWD and MeteoFrance) provided fast response to the data request. However, when requesting large amounts of data technical problems occurred with DWD. The request with MeteoFrance was not successful. For MeteoFrance it was unclear if Waterboard Limburg is accredited to access forecast data freely. We could therefore not include these model results in this analysis.
We recognise that it is beneficial for all waterboards in the Netherlands to improve relations with foreign meteorological agencies for improved data exchange and therewith improved water management.

4.3 Analysis of Harmonie data

For each accumulation period and time step scatterplots are created to analyse the performance of the forecasts. Figure 10 provides an overview of the 24-hour accumulation period and the first time step (0-24 hours ahead). Please mind that the scales of the axis differ in the plots (e.g. in winter the scale is > 30mm, whereas the scale for summer and growing season is more than 100 mm). The figures for all other accumulation periods and time steps are provided in appendix A.

We see that during winter, a stronger correlation between forecasts and measurements exist. During growing season and in summer, the correlation is clearly less significant between forecasts and measurements. This means that rainfall in winter can be better forecasted compared to rainfall during summer or during the growing season. The poor correlation in summer indicates that heavy, convective rainfalls are less likely to be forecasted at the correct location.

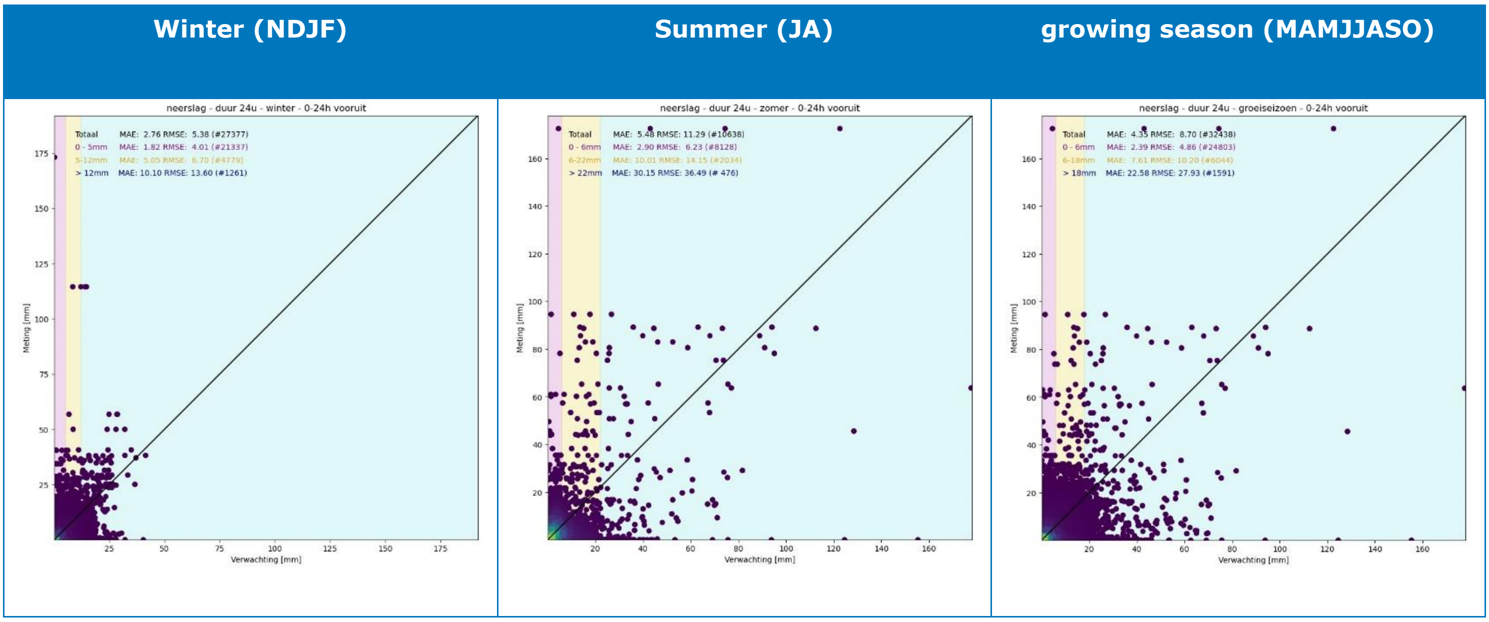


Figure 10 Comparison of the scatterplots for the same accumulation period for the three seasons. These figures are placed next to each other to highlight the differences between them. For larger picture size we refer to appendix A.

Figure 11 shows the mean absolute error (MAE) for each season for the four accumulation periods and all time steps. These figures show a light trend in increase of the MAE for each time step. This is logical as the forecast performance usually decreases with a longer lead time. For the high intensity rainfalls (e.g. above 95% percentile) no clear relation between MAE and lead time can be seen. It is most likely that this relation is less clear, as the total number of events in this percentile is low, resulting in larger noise to signal ratio.

We also see that the accuracy of the forecast in winter is higher than in summer. In winter the MAE is < 2mm whereas in summer and the growing season is > 2mm. This is a logical result as in summer and the growing season high rainfall intensities are more likely, which are harder to forecast.

In Appendix A, a similar analysis is carried out to the one in Figure 11, but now analysing the root mean square error (RMSE). This indicator shows a similar pattern to the MAE.
All in all, these result are well comparable to the results in HKV (2023).

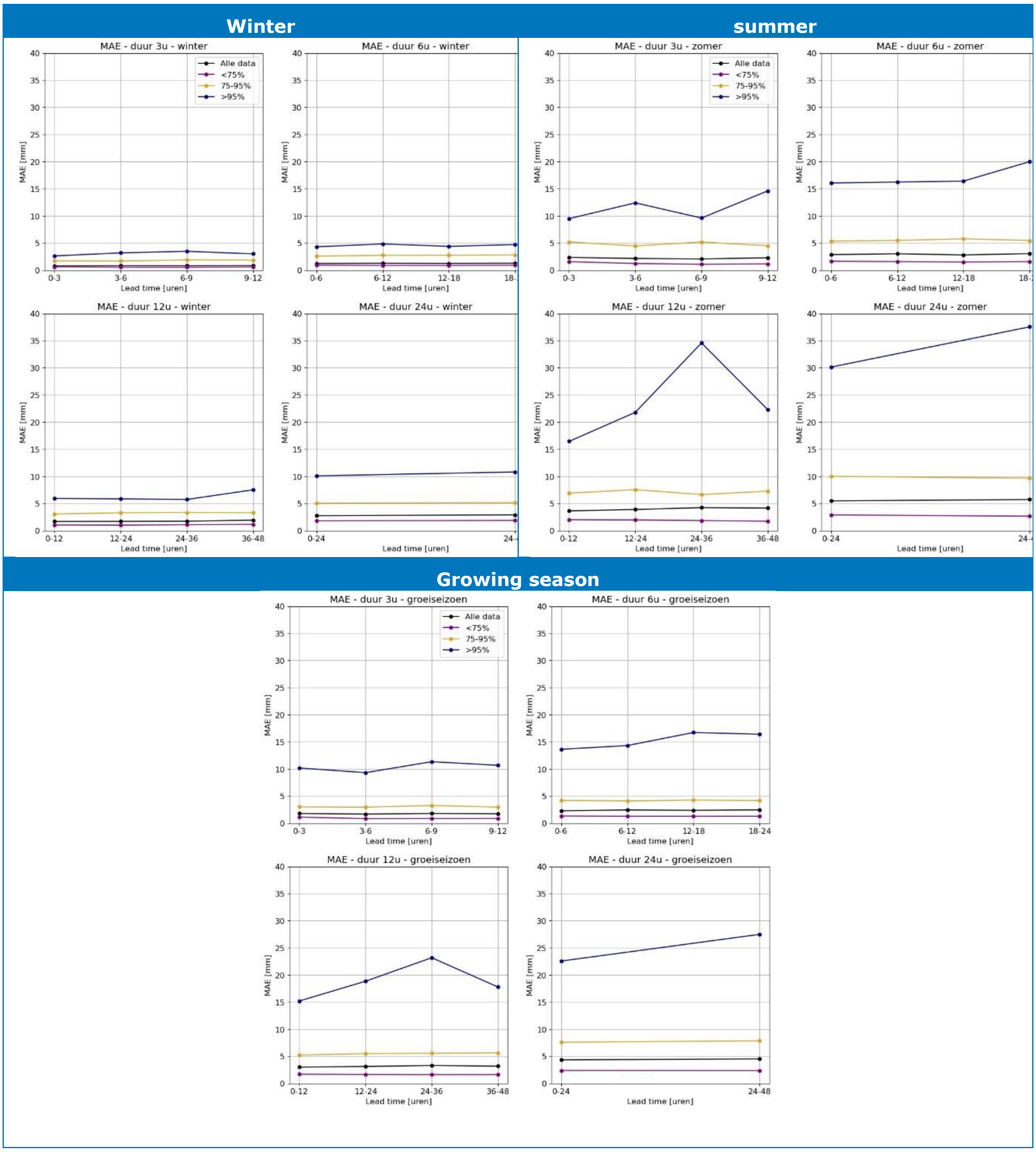


Figure 11 Example of the Mean absolute Error (MAE) analysis.

4.4 Spatial scales of forecasts

The analysis in the previous chapter focused on the quality of forecasts compared to a ground station. In other words: does the predicted rainfall at a single location match the measured rainfall?

However, for water management purposes it is also important to understand what the quality of the forecasts is based on larger scales, e.g. catchment scales.

For this analysis we do not only analyse the performance of a ground measurement with *one* pixel of the Harmonie forecast but created a buffer of about 5 km (roughly 10 km^2)[1] around each of the ground stations. The forecasted rainfall of the buffer was averaged for the area. In this way we can analyse the effect of spatial scales in forecast quality. Said differently: Is forecasted rainfall in the close proximity of a ground station observed at the station?

Table 3 show the outcomes of the analysis (right column) in comparison with the results based on the direct link between ground station and forecasted rainfall in the same pixel (left column). In this table the outcomes for the growing season are presented. All other figures (compared to the ones in the previous section) are included in appendix A.

We see that for the South Limburg region the spatial average has little influence on the performance of the forecast quality. Or said differently: There is a little higher chance that rainfall forecasted in a region of about 10 km^2 around the ground station is forecasted correctly.
In winter the differences are marginal, the highest differences we observe during summer and growing season and especially for the heavy rainfalls (> 95%). This is logical as heavy rainfalls have a larger spatial variability where they occur.

[1] Harmonie is setup in a raster by decimal degrees. The indication of kilometers are therefore approximations.

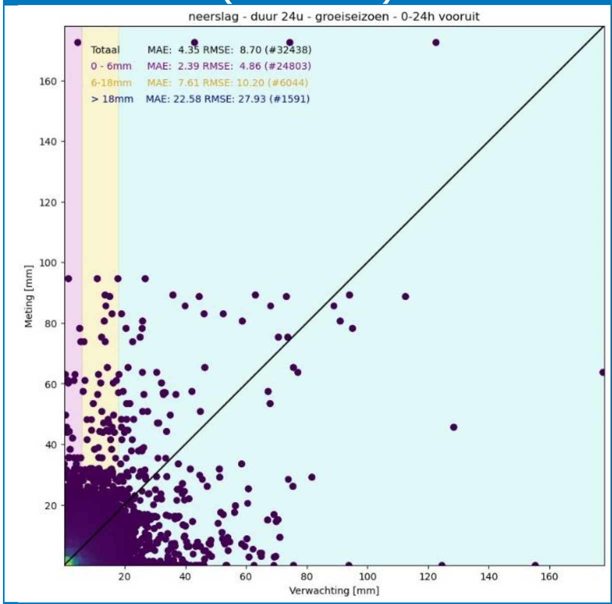
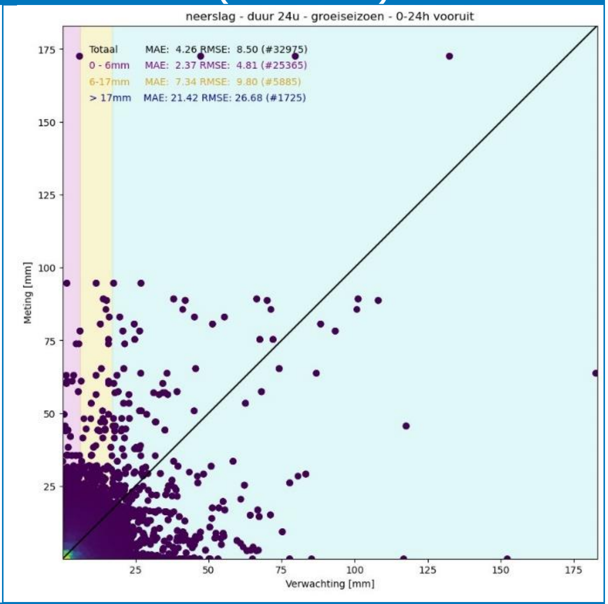
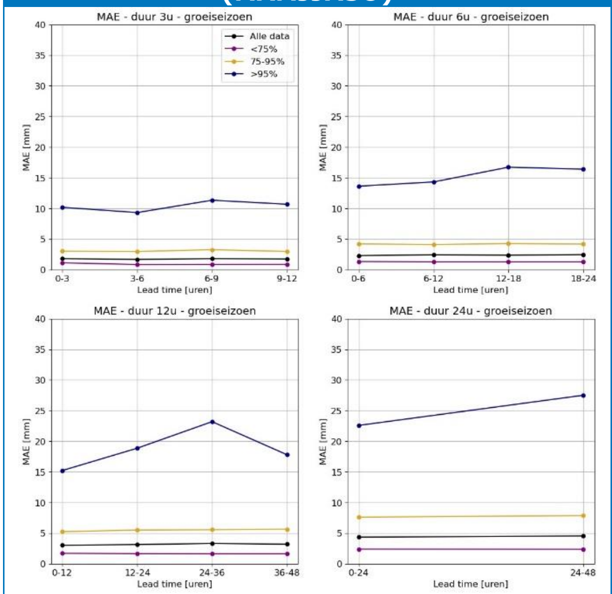
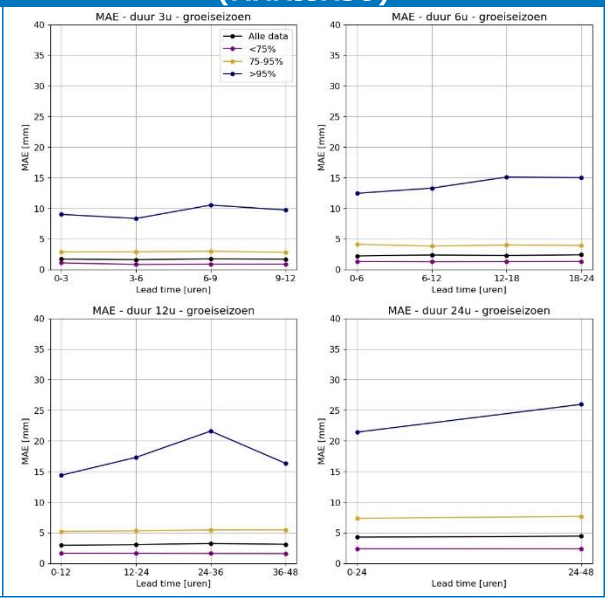
growing season ground station (MAMJJASO)	growing season spatial average (MAMJJASO)
	
MAE plot growing season ground station (MAMJJASO)	**MAE plot growing season spatial average (MAMJJASO)**
	

Table 3 Comparison between the correlations of the observed and forecasted rainfall for a ground station (top left) and an average around the ground station (top right). The lower figures show the plots of the mean absolute error (MAE).

These result match with the analysis made in HKV (2023). In this study the MSL (Maximum Skillful Lead Time) is analysed for 6, 12 and 24 hours. Figure 12 shows the outcome of this analysis for the 24-hour aggregation period for the three seasons. On the y-axis the spatial scale (km) is given and on the x-axis the threshold of rainfall intensities. The observed data set is the Final Reanalysis product of the IRC (International Radar Composite, available through WIWB).

These figures show that in winter low rainfall intensities (< 0.08 mm) can be forecasted 48 hours ahead for all spatial scales. Higher rainfall intensities (>4mm) cannot be forecasted with skill. In Summer and the growing season the skillful lead times are even less.

It is striking that the MSL for growing season is less than for summer. According to HKV (2023) this is due to spring month (March, April and May). If these months are not taken into consideration the MSL for the growing season is higher than for summer.

We remark that this analysis was made for the Netherlands and not only for the South Limburg region.

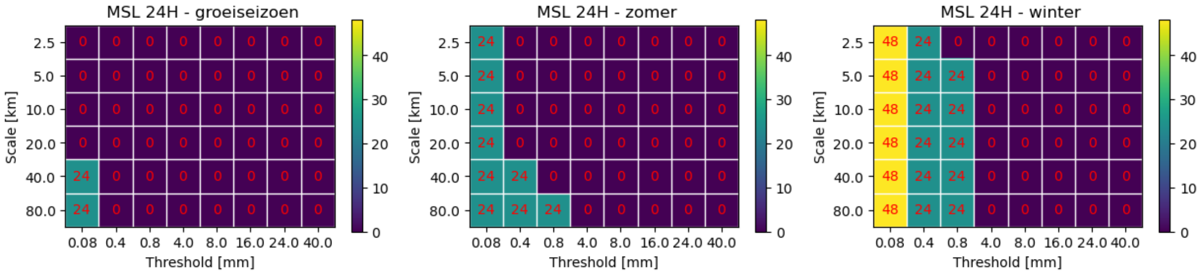


Figure 12 Maximum Skillful Lead Time (MSL) for the 24-hour aggregation period and for the growing season (left), summer (middle) and winter (right), taken from HKV (2023).

4.5 Comparison of the forecast in South Limburg to the Netherlands

This analysis focuses on the quality of forecasts for the South Limburg region. In HKV (2023) the focus of the analysis was on the Netherlands. Table 4 shows the comparison of the performance of the forecasts for the Netherlands (left) and the South Limburg region (right). In this table the plots of the MAE are given for the growing season and for all analyzed aggregation periods (e.g. 3, 6, 12 and 24 hours). Please note that the axis scales of the plots are different.

This comparison shows that for the growing season, the performance of the forecasts in South Limburg is significantly less in South Limburg than in the Netherlands. For example, the most extreme rainfalls (blue lines) for the 24-hour aggregation period have a MAE of about 21,5 mm for the upcoming 24 hours, whereas for the Netherlands the MAE is about 12,8 mm. For the other aggregation periods the differences are percentage wise comparable. For the winter and summer season we observe a comparable difference.

If we compare the scatterplots for the 24-hour aggregation period and the first 24-hour interval for the South Limburg with the Netherlands, we see, that the total sample size is about 20% (combination of time steps and stations) less for South Limburg, on the other hand the percentile groups are well comparable (differ with 1 mm in rainfall intensities). Given this the scatter plots and percentile groups are well comparable between the analysis for the Netherlands and South Limburg.

