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The use of radardata in HARMONIE AROME for MetCoOp

Validation of first results

Martin Ridal and Solfrid Agersten

Front:
The radar station at Vilebo, Sweden.

MetCoOp

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and
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Summary

High resolution numerical weather prediction models are expected to perform better when high resolution observations are used in the data assimilation. In order to utilize the information from these observations, especially humidity, the model needs to be updated frequently, i.e. a short data assimilation cycle. In this report radar data is used for the numerical weather prediction model HARMONIE AROME. The model is run with a horizontal resolution of 2.5 km. From radar observations there are two parameters that can be used, reflectivity and radial winds. In the experiments presented here only reflectivity was included. The reason being that an additional quality control needed for radial winds was not available at the time of the experiments. Quality control has been shown to be very important for radar data. For reflectivity there are quality control packages available, but not for wind (at the time when this experiments were run). It was found however, that the results improved when the entire lowest scan was removed from the radar observations, which indicate that there still are unsolved issues with the data quality close to the ground. The results in the report shows that the model forecasts are improved when the model is run with a three hour data assimilation cycle, without radar data, compared to a six hour cycling. When radar reflectivity is included the three hour cycling results are further improved for most of the model variables.

Sammanfattning

Väderprognosmodeller med hög horisontell upplösning förväntas ge bättre resultat när högupplösta observationer används i dataassimilationen. För att bättre utnyttja dessa observationer, speciellt fuktighet, behöver modellen täta uppdateringar, dvs en relativt kort assimilationscykel. I den här rapporten beskrivs hur radardata används i väderprognosmodellen HARMONIE AROME. Modellen körs med en horisontell upplösning på 2.5 km. Från radarobservationer kan två parameterar användas, reflektivitet och radiell vind. I experimenten som presenteras här används bara reflektivitet. Anledningen till det är att för vind behövs en extra kvalitetskontroll som inte fanns tillgänglig vid tiden för experimentkörningarna. Det har visats att kvalitetskontroll är väldigt viktigt för radarobservationer. För reflektivitet finns det bra kvalitetskontroller tillgängliga. Det visade sig dock att resultaten blev bättre då hela det lägsta svepet plockades bort vilket tyder på att det fortfarande finns störningar som slinker igenom kvalitetskotrollen nära marken. Rapporten visar att prognoskvaliteten förbättras då modellen körs med en tre-timmars assimilationscykel jämfört med en sex-timmarscykel, även utan radardata. När sedan reflektivitet från radarobservationer adderades förbättrades resultaten ytterligare för de flesta prognostiska parametrarna.

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1 Introduction

MetCoOp (Meteorological Co-operation on numerical weather prediction) is a project where the Norwegian Meteorological Institute and Swedish Meteorological and Hydrological Institute (SMHI) co-operate in order to have a common production of numerical weather prediction (NWP). The goal is to produce and deliver the best short range numerical weather forecasts for a common domain. In 2011 it was decided that the co-operation should focus on the non-hydrostatic HARMONIE model with high resolution (2.5 km) and with AROME physics (General description by Driesenaar [1]). The model version used in the MetCoOp project is described and verified against other models in a first verification report “Verification study. HARMONIE AROME compared with HIRLAM, UM and ECMWF”, 01/2012 METCOOP MEMO (Køltzow et.al [2]).

As model resolution increases the demand for high resolution observations increases. In order to deliver “the best short range numerical weather forecasts” it is necessary to include high resolution observations such as radar data, satellite observations or ground based GNSS data. The impact of these observations on the initial condition of the model forecast is expected to be significant in high resolution models. To utilize the benefit of these observations it is necessary to update the model frequently. Experiments run with three our cycling are expected to have a positive effect on the results.

It is also important that the new observations are made at high altitudes since, up until recently, the only source has been radiosondes and to some degree aircraft measurements. With three hour cycling there will be more analysis times without radiosondes and also less aircraft measurements especially during the night.

In this report the focus is on use of radar observations. Both Sweden and Norway have radar networks that cover their respective countries. By using volume data, i.e. data from each elevation angle from every radar, a three dimensional coverage of a large part of the model domain is obtained. This will give a much better spatial and temporal coverage than radiosoundings and aircraft data that until now have been the only upper air measurements.

The results from the experiments performed are presented using verification scores described in the first MetCoOp verification report (Køltzow et.al [2]). These are commonly used standard scores.

In section 2 the experiments using a rapid update cycling (three hours) are described and evaluated. Section 3 describes the radar data used and how it is quality controlled, while section 4 gives a more detailed description of retrieval of the humidity profile from the simulated reflectivities. The results from the verifications are presented in section 5 and finally, section 6, concludes the findings in this study.

2 Rapid update cycling (RUC)

Mesoscale non-hydrostatic models are more or less designed for rapid updates and shorter forecasts compared to hydrostatic synoptic scale models. In order to utilize the full potential of high resolution observations in the model experiments need to be run with a more frequent updating (assimilation) cycle than for the synoptic scale observations. Moisture is especially important because of the development of clouds and convective processes in the model. These are rather rapid processes and the models tend to create its own moisture fields. Therefore it is important with rapid updates of the model using moisture observations through data assimilation in order to create realistic analysis as often as possible. In this study experiments was run with a three hour assimilation cycle which is referred to as RUC even though this terminology may also be used for even higher updating frequency e.g. one hour cycling. RUC will update the model frequently and thereby keep the information from the observations fresh in the model.

If the model is run with a rapid update cycling using only conventional observations it might be expected that the RUC experiment would perform worse than a similar experiment using six hour update cycling due to fewer observations in the intermediate analysis times (03, 09, 15 and 21). However, as the majority of observations today are automatic there is no big difference between the number of observations for the different hours during the day. The only noticeable difference is that there are somewhat less aircraft observations during the night and more analysis times without radiosonde observations in the RUC cases. This might have an effect on high altitudes.

To investigate the effect of the RUC itself, a reference experiment using only conventional observations (no radar data) with three hour cycling was compared to a reference experiment with six hour cycling. Every six hours a longer forecast was made, up to 30 hours, while for the intermediate analysis times only a three hour forecast was made in order to feed the data assimilation.

2.1 Results

Some examples of results from the experiments are presented in Figures 1-3, where Figure 1 shows the vertical profiles for temperature (upper) and relative humidity (lower). Figure 2 shows the temperature at 925 (upper) and 500 (lower) hPa and Figure 3 shows relative humidity at 925 (upper) and 500 (lower) hPa. Compared to the experiments using six hour cycling, the RUC experiments show very good results (also for parameters not shown). Almost all scores show improvements with 3 hour cycling, except at 500 hPa. This may be connected to the relatively fewer observations from radiosondes.
For more verification results from this study, see:
http://metcoop.met.no/verif/201108_37h11_3hcy_vs_6hcy_export/ (internal link for SMHI and MET Norway)

3 Radar data

From radar observations there are two parameters that can be used for data assimilation in NWP models, radial velocity and reflectivity. The radial velocity is obtained from the motion of the echoes by measuring the Doppler shift in the sent and received signals. This yields a measure of how fast the hydro-meteors (or other meteors) are moving towards or away from the radar which is translated into wind observations. The reflectivity is the radar echo that is returned from any object in the line of sight of the radar beam. These objects are in most cases precipitation but it can also be reflected by birds or insects. If the radar beam hits the ground or a mountain it can also be returned as a “false” echo.

Quality control of the data is therefore an important issue. The radar data must be quality controlled before it is introduced into the model system in order to remove any non-precipitating echoes such as echoes due to ground or sea clutter, birds and insects or other anomalous echoes. In the HARMONIE assimilation system all observations that are identified as “false” echoes are removed in the reading of the data. The only identification (or classification) of reflectivity observations after the data has entered the model is clear sky or rain.

For the radial wind, aliasing effects can be seen if the wind speed is high enough for the wind to pass over two observation points (range bins) between two observations. The effect can be seen as sudden changes in the wind direction or just erroneous wind strength. It is therefore important to do a de-aliasing of the wind data. In this study no de-aliasing of the radial wind was made since it was not available in the quality control packages at the time. In later versions however, the possibility to do de-aliasing is available and will be included in experiments run for other periods with higher wind speeds.

The radar observations in this study have been introduced into the HARMONIE model system in addition to the conventional observations. Radar data from both Swedish and Norwegian radars have been used together. From almost all radars both radial winds and reflectivity is provided. Quality controls are applied, described in the following sections, but it was discovered that the lowest elevations still contained false echoes. It is also possible that removed false observations, e.g. from a mountain, is interpreted as an observation of “no precipitation” and used as a clear sky echo. In the assimilation experiments presented below the lowest elevation was therefore removed completely for all radars. By doing so we lost good observations, but that is better compared to assimilating false observations.