Another important difference between the South Limburg region and the Netherlands is that South Limburg has more relief (e.g. height differences) than the Netherlands. It is worth analyzing what the impact of relief on the measurements of ground stations is as well as the impact on the Harmonie forecast.

All in all, we can conclude from this Harmonie forecasts are less accurate in South Limburg compared to the Netherlands.

Based on this assignment we cannot point out the exact reason of the difference. We recommend that further research is carried out to get a better understanding of the forecast quality.

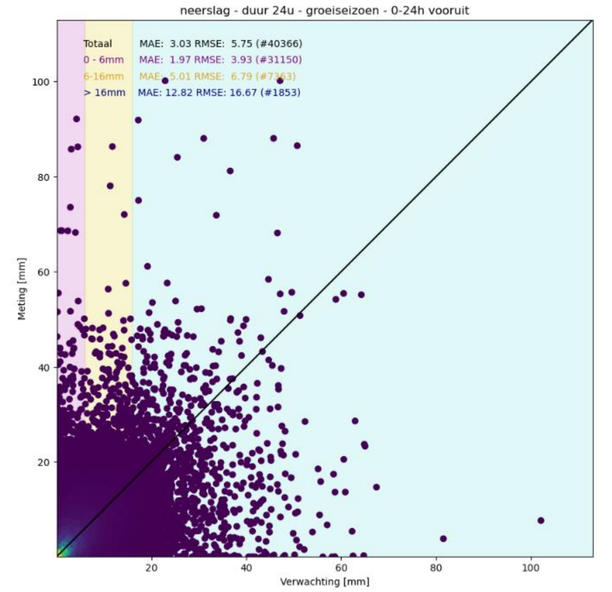
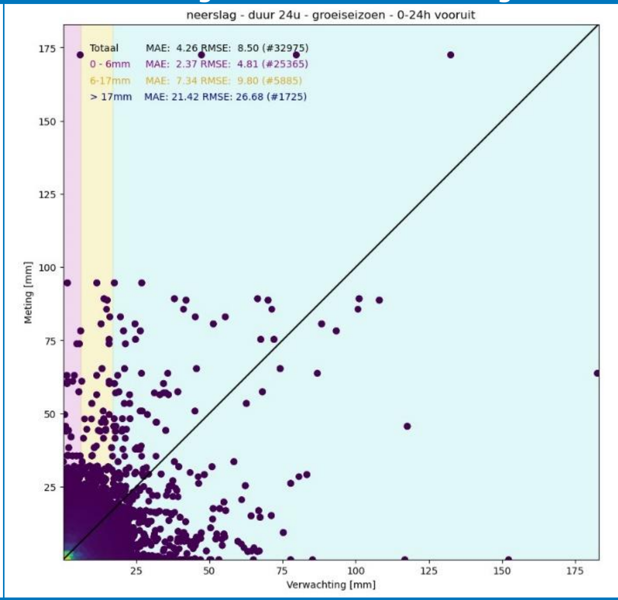
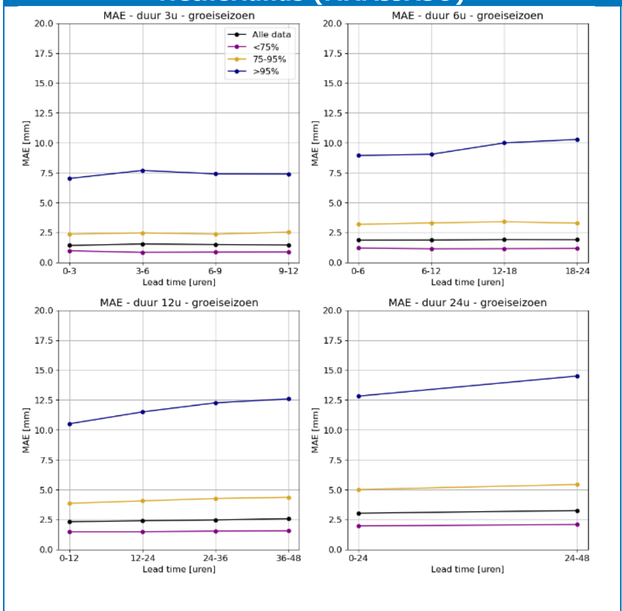
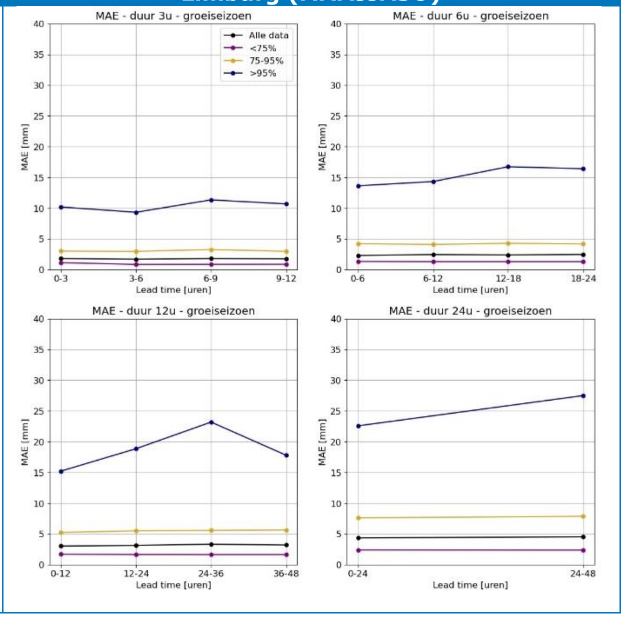
Growing Season – The Netherlands	Growing Season – South Limburg
	
MAE plot growing season ground station The Netherlands (MAMJJASO)	**MAE plot growing season ground station South Limburg (MAMJJASO)**
	

Table 4 Comparison of the forecast quality for the Netherlands and the South Limburg region. Please mind the difference in axis-scales of the plots.

5 Conclusions and recommendations

This assignment took a closer look on the quality of forecasts for the South Limburg region. At first an introduction to weather forecasts is given and a look is taken into the available forecast for the South Limburg region. Afterwards the methodology and outcomes of this analysis is presented.

Based on this analysis we can draw the following conclusions:

- Many forecasts from different models are available. The different regionalized models are based on global models for which (in West-Europe) four models exist (ECMWF, ICON, APREGE, UKMO).
- It is difficult to retrieve data for historical forecasts from meteorological agencies. Due to this, the quality assessment could only be conducted for Harmonie model.
- Forecasts perform better in winter than summer and the growing season and perform better on short time scales (e.g. up to 12 hours) than longer scales (up to 48 hours).
- Large scale, stratiform rainfall systems are more predictable than small scale, convective rainfalls.
- The quality of the rainfall forecasts in South Limburg is less accurate than for the Netherlands in general. The exact reason for the big difference in accuracy cannot be given within this assignment. We expect that the difference in forecast quality is mainly due to the terrain.

Based on this analysis we can provide the following recommendations:

- **Further research on forecast quality in hilly terrain**: This assignment showed that the quality of forecasts in South Limburg is less than in the Netherlands. To fully understand the difference in accuracy we recommend to further analyse the impact of hilly terrain on forecast quality and on the accuracy of ground station measurements and on how to accurately compare ground stations with gridded forecasts.
- **Operational forecasts are available with DWD and MeteoFrance:** Using more than one forecast source might be valuable for operational water management to provide insight in forecasted rainfalls and the variability of rainfalls.
- **Creating an own archive of forecasts:** When storing the forecasts at Waterboard Limburg, sufficient data will be available to assess the quality of the forecasts in a similar way to the Harmonie-analysis. Within the Netherlands Harmonie-forecasts are stored within the WIWB-project.
- **Nowcast and blending into forecasts:** This development focuses on a short timescale (now up to the coming 6 hours) so this is very interesting and promising for the application in water management in South Limburg. We recommend for the Waterboard Limburg to follow the developments closely.
- **Relations between waterboards and foreign meteorological agencies:** We recognise that it is beneficial for all waterboards in the Netherlands to improve relations with foreign meteorological agencies for improved data exchange and therewith improved water management.

6 References

HKV, 2023.
Beoordeling kwaliteit weerverwachtingen - Meteo-onderzoek ten behoeve van het waterbeheer: Deelrapport 4. PR4736.10. Ruud Hurkmans and Dorien Lugt, in cooperation with KNMI. Commissioned by: STOWA.

Link	Description
https://portal.hydronet.com/data/files/Technische%20Instructies%20WIWB%20API.pdf	Description of the WIWB API to access the data catalogue
https://www.dwd.de/EN/ourservices/pamore/pamore.html (desciption) *https://webservice.dwd.de/cgi-bin/spp1167/webservice.cgi (data portal)*	Link to the DWD Pamore data catalogue
https://opendata.dwd.de/climate_environment/CDC/observations_germany/	DWD portal for ground stations
https://opendata.meteo.be/	KMI download portal

Table 2 Overview of used data portals

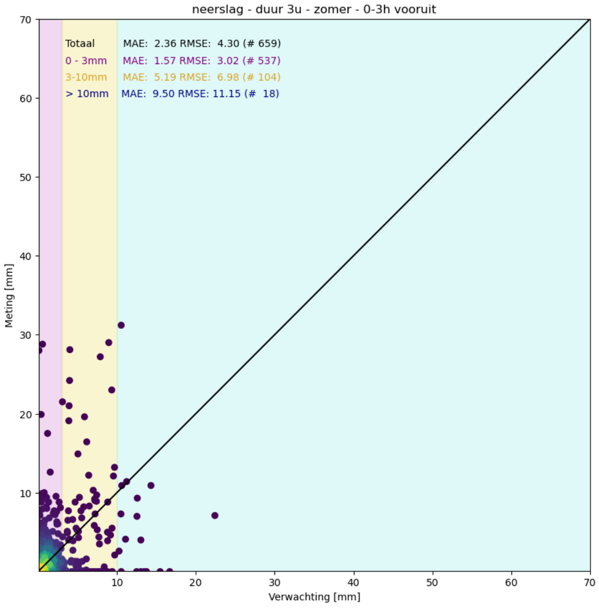
Appendix

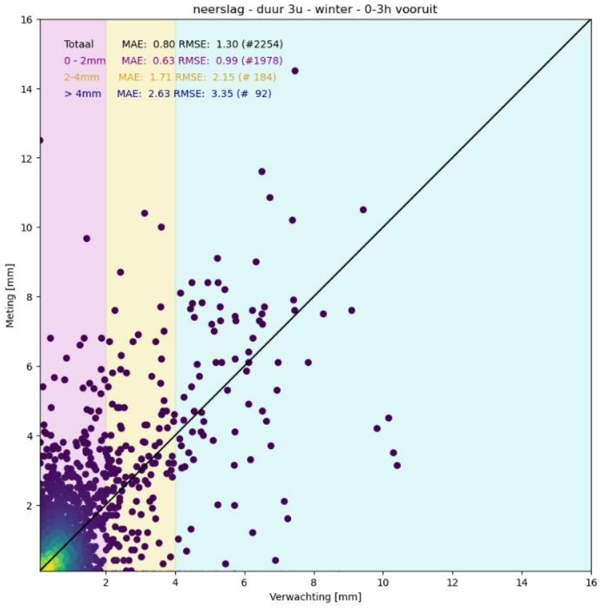
A Detailed analysis plots

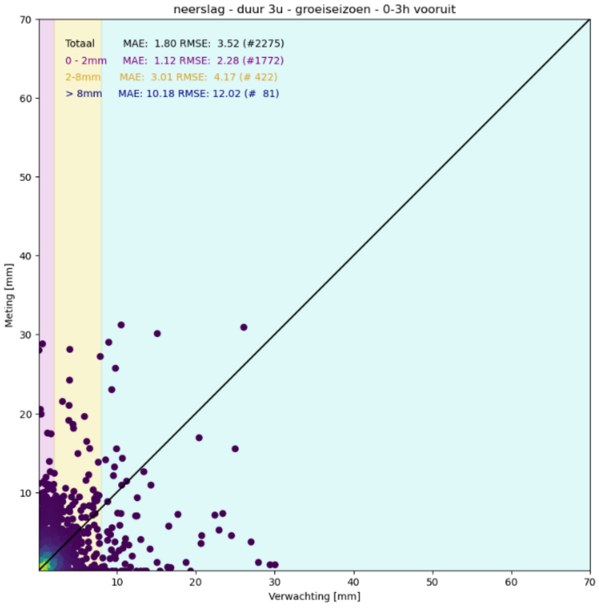
A.1 Comparison on ground station level

A.1.1 Accumulation period 3 hours

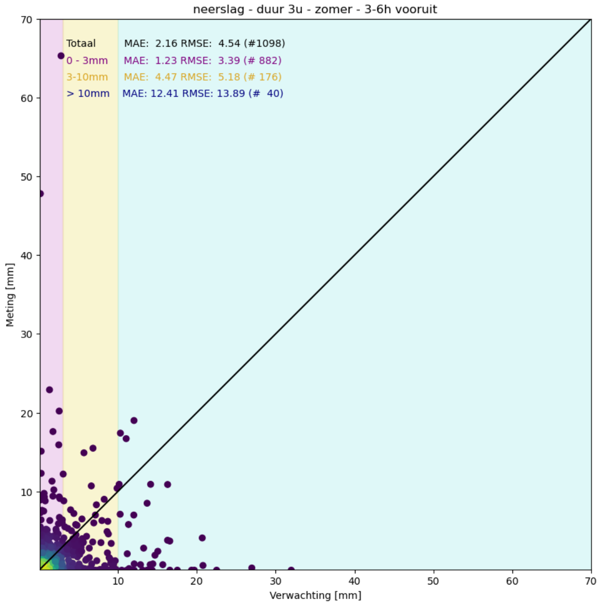
0 – 3 hours ahead

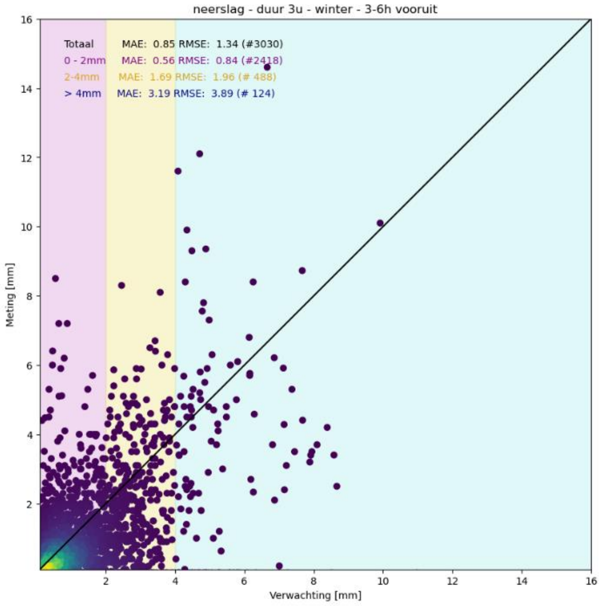


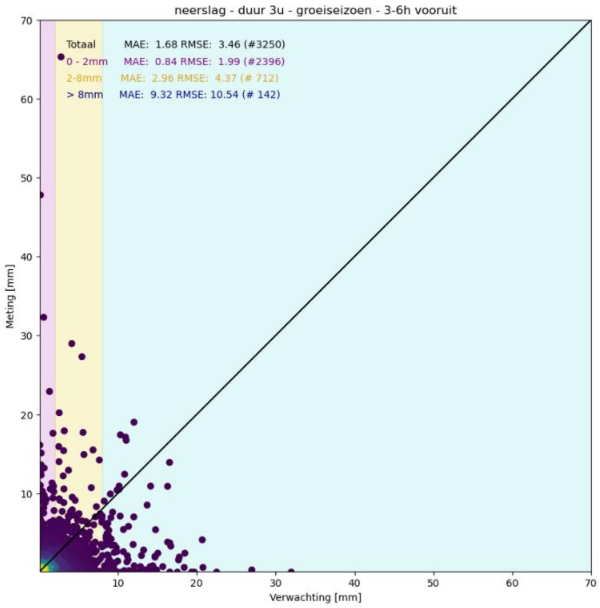




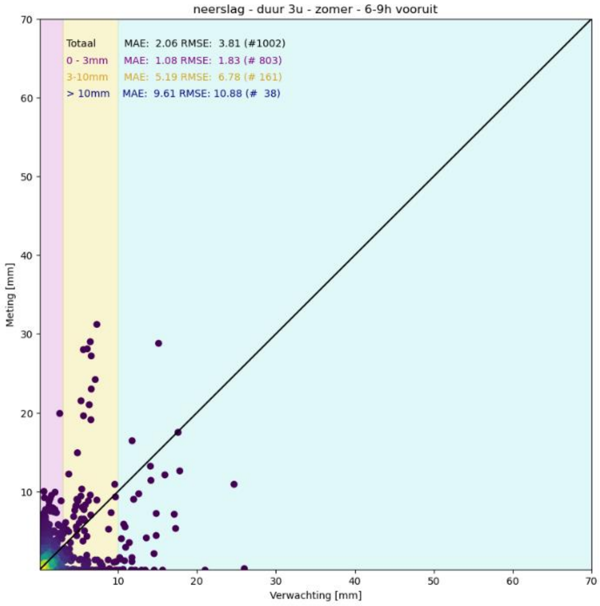
3 – 6 hours ahead

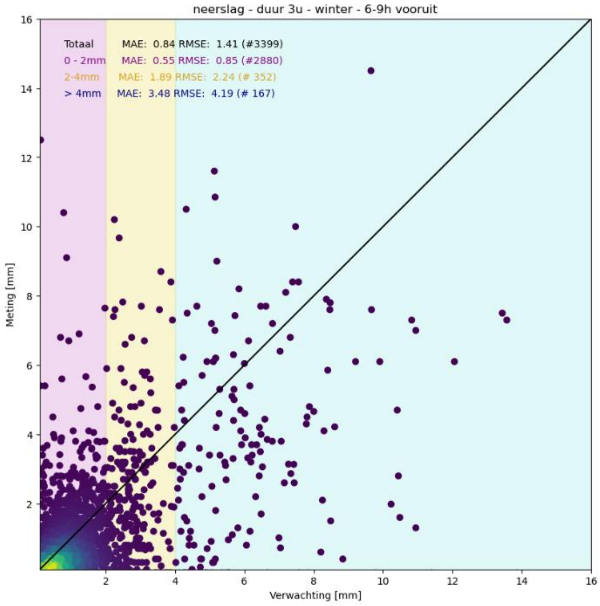


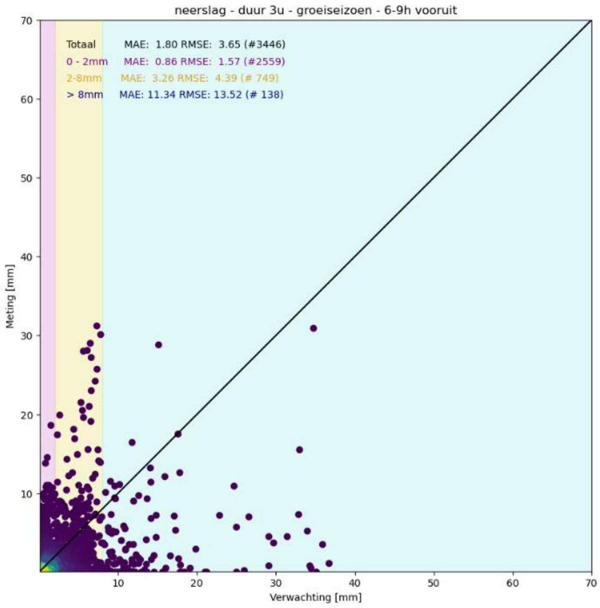




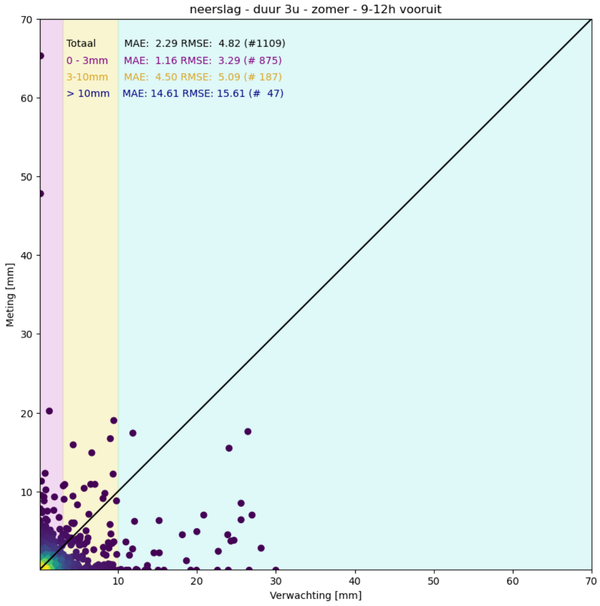
6 – 9 hours ahead

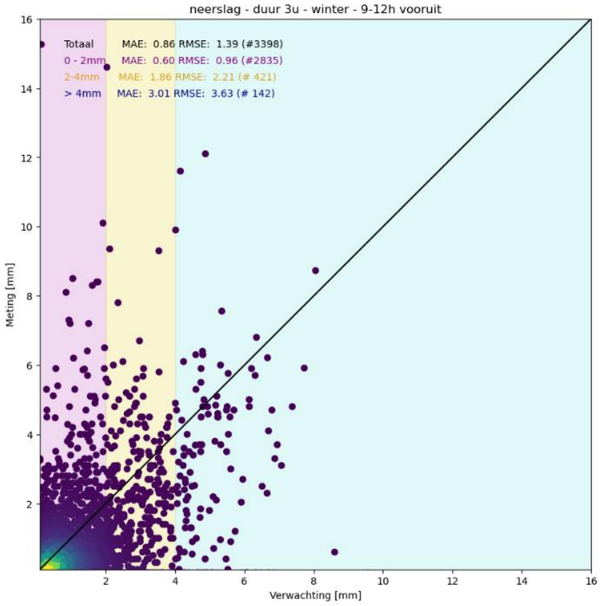


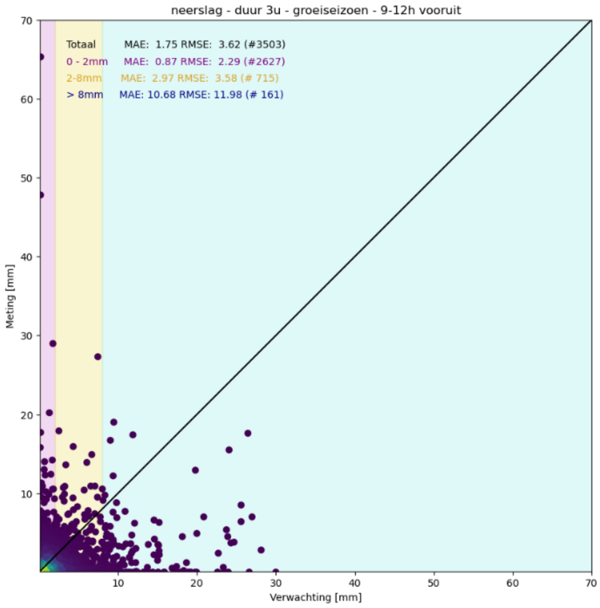




9 – 12 hours ahead

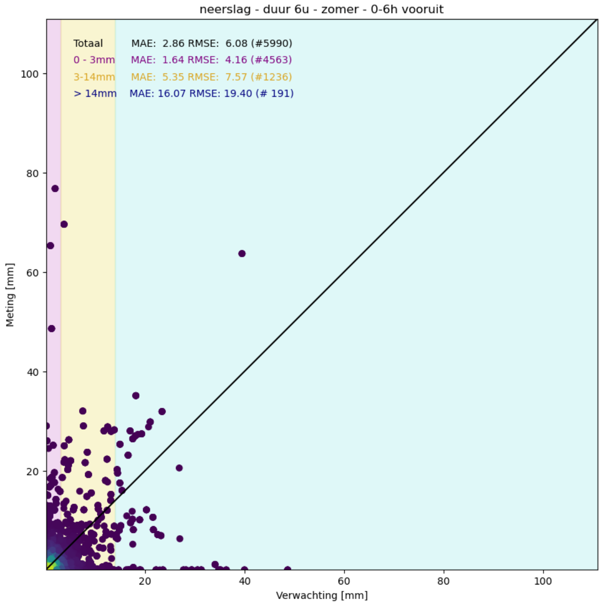


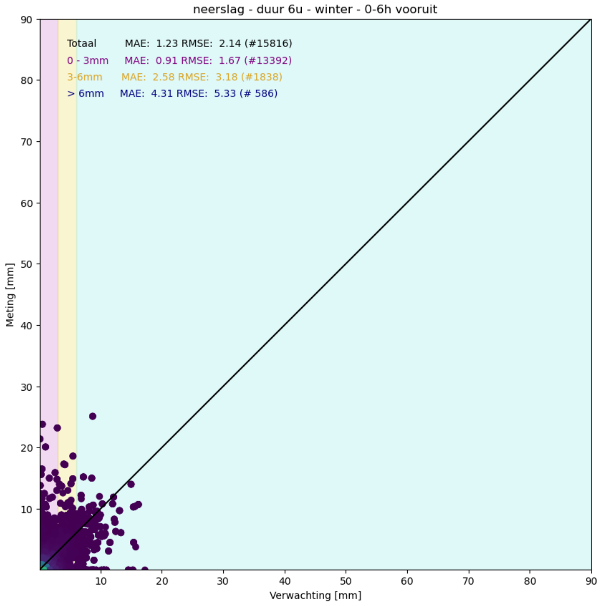


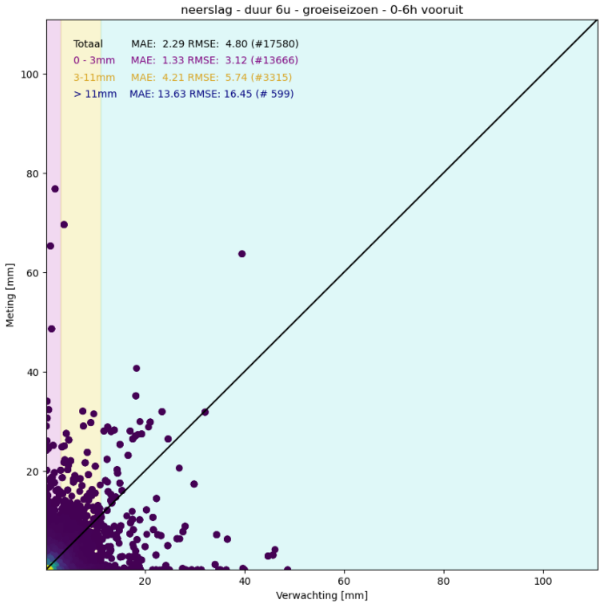


A.1.2 Accumulation period 6 hours

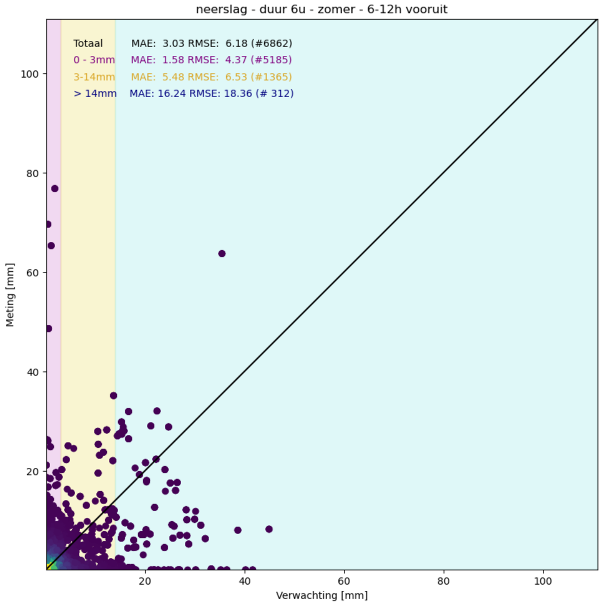
0 – 6 hours ahead

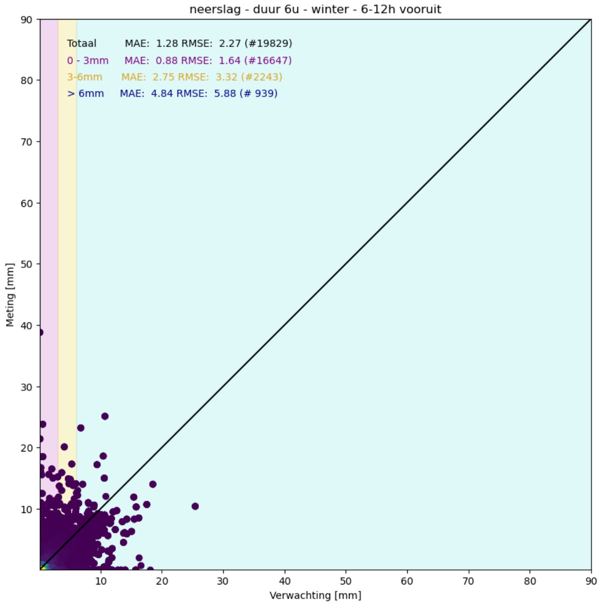