Radar data from both countries were provided in polar coordinates. This means that one dimension is azimuth angle and the other is range bins away from the radar. The horizontal resolution of the range bins can be different, both between the different radars but also for different elevation angles.

3.1 The Swedish radar network – SWERAD

The Swedish radar network consists of 12 C-band radars. These are evenly distributed to get an almost complete coverage of the whole country.

The Swedish radars have a different scan strategy depending on elevation angle. The lowest three angles, 0.5, 1.0 and 2.0 degrees, measure with a horizontal resolution of 2 km away from the radar. For higher elevation angles the horizontal resolution is 1 km but the number of measurements is still the same. This means that the higher elevations will not reach as far from the radar as the lower elevations.

3.1.1 The BALTRAD toolbox

The Swedish radar data were quality controlled using the BALTRAD toolbox. BALTRAD is the official software provided in the EUMETNET programme OPERA (Operational Programme for the Exchange of weather RAdar information). The BALTRAD toolbox contains various quality indicators that can be flagged or removed from the dataset. The toolbox is described in detail and evaluated in Michelson and Henja (2012) [3].

The quality indicators used for the Swedish radars were ground clutter, biometeors, emitters and specks. The latter means different local anomalies.

An example of the anomaly removal is shown in Figure 4, where the upper panel shows the raw observation and the lower panel the quality controlled observation. The data shown is the lowest elevation of the radar in Hudiksvall in Sweden from 20110820 at 1800. Many weak isolated echoes were removed but also the edges of the larger precipitation patterns were made sharper.

Another example is shown in Figure 5 which demonstrates the importance of quality control in a case where there was very little precipitation. This shows the radar in Vara, Sweden for the same date as in Figure 4. There are many anomalies close to the radar that were removed correctly by the quality control.

3.2 The Norwegian radar network

The Norwegian radar network consisted of 8 C-band radars at the time of the experiment period. It has since then been extended with one radar and yet one more is planned in 2014. They are mostly placed along the coast of Norway but give a good coverage of the country.

The radar data output is of very high horizontal resolution. The reflectivity output is in bins of 250 metres while for radial winds the resolution is 130 metres. This causes problems with memory in the assimilation as well as being very time consuming. A pre-thinning of the data was therefore needed. For this study a simple thinning was made to reduce the number of measurement points to a resolution close to the resolution of the Swedish radars, i.e. ~2 km for reflectivity and around 1 km for radial winds (not used). Since the assimilation process also reduces the data it is assumed that not much information was lost through this thinning procedure.

3.2.1 The PRORAD quality control

The radar data from the Norwegian radar network are quality controlled using the PRORAD software, for more information see Elo [5]. The quality indicators used today are ground- and sea-clutter as well as an indicator for other not as specific clutter, corresponding to specks in the BALTRAD toolbox. This software is developed in Norway and produces XML files containing reflectivity and quality flags. The PRORAD XML format was converted to BUFR-files which is one of the formats that can be read by the assimilation software in HARMONIE. More about the conversion software and the dataflow can be found in Grønsleth and Randriamampianina [6].

4 Experiments and methodology

4.1 Experiments

In this study HARMONIE AROME with cycle 37h1.1 was used for the summer 2011 period described in Køltzow et.al [2]. The model was run over the MetCoOp domain (indicated by the border in Figure 10) with a 2.5 km horizontal resolution and 65 vertical levels. The model uses a three dimensional variational (3D-Var) data assimilation scheme to create an analysis as close to the true atmospheric state as possible. All experiments included the so-called conventional observations such as synop stations, ships, radiosondes and aircraft observations. In addition radar observations of reflectivity were added. No satellite data was used for this study.

4.2 Reflectivity and humidity pseudo observations

The reflectivity itself is used to get a measure of the precipitation intensity and to analyse where the precipitation is located. An observation of reflectivity will moisten the model where it has no precipitation or adjust the intensity in precipitation areas. Observations of “no echoes” are equally important to dry the model in areas where the model indicates precipitation while the radar does not see any echoes. The reflectivity is not directly assimilated into the model since there is a complicated, non-linear relation between the model variables and reflectivity. This includes micro physical parameters and non-Gaussian error distributions. Instead a vertical moisture profile is retrieved through a one-dimensional Bayesian retrieval from simulated reflectivities. This humidity profile is then used in the 3D-Var assimilation scheme. The method is described in detail in Caumont et. al (2007) [4].