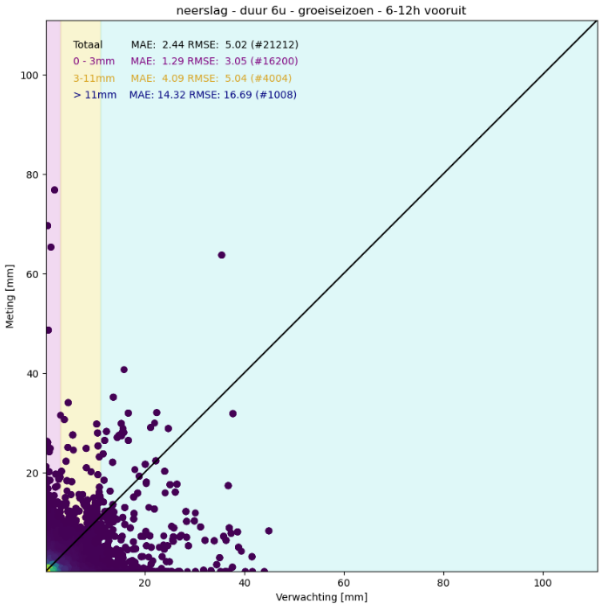




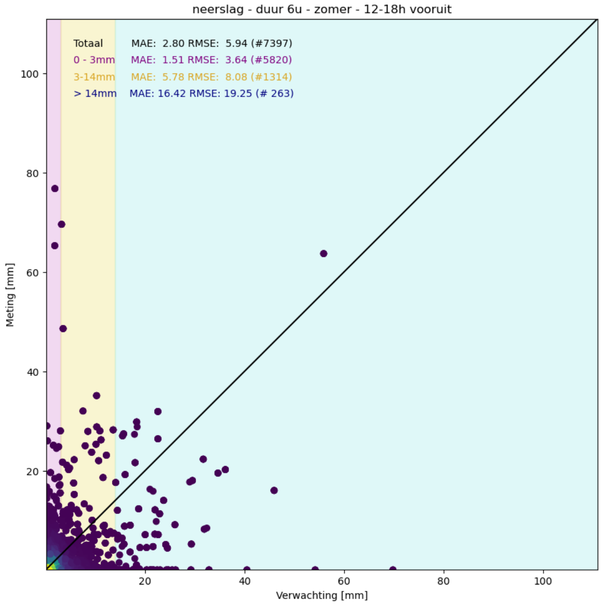
6 – 12 hours ahead

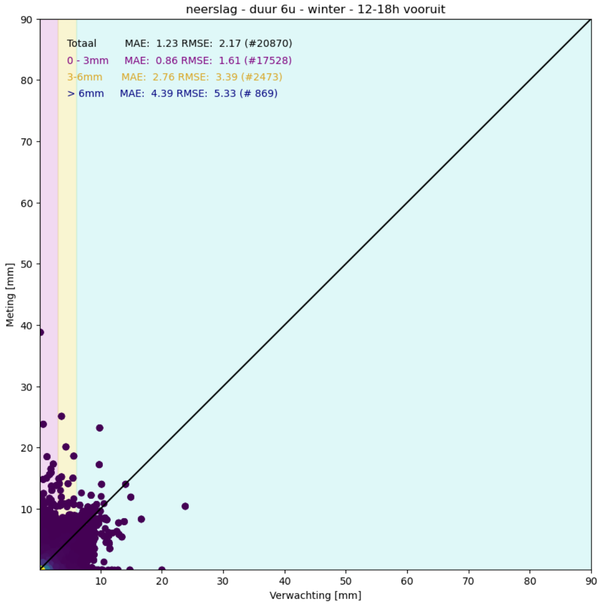


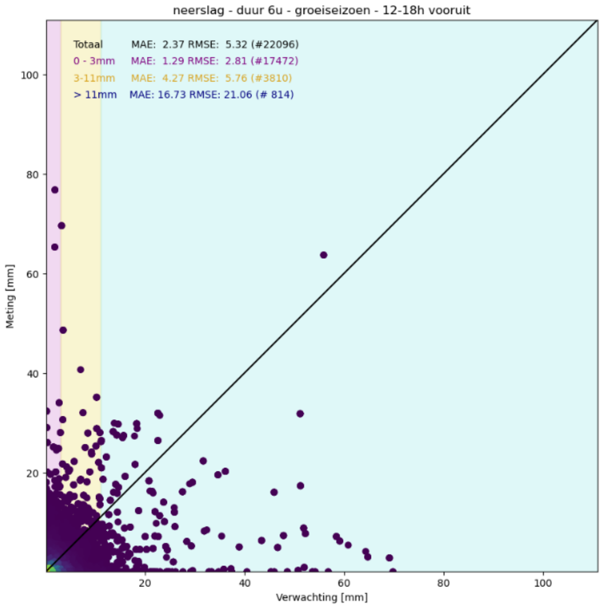




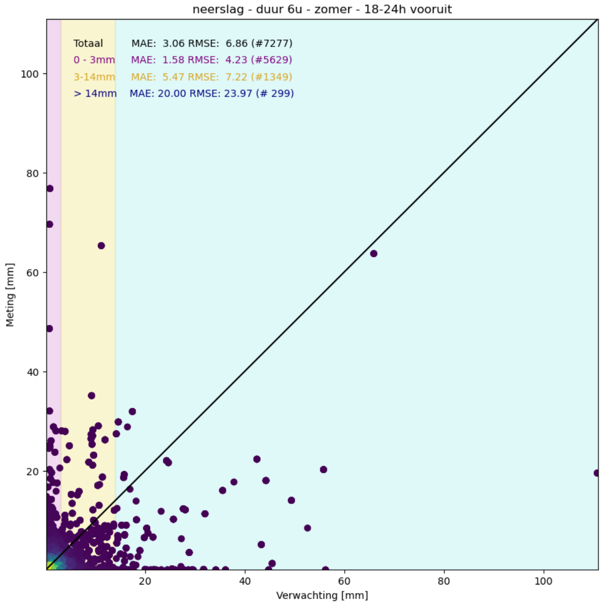
12 – 18 hours ahead

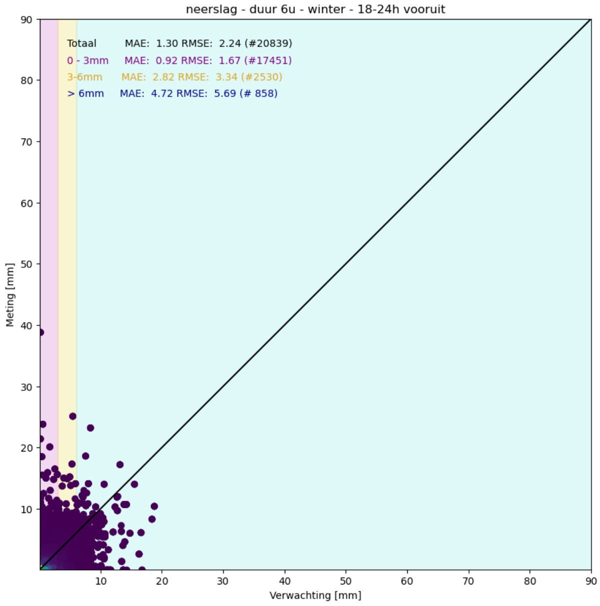


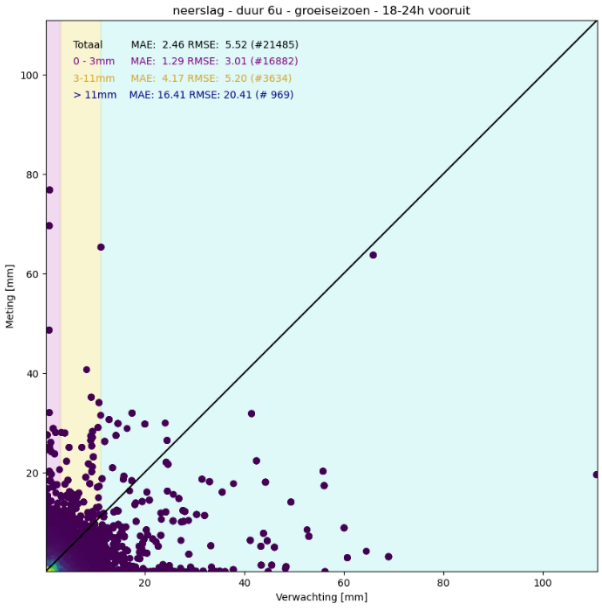




18 – 24 hours ahead

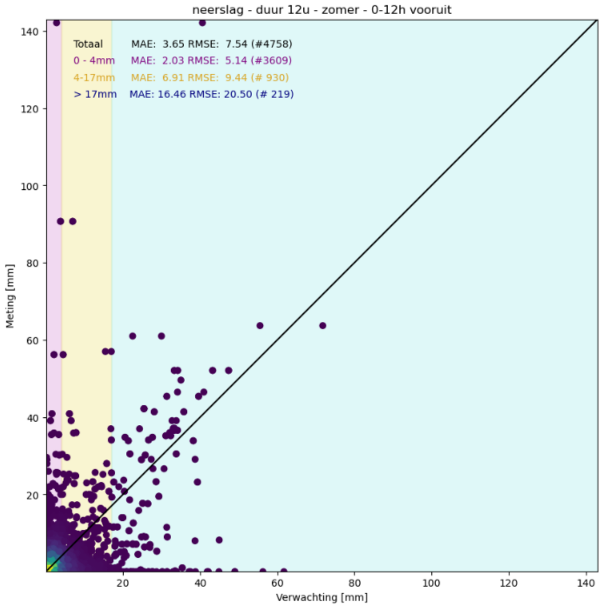


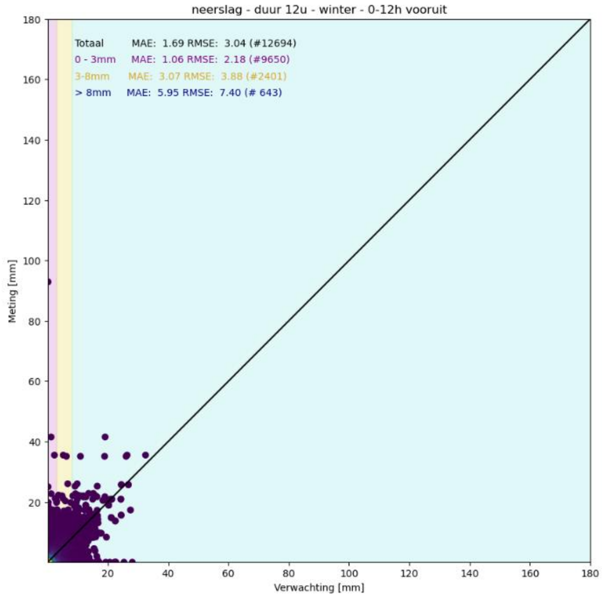


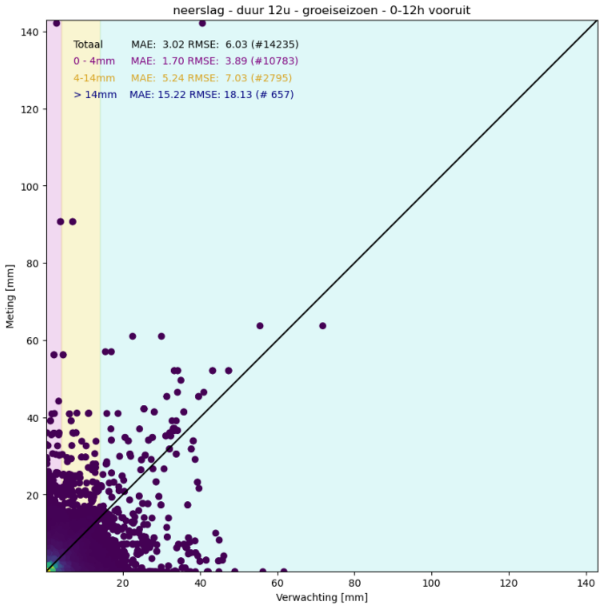


A.1.3 Accumulation period 12 hours

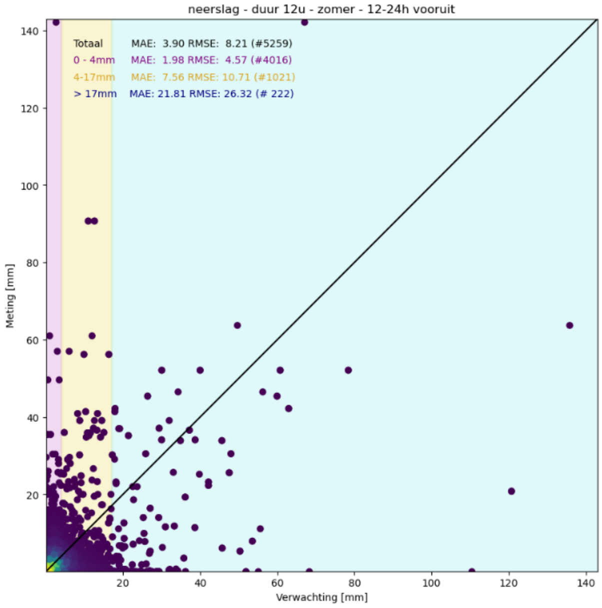
0 – 12 hours ahead

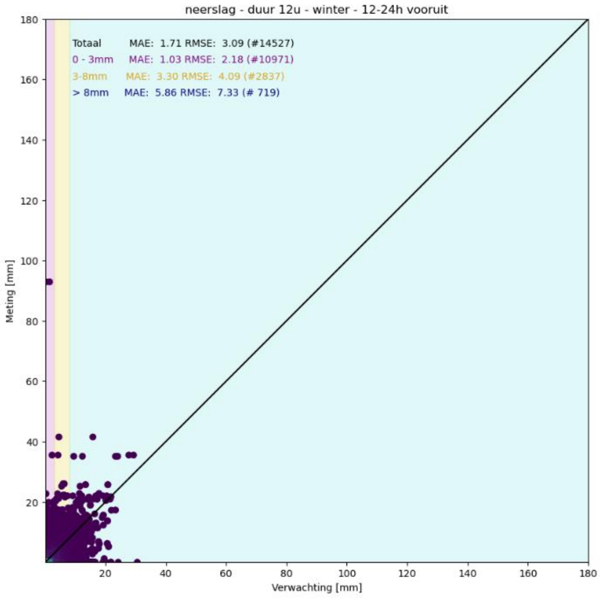


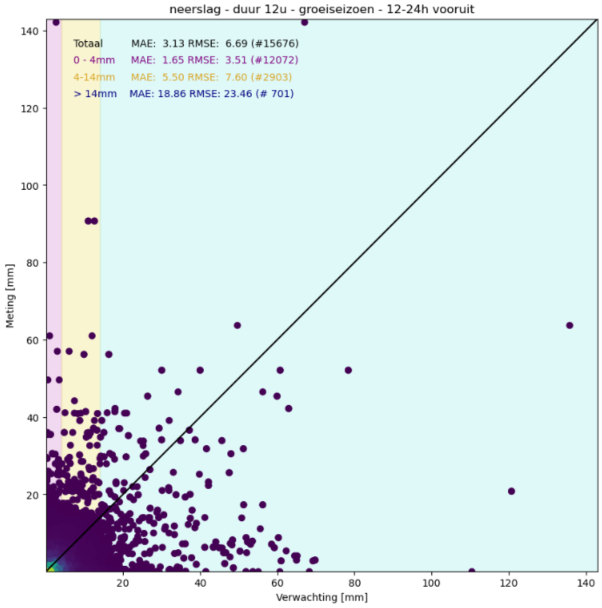




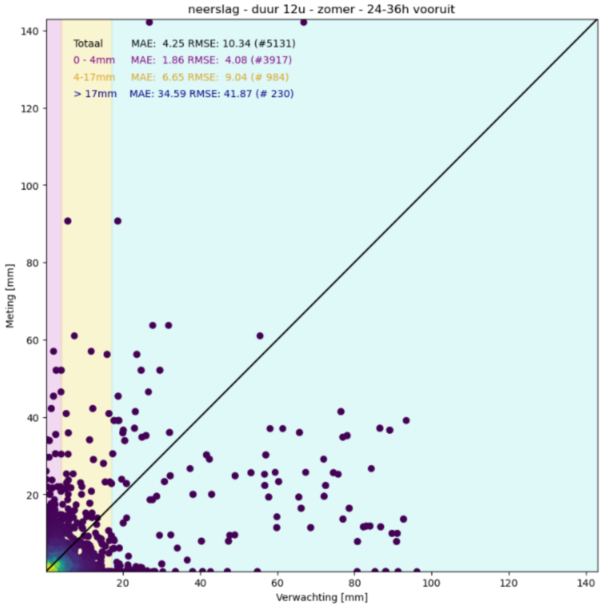
12 – 24 hours ahead

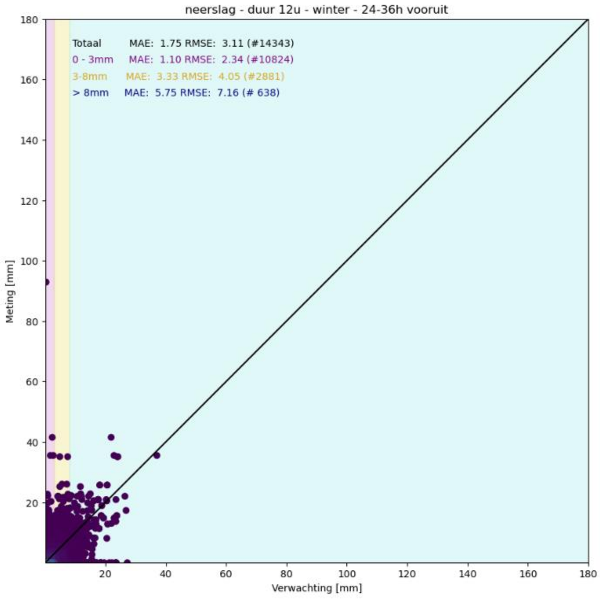


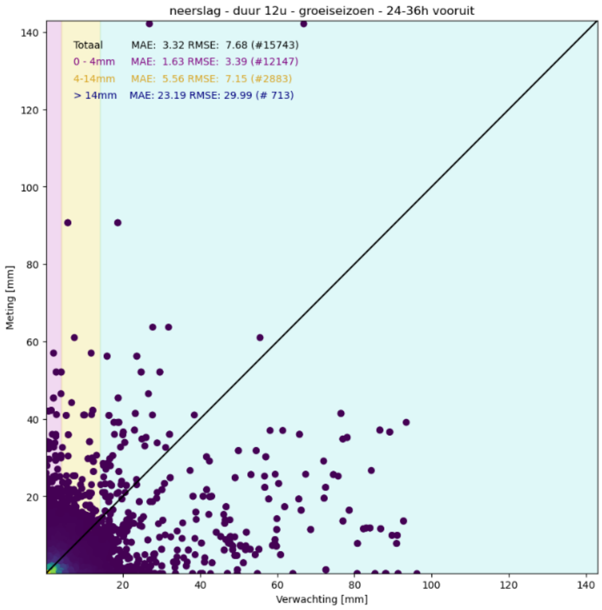




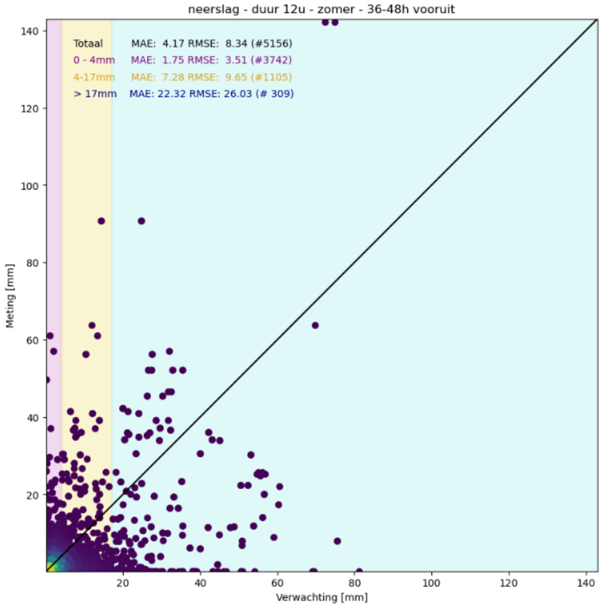
24 – 36 hours ahead

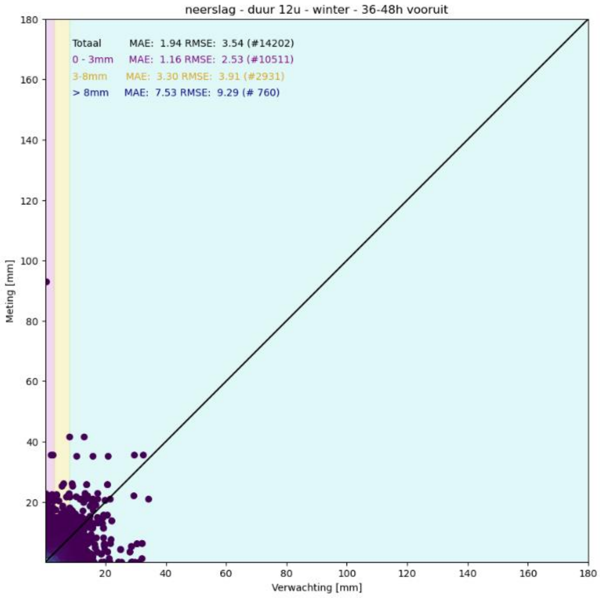


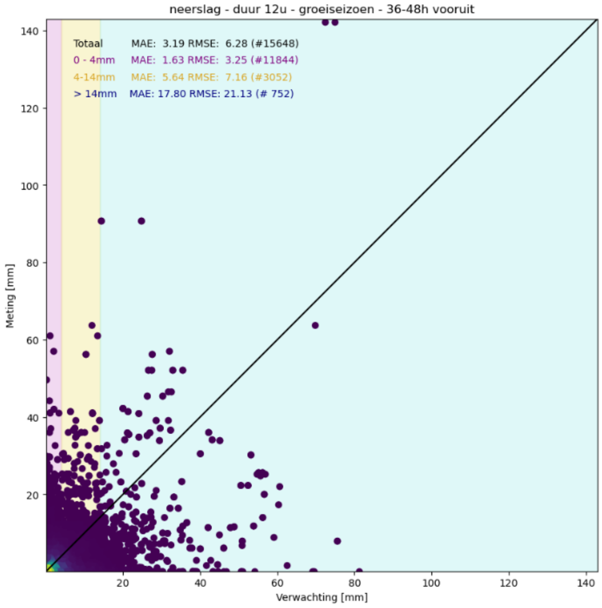




36 – 48 hours ahead

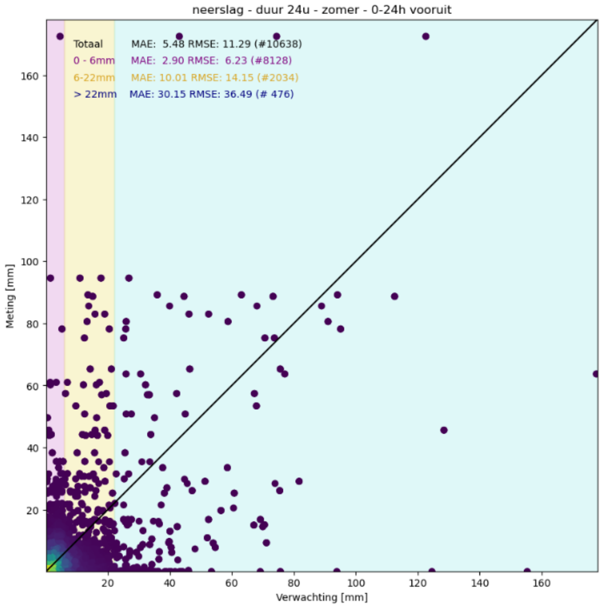


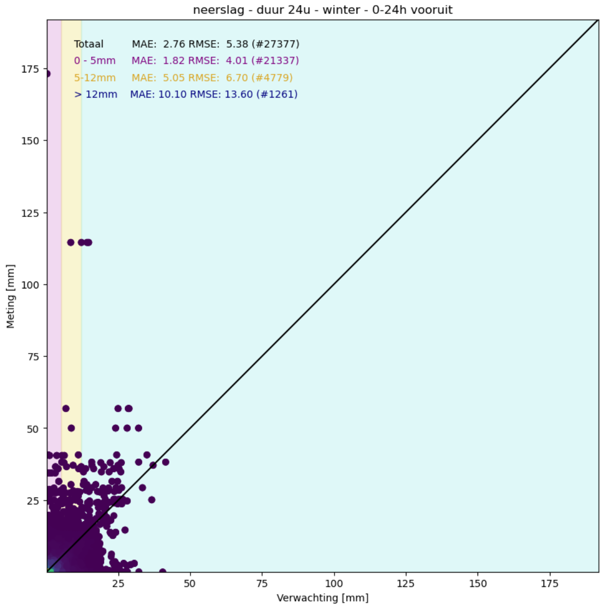


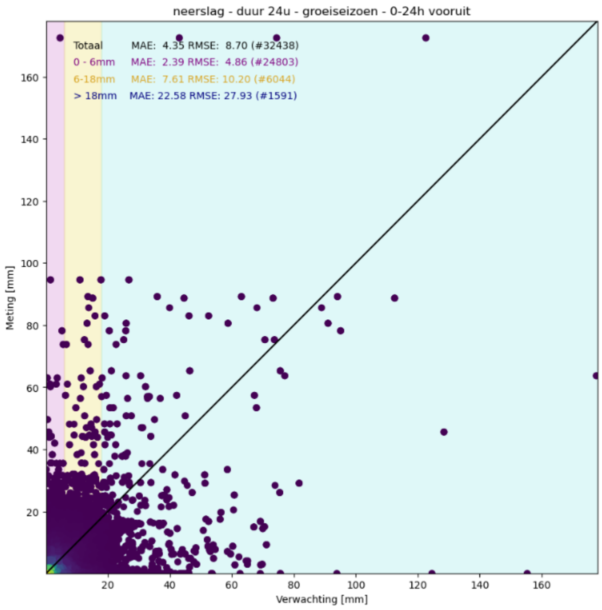


A.1.4 Accumulation period 24 hours

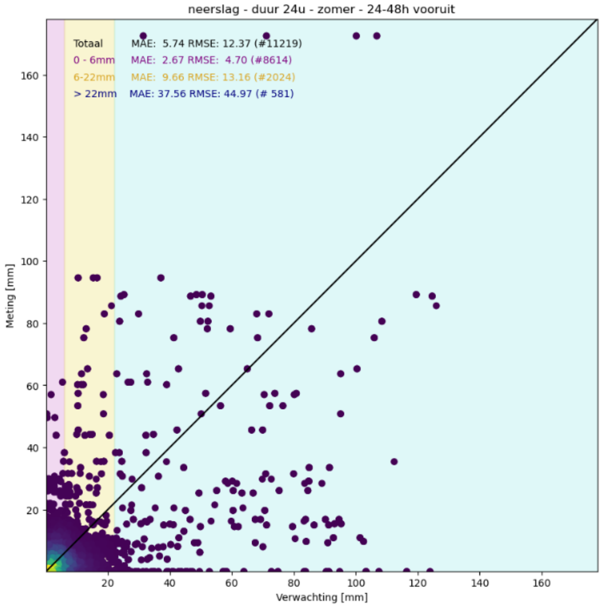
0 – 24 hours ahead

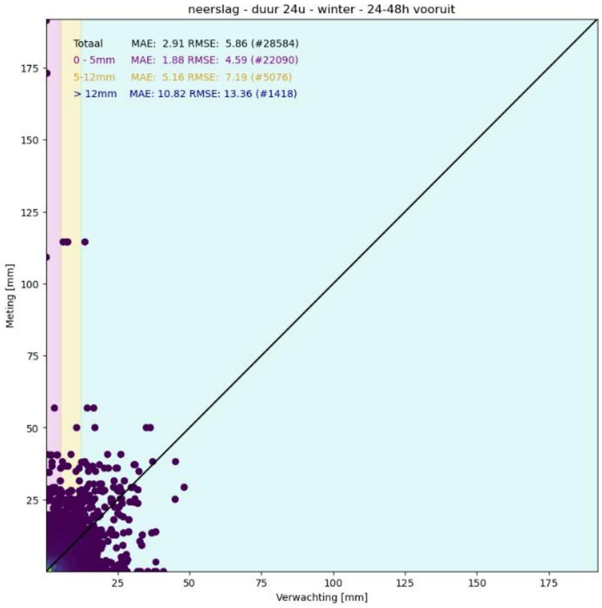


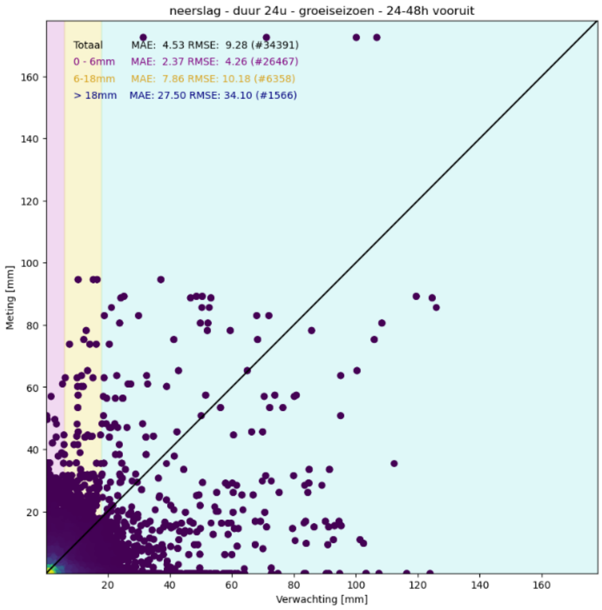




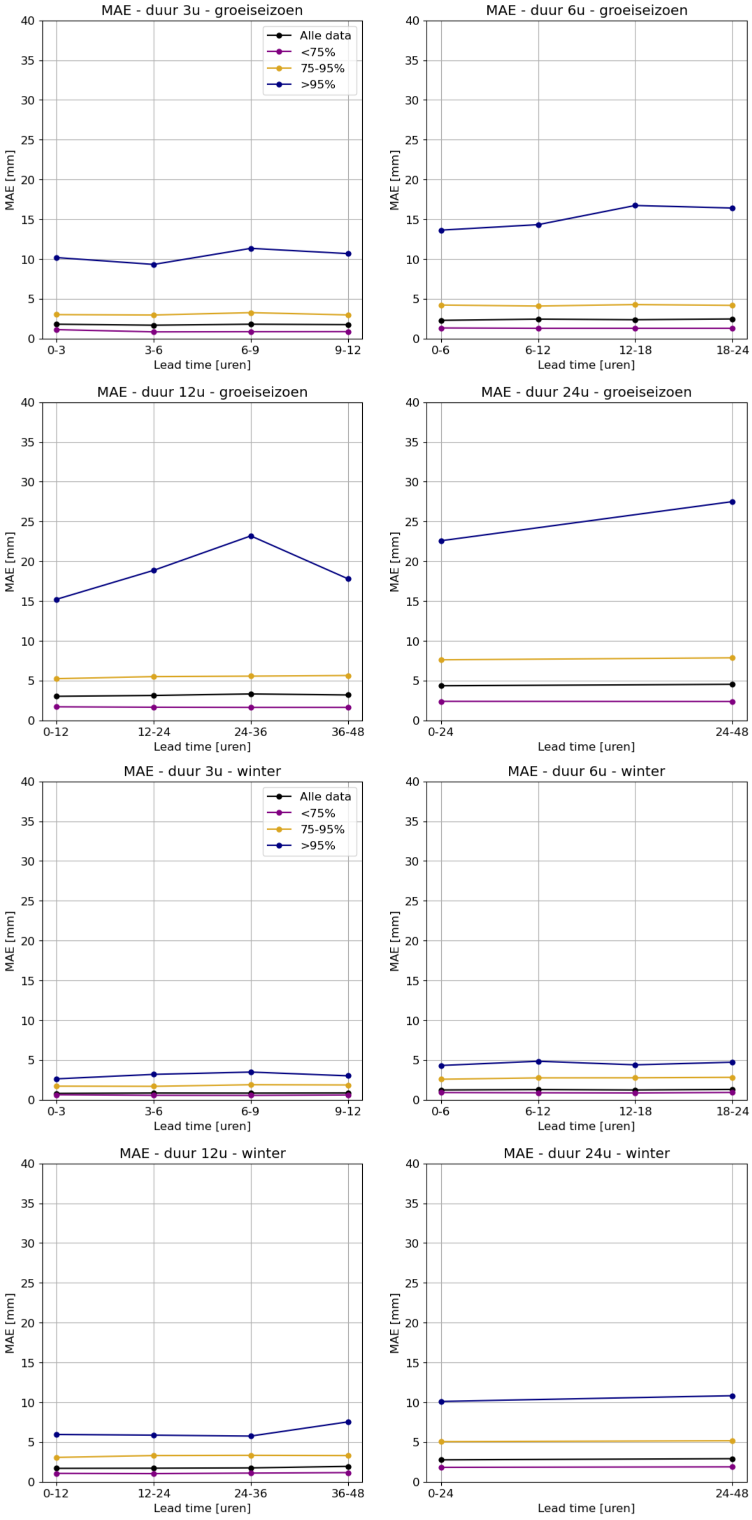
24 – 48 hours ahead

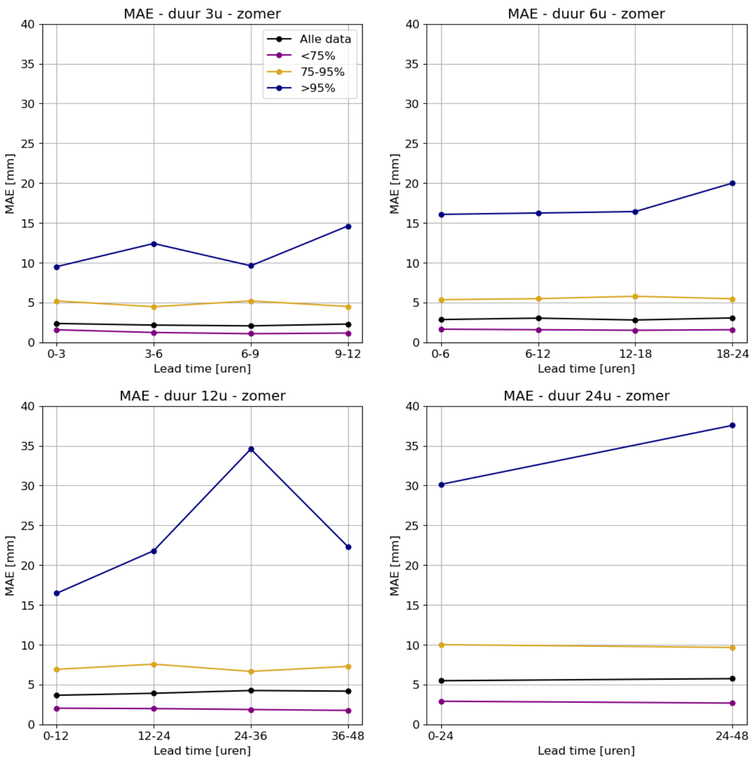




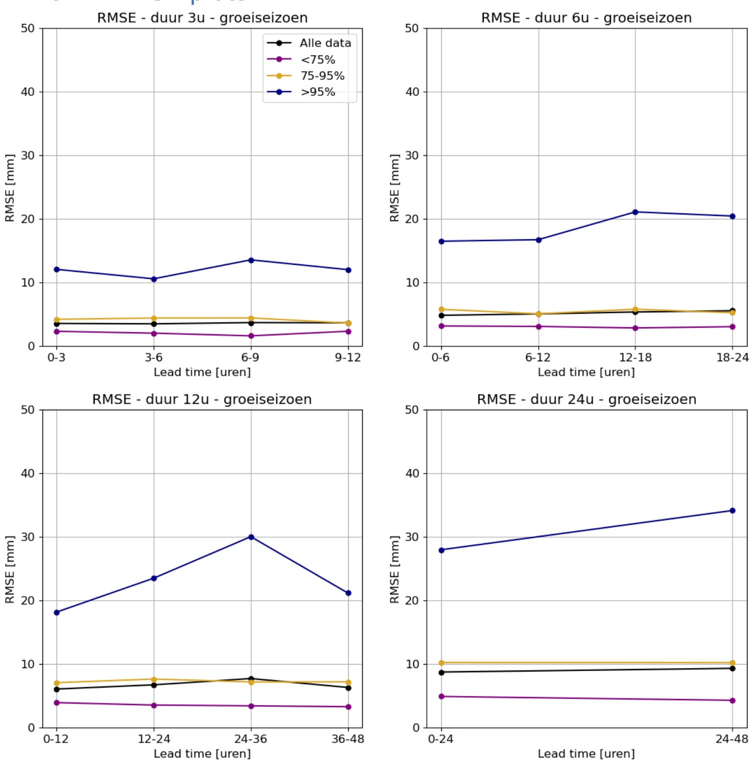


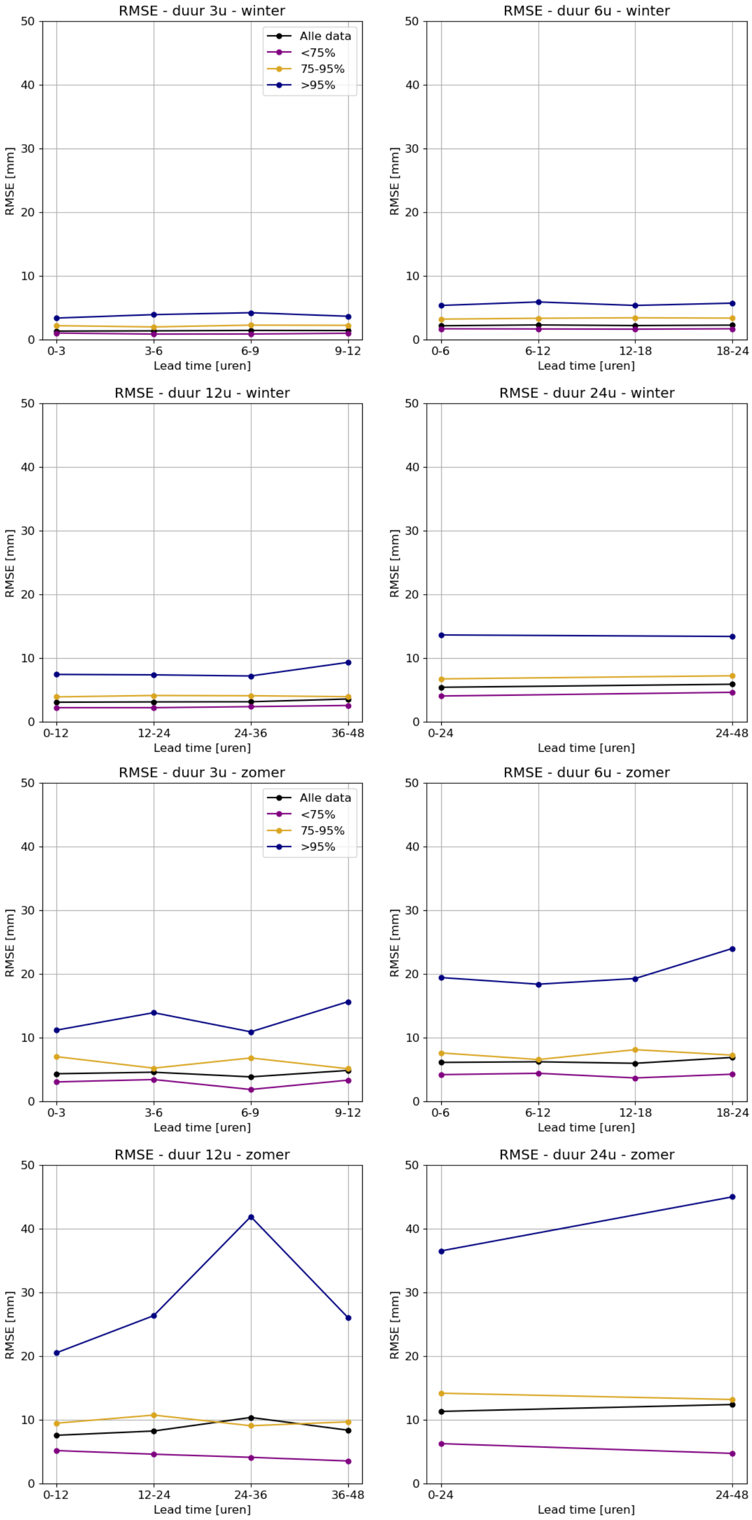
A.1.5 MAE plots





A.1.6 RMSE plots

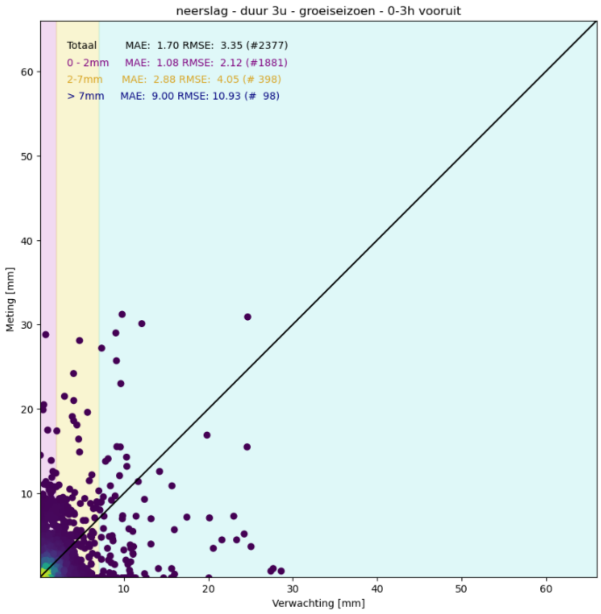


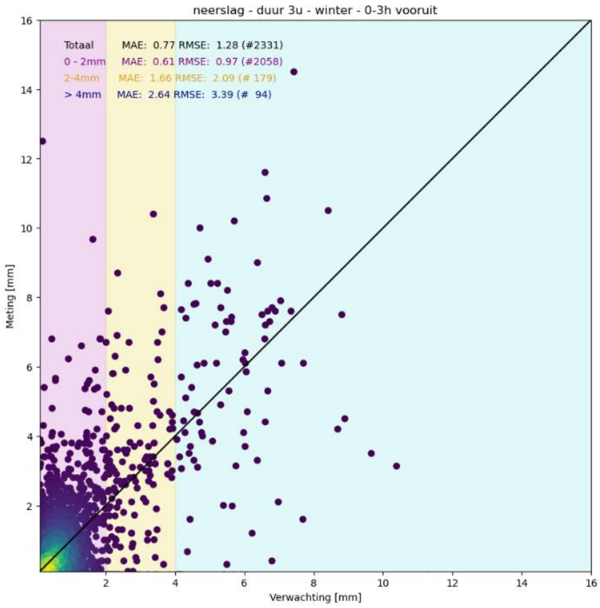

RMSE - duur 3u - winter
RMSE - duur 6u - winter
RMSE - duur 12u - winter
RMSE - duur 24u - winter
RMSE - duur 3u - zomer
RMSE - duur 6u - zomer
RMSE - duur 12u - zomer
RMSE - duur 24u - zomer
Alle data
<75%
75-95%
>95%
RMSE [mm]
Lead time [uren]
0
10
20
30
40
50
0-3
3-6
6-9
9-12
0-6
6-12
12-18
18-24
0-12
12-24
24-36
36-48
0-24
24-48

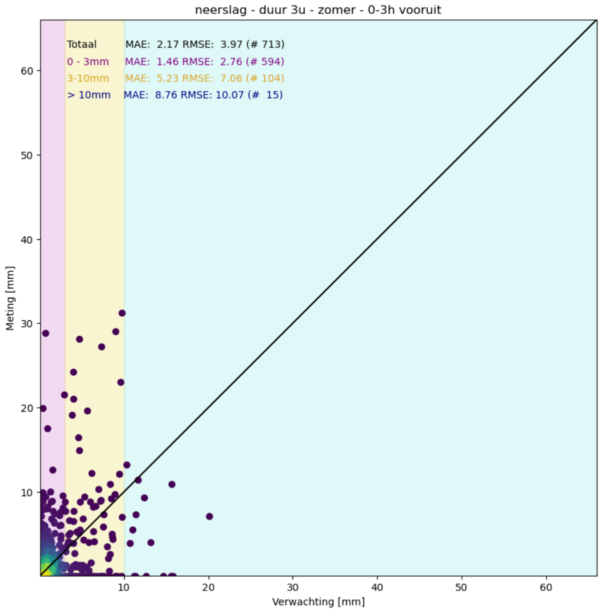
A.2 Comparison on spatial average around groundstations

A.2.1 Accumulation period 3 hours

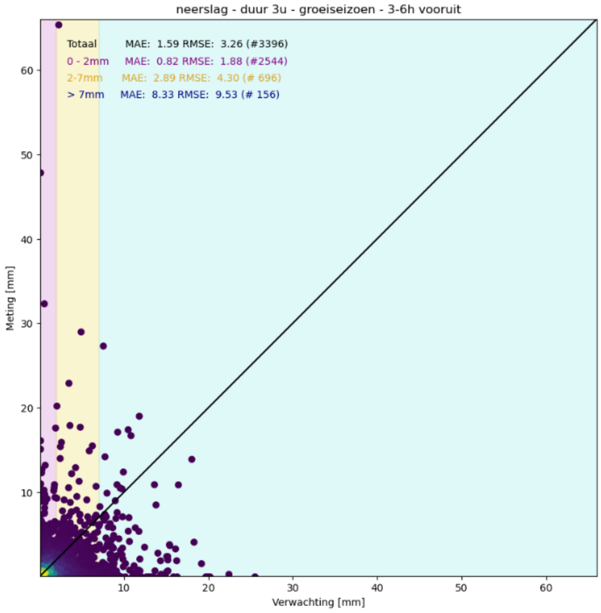
0 – 3 hours ahead

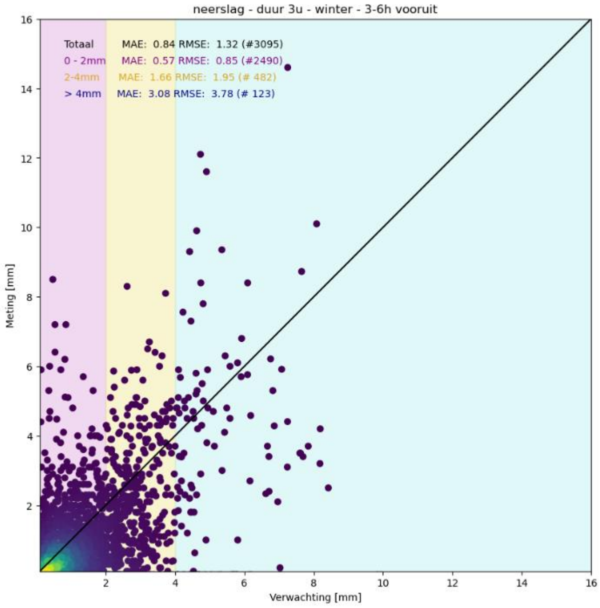


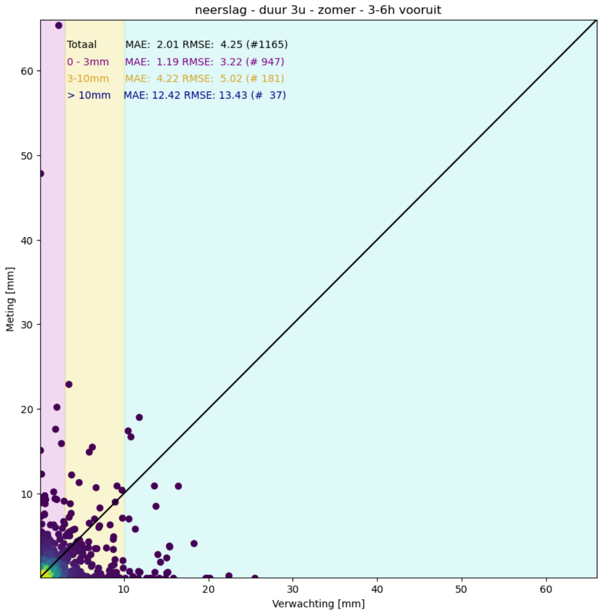




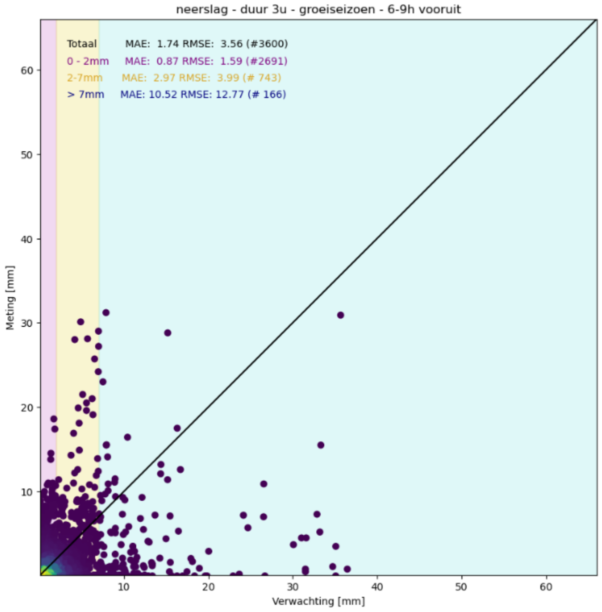
3 – 6 hours ahead

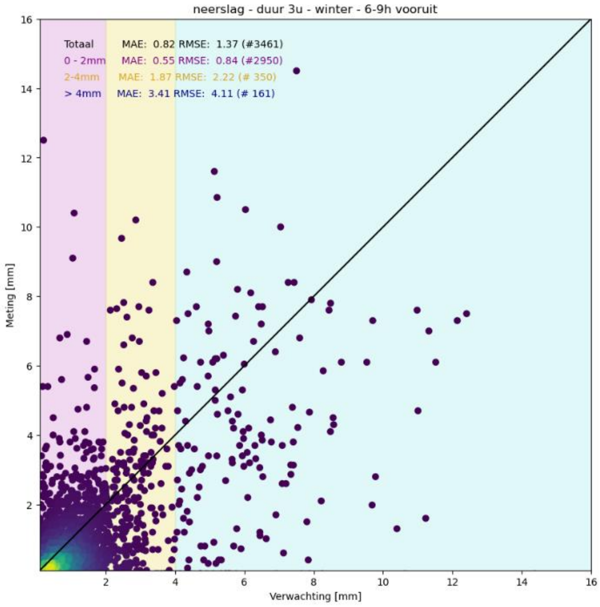


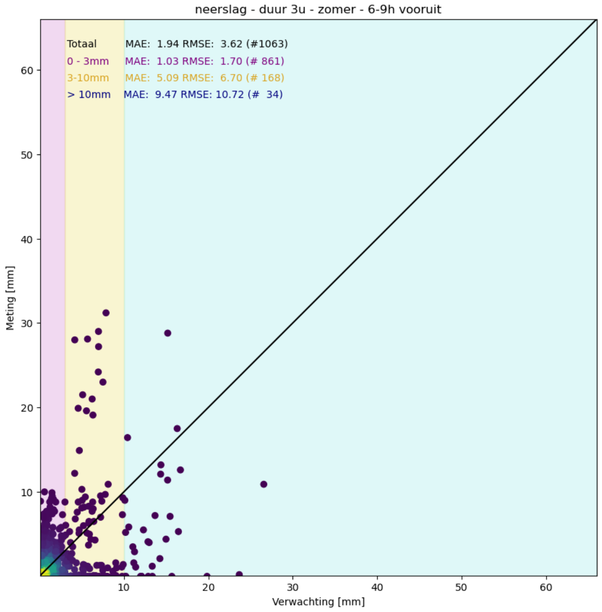




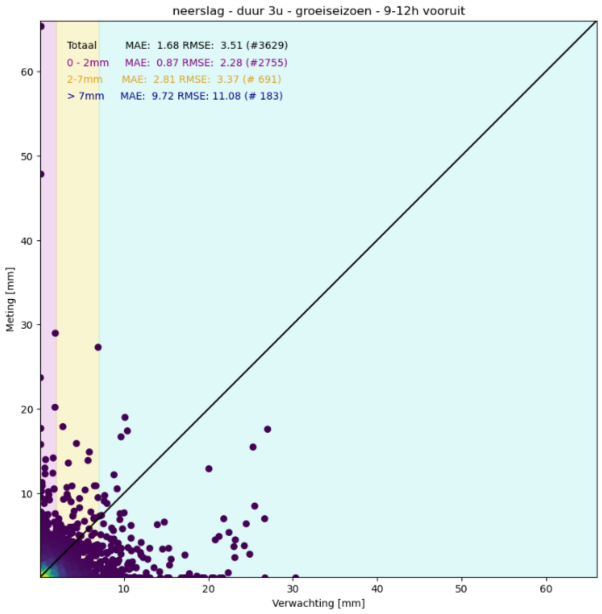
6 – 9 hours ahead

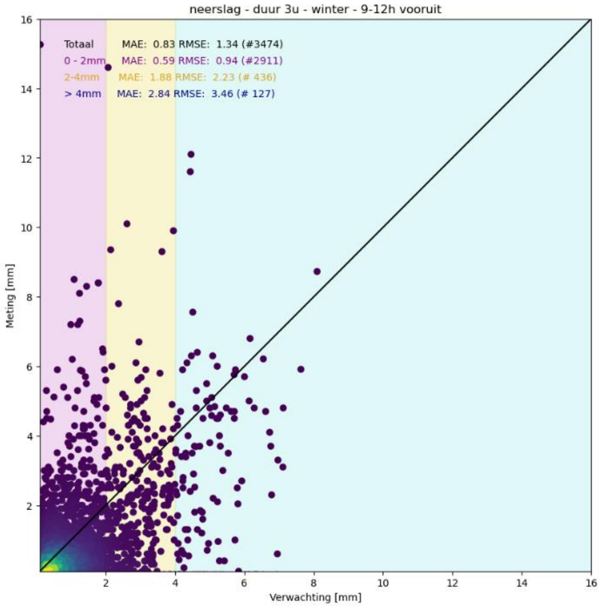


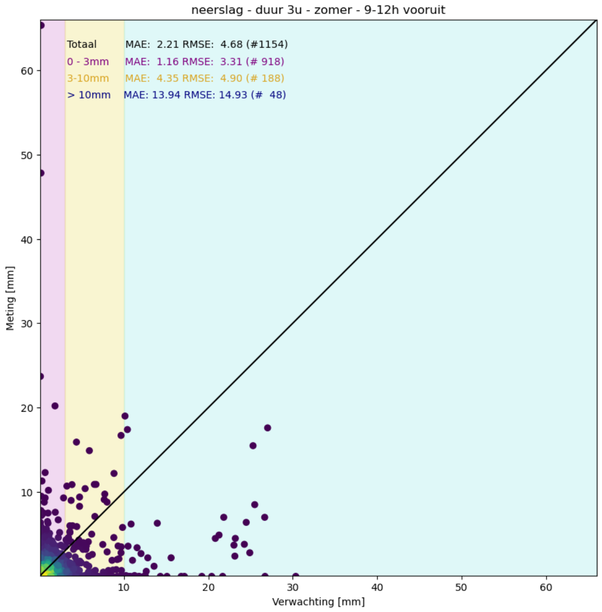




9 – 12 hours ahead

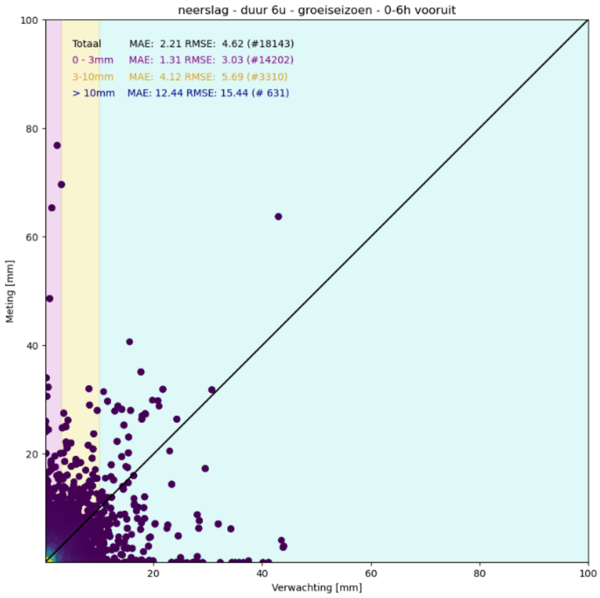


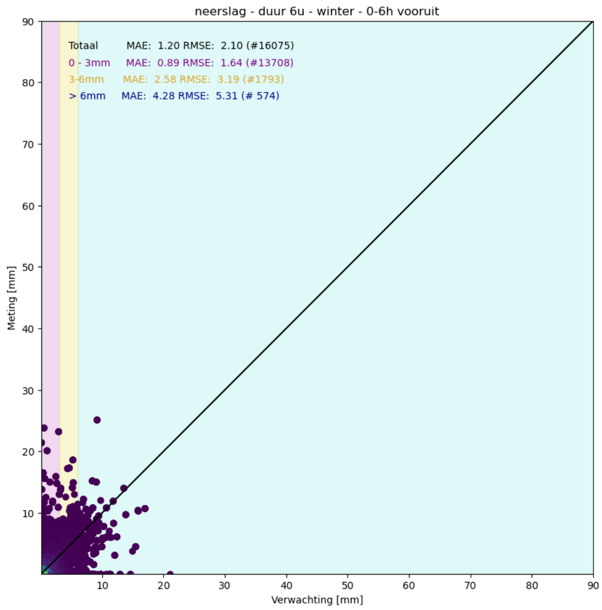


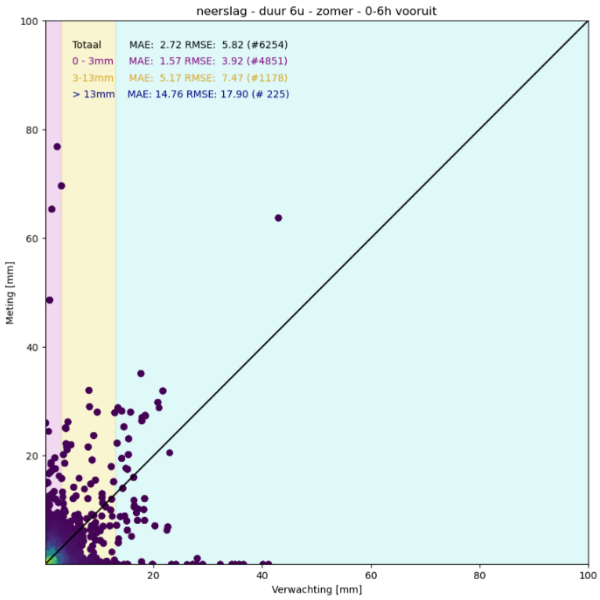


A.2.2 Accumulation period 6 hours

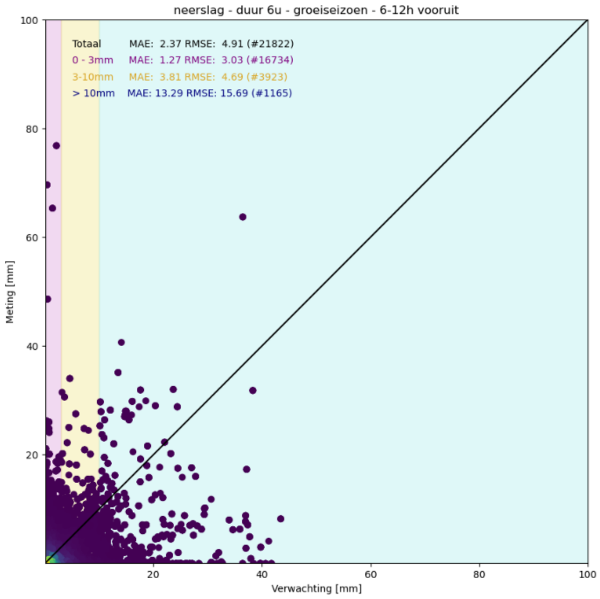
0 – 6 hours ahead

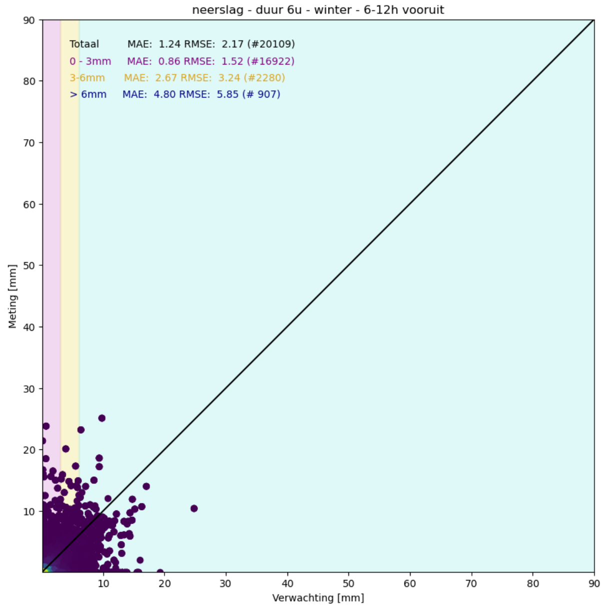


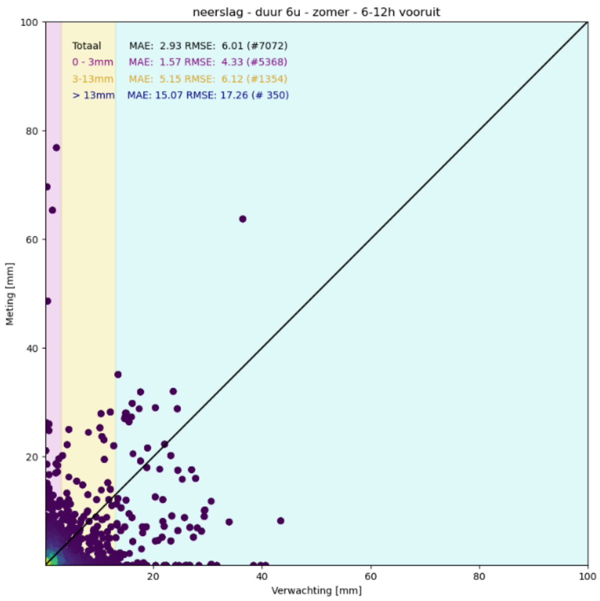




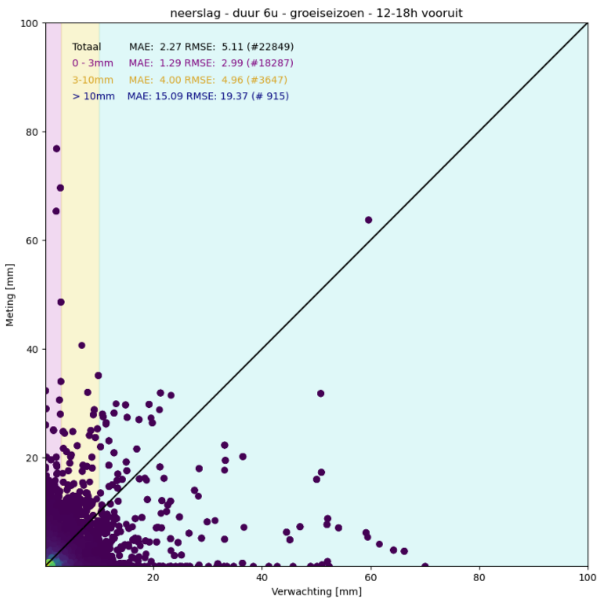
6 – 12 hours ahead

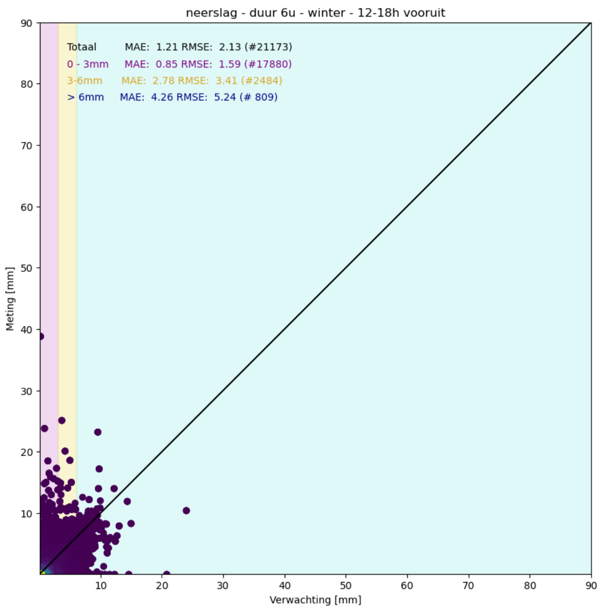


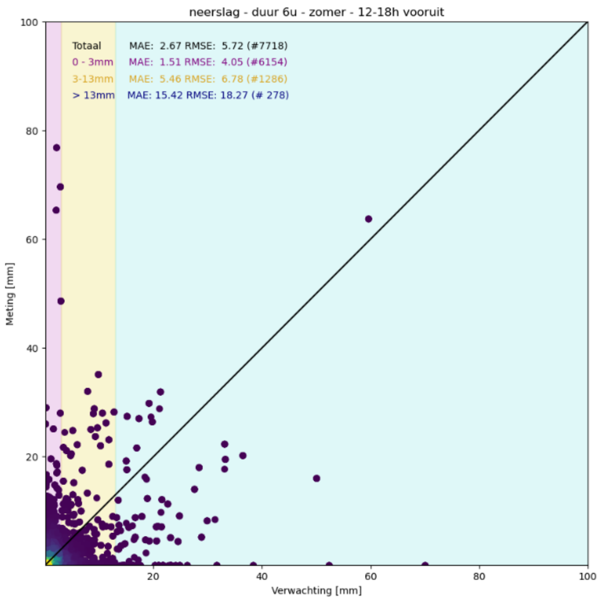




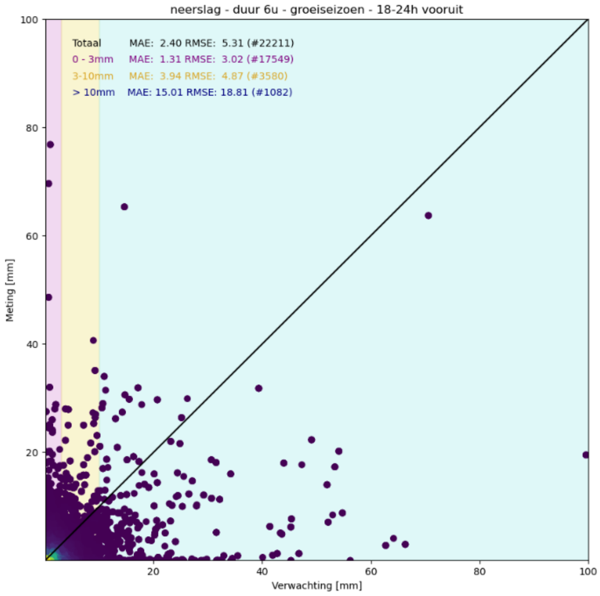
12 – 18 hours ahead

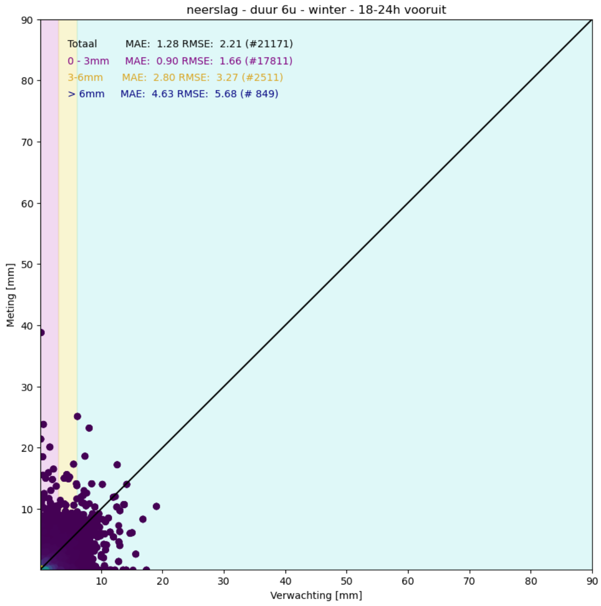


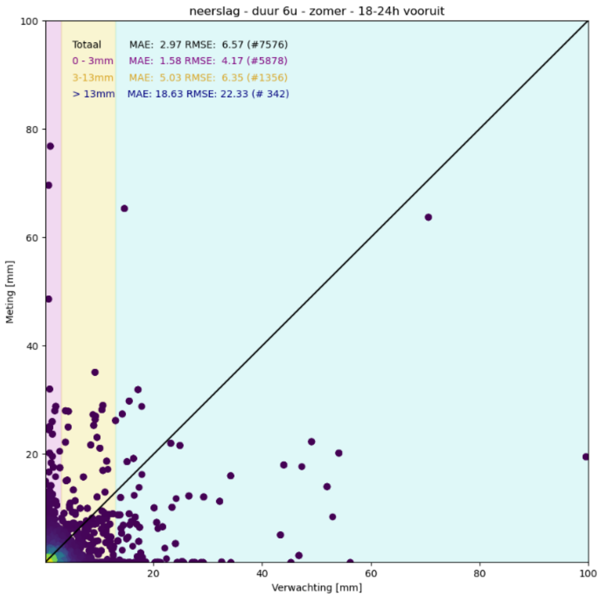




18 – 24 hours ahead

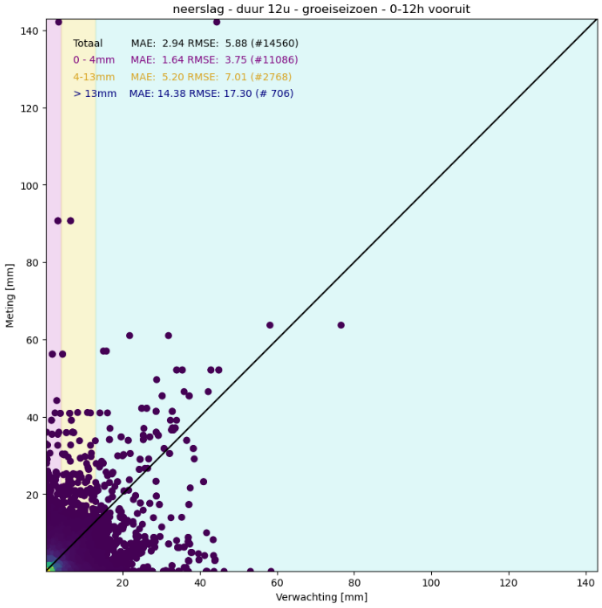


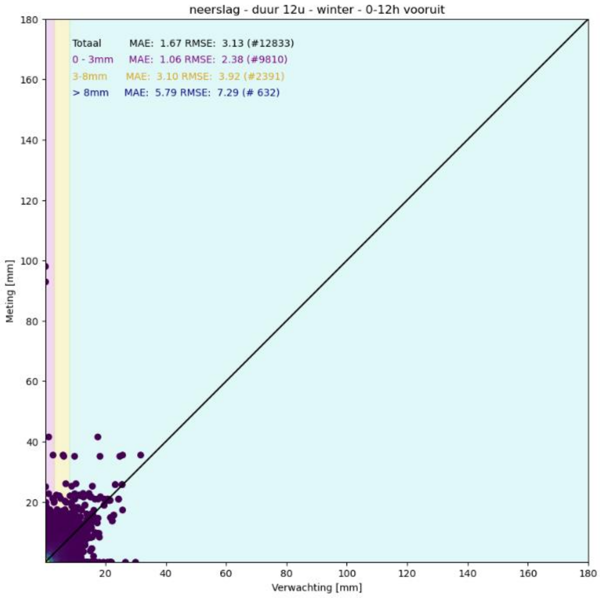


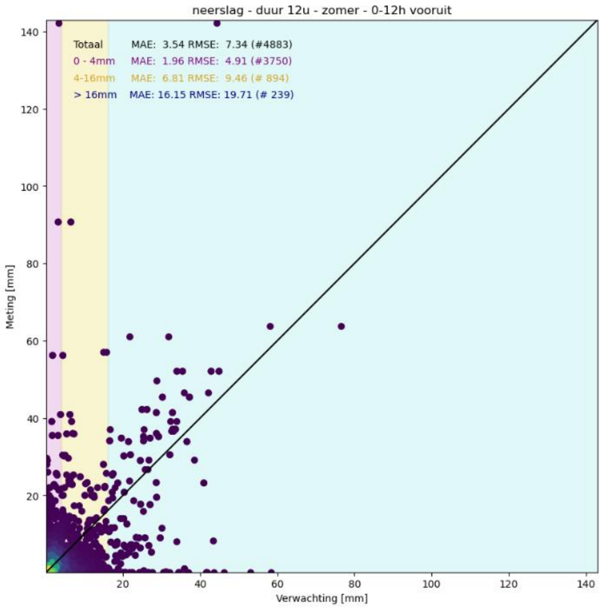


A.2.3 Accumulation period 12 hours

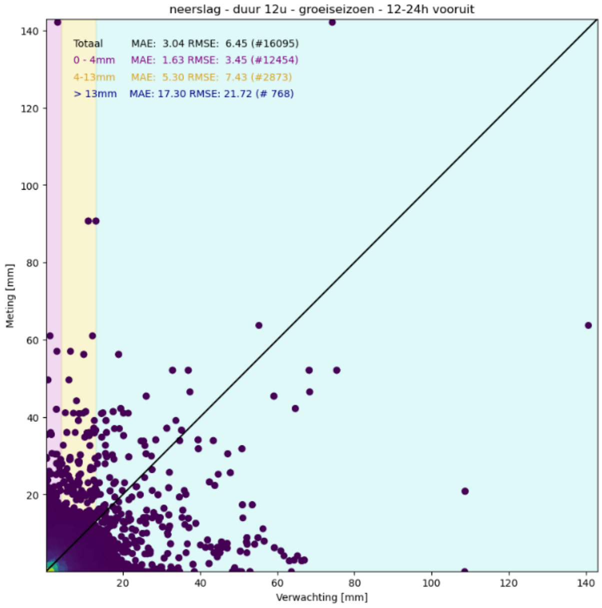
0 – 12 hours ahead

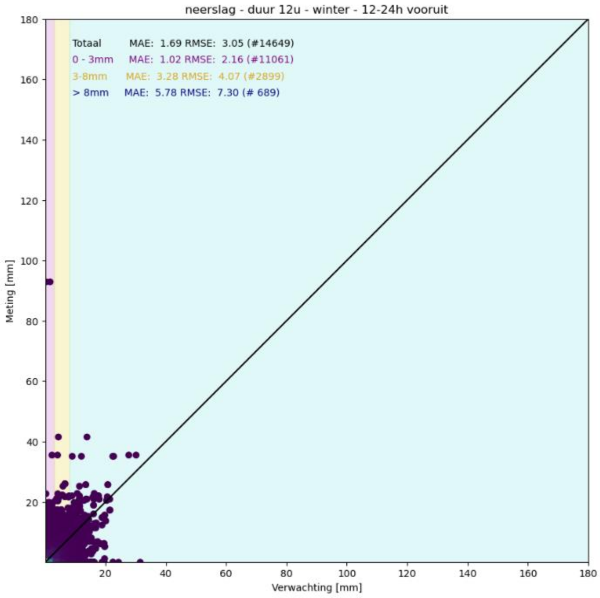


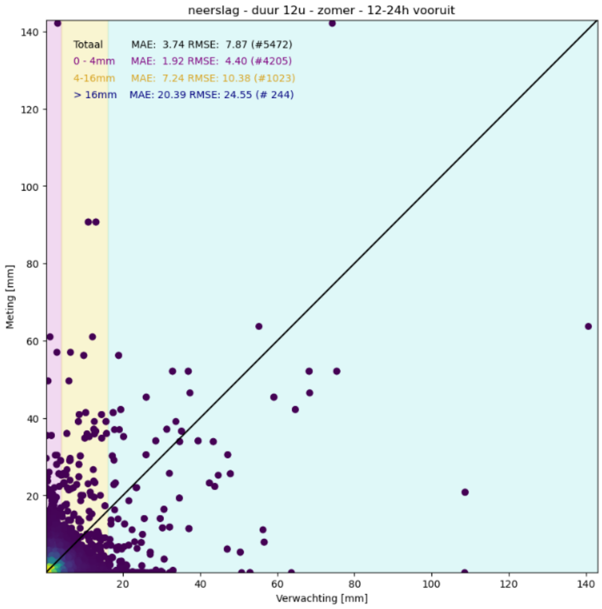




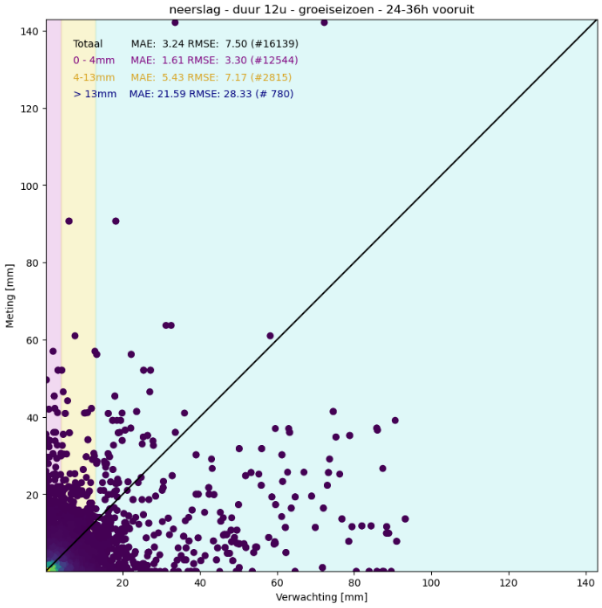
12 – 24 hours ahead

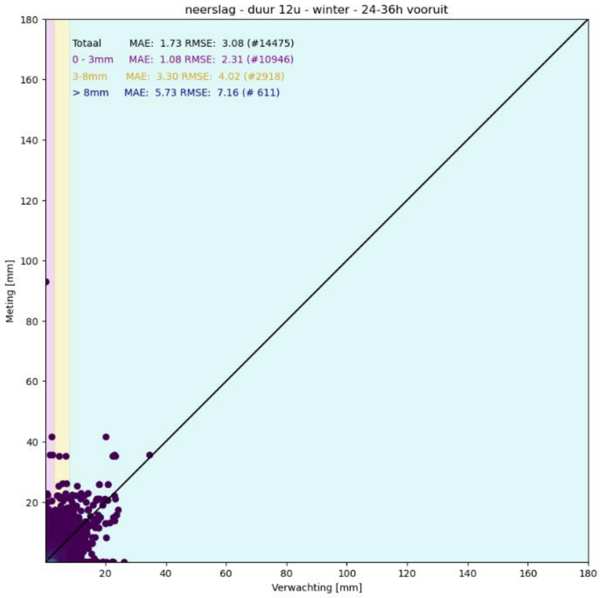


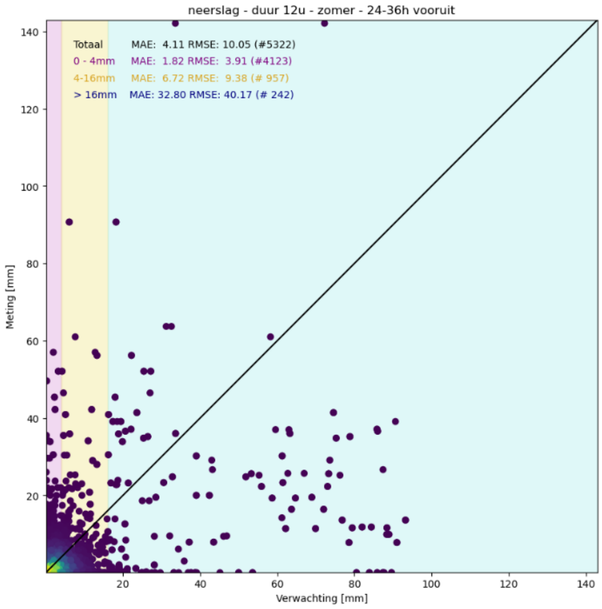




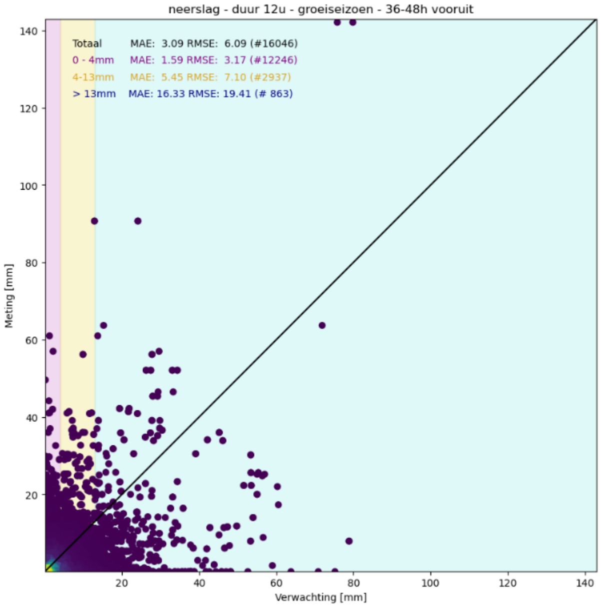
24 – 36 hours ahead

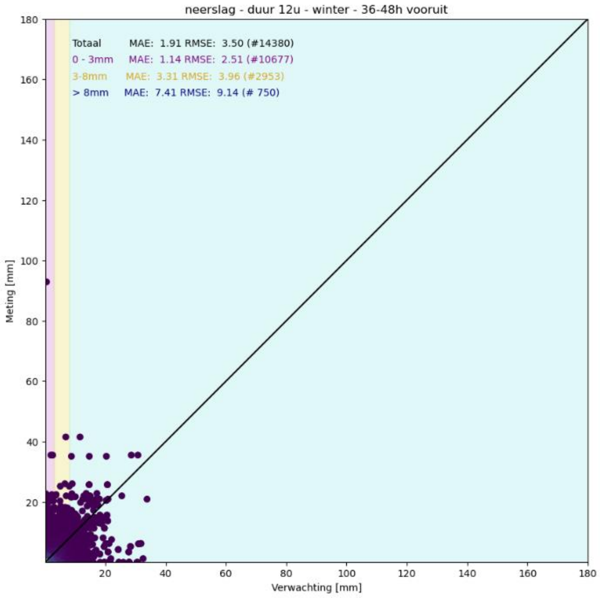


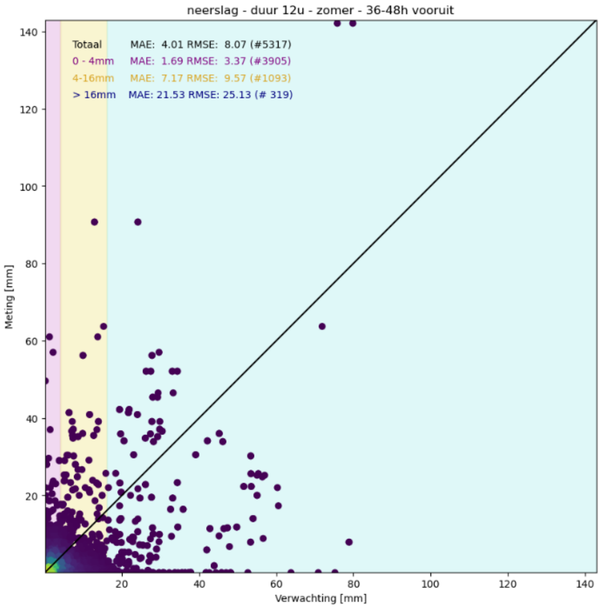




36 – 48 hours ahead

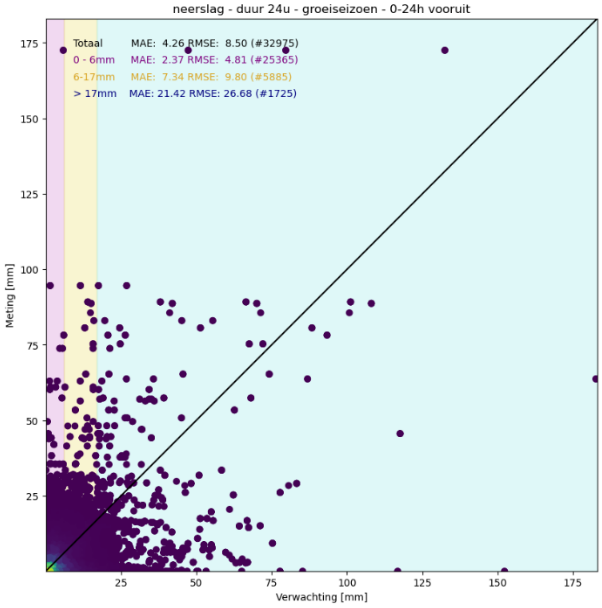


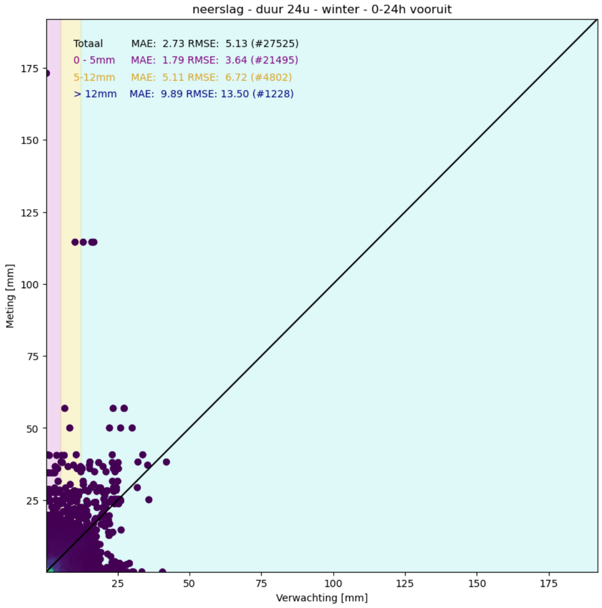


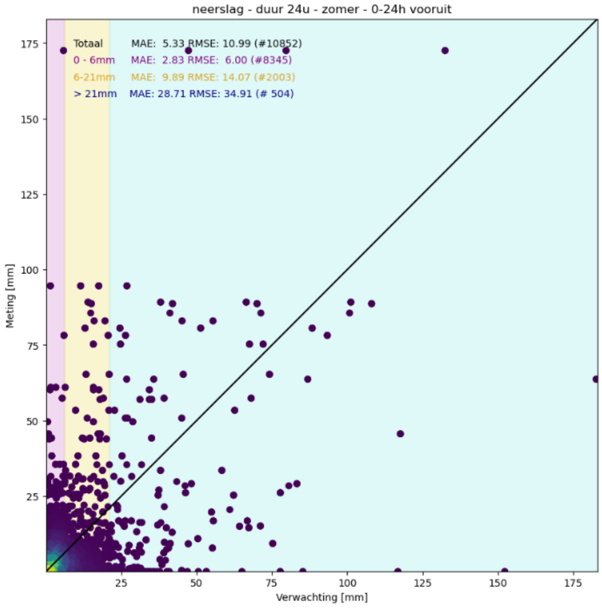


A.2.4 Accumulation period 24 hours

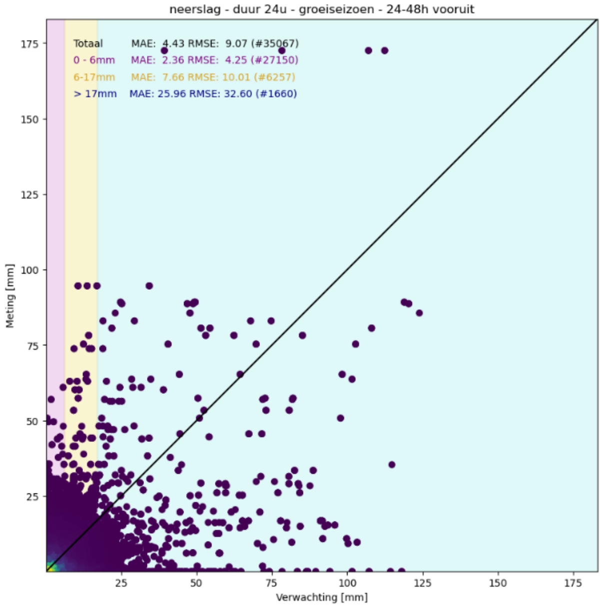
0 – 24 hours ahead

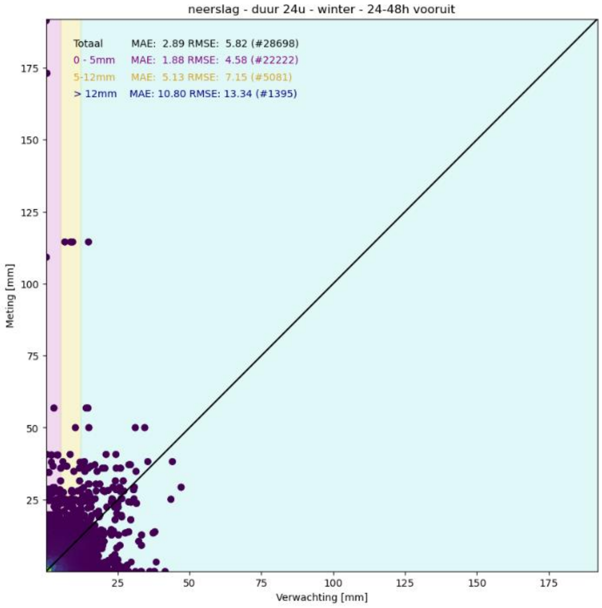


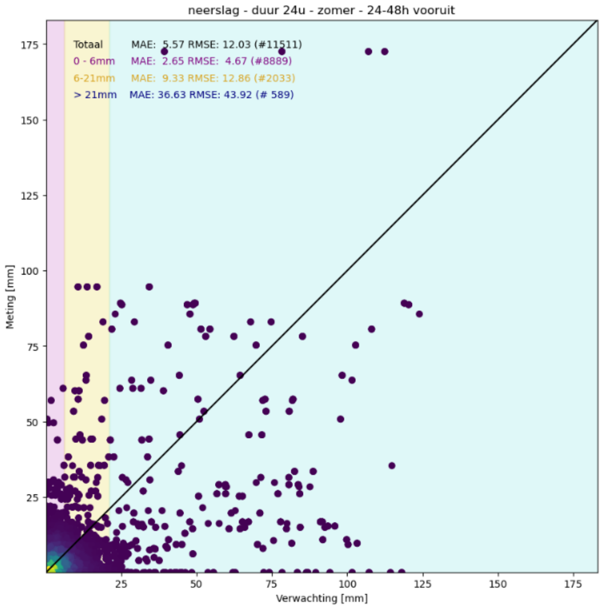




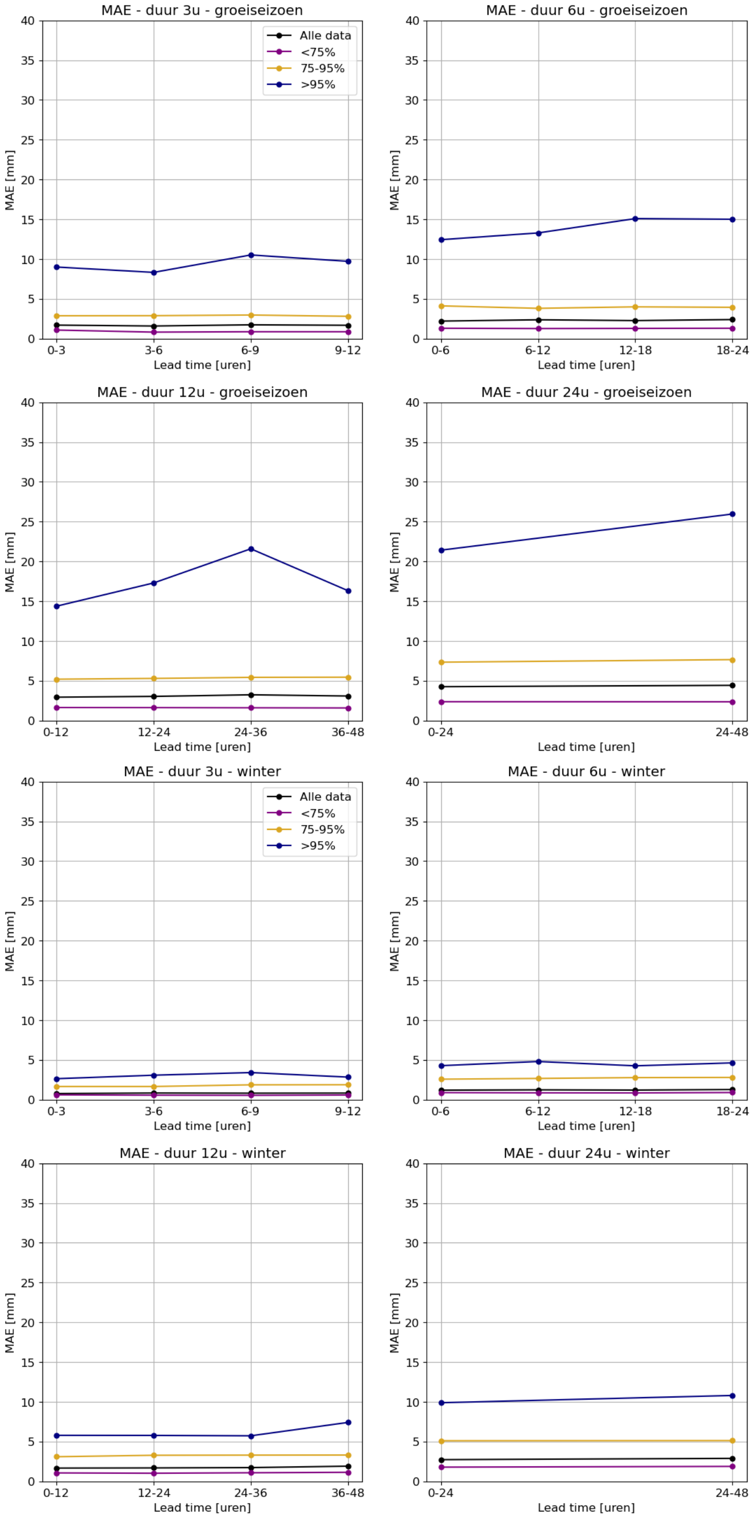
24 – 48 hours ahead

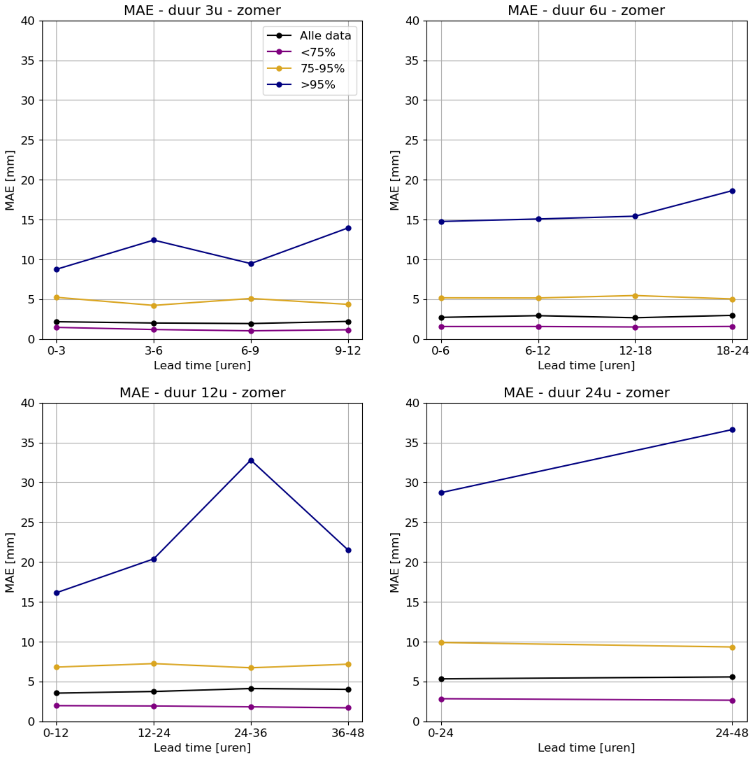




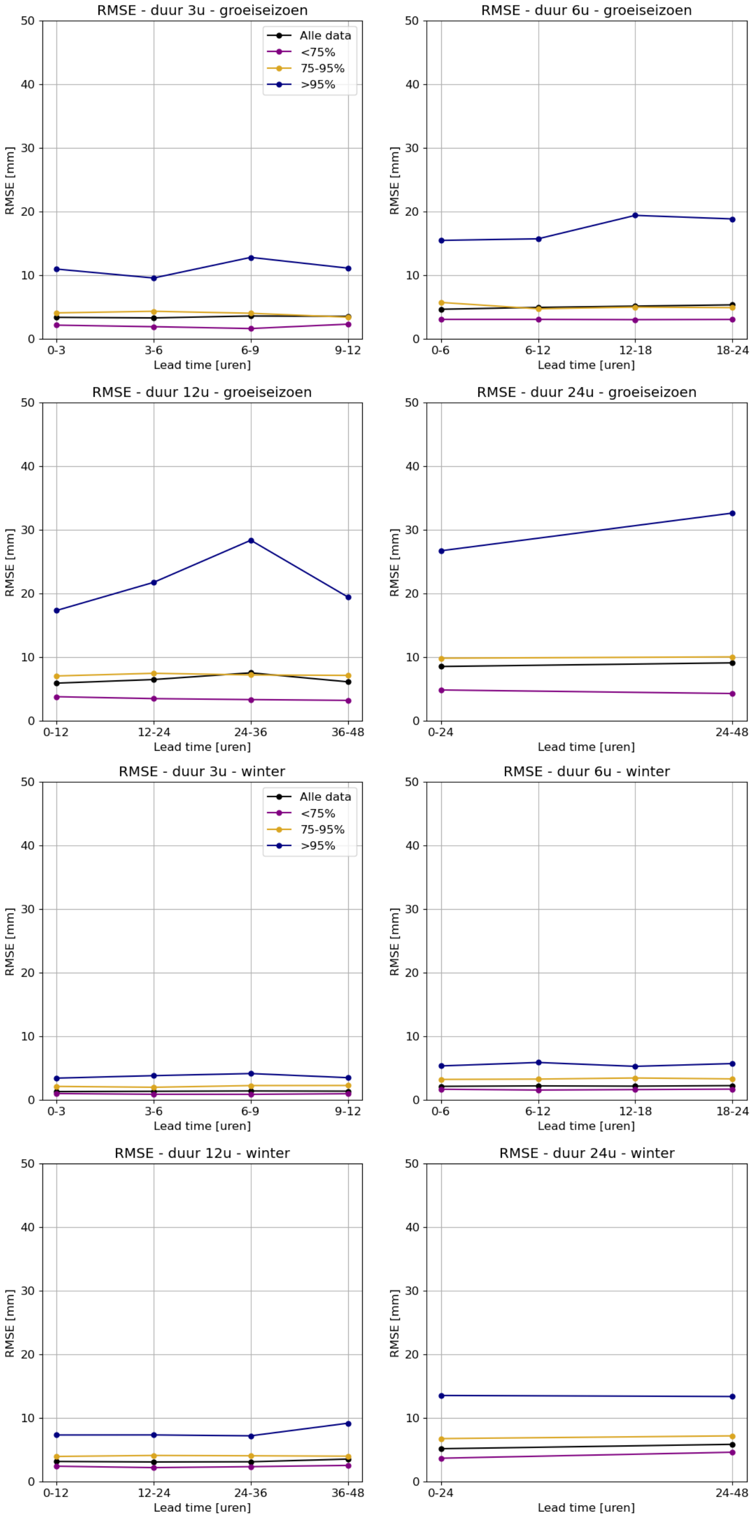


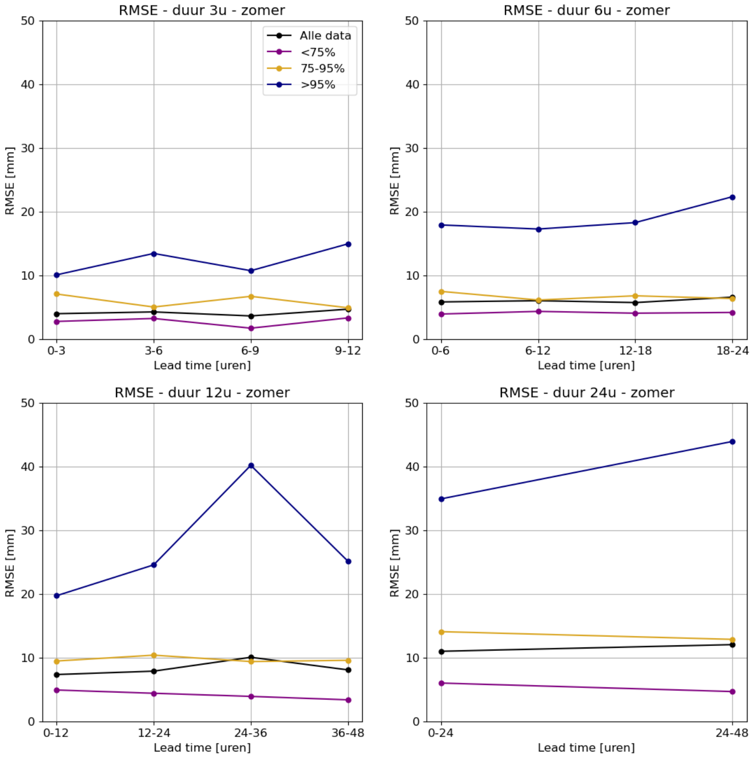
A.2.5 MAE plots




MAE - duur 3u - zomer
MAE - duur 6u - zomer
MAE - duur 12u - zomer
MAE - duur 24u - zomer
Alle data
<75%
75-95%
>95%
MAE [mm]
Lead time [uren]
0-3
3-6
6-9
9-12
0-6
6-12
12-18
18-24
0-12
12-24
24-36
36-48
0-24
24-48

A.2.6 RMSE plots





RMSE - duur 3u - zomer
RMSE - duur 6u - zomer
RMSE - duur 12u - zomer
RMSE - duur 24u - zomer
Alle data
<75%
75-95%
>95%
RMSE [mm]
Lead time [uren]
0-3
3-6
6-9
9-12
0-6
6-12
12-18
18-24
0-12
12-24
24-36
36-48
0-24
24-48