In the case where there is precipitation both in the model and in the radar observations (H for Hit, see Figure 6) the model performs a one-dimensional humidity retrieval. The model simulates radar reflectivities in a number of grid points surrounding the observation using the microphysics of the model. It then calculates weights for each grid point by comparing simulated reflectivity to the observed reflectivity. These weights are then used to calculate a humidity observation from the same model grid points at the point of the observation. A pseudo observation of humidity is created.

The model also creates pseudo observations of humidity for the two special cases F (false alarm) and M (misses), as seen from Figure 6. In the false alarm case there are no observations of precipitation in the radar data but the model indicates precipitation (F). The number of surrounding grid points will in this case be increased and the humidity is calculated using only grid points without precipitation in the model, leading to a pseudo observation with humidity lower than 100%.

If the model is dry while there is precipitation in the radar observations (M), the humidity is set to 100%.

In the case where there is no observed precipitation and no precipitation in the model (Z for Zero in Figure 6), nothing is done.

4.3 Results

In Figure 7 a comparison, between the simulated, i.e. first guess and the observed reflectivities, is shown. The upper panel shows all incoming observations, while the lower panel shows what is left after the screening and thinning. It can be seen that there is an even distribution of observed and simulated values and that many cases of strange observations and/or simulated values was removed in the screening. It is also clear that there are two special cases (F and M): The first is observed values at -10.5 dBz, which is the minimum value that can be represented in the BUFR-files containing the radar observations, i.e. the case where there is no observed reflectivity although there is precipitation in the model (M). These cases will dry the model. The second special case, where there is no precipitation in the model but there are observed reflectivities (F), appear as a straight line of modelled reflectivity of -120 dBz. This is just an arbitrary value set to represent no precipitation in the model.

Figure 8, upper panel, shows the corresponding pseudo observation of relative humidity. These observations correspond to the lower panel of Figure 7. An even distribution with concentrations around the value one (both axis) is seen here. This represents no precipitation in the model (M) or in the observations (F). There was thus both a moistening and a drying of the model from the radar observations for this particular case. In the lower panel the same observations are compared to the resulting analysis (see section 5.1 and Figure 11) and it shows that even if there still is a spread it is more centred along the one to one line. This means that the model did take these observations into account.

Another way to visualize this is presented in Figure 9. The upper panel shows the observed reflectivities for the second lowest elevation that enters the model and the lower panel shows the corresponding pseudo humidity observations. In the example shown here, from 20110819_06, there was a precipitation system moving from south to north. The NWP forecast moved the precipitation a bit too fast compared to the observations. This is seen as a drying in the northern part of the system, i.e. the humidity pseudo observations are less than 1 (100%). For comparison, the model field of precipitation valid at the same time, is shown in Figure 10 where it can be seen that the model precipitation is located further north compared to the observed reflectivity (upper panel of Figure 9).

This case illustrates the importance of assimilating data where the radar measures “no precipitation”, i.e. a good measurement without reflected echoes. There is thus a need for a good quality control as well as knowledge about the surrounding terrain in order to treat a mountain or building as a blocked area without observations.

5 Verification results

Two types of experiments have been run to present results from the radar data assimilation, to:

1. investigate the impact on the analysis: Short experiments for only one assimilation cycle to compare analysis with or without radardata assimilation
2. investigate the impact on the forecasts: Running the model experiment for a longer period to verify the forecasts against observations.

5.1 Impact on the analysis

To investigate the impact the radar data gives on the resulting analysis an experiment with only one assimilation cycle was run. By doing so two runs with the same start value can be compared; one reference experiment using only conventional observations and one experiment using radar observations in addition to the conventional observations.

Figure 11 shows the difference between an analysis including radar reflectivities and the analysis from the reference. The date and time is the same as for the examples in section 4, i.e. the resulting analysis including radar data used the observations presented in Figures 7 to 9. The plotted field is humidity at level 55, i.e. rather close to the ground. The reason for displaying such a low level is to make it comparable to the reflectivity and humidity for the second lowest radar elevation angle shown in the previous figures. For the precipitation in southern Sweden there appears to be a drying of the model (dashed lines) in the northern part, i.e. the front of the precipitation system. In the southern part of the system there is instead an increase in the humidity (solid lines). This is in agreement with what can be expected from the figures seen in section 4.

5.2 Verification

To verify the results when using radar data as an additional observation type over a longer period the HARMONIE AROME model was run for the so called summer period (Køltzow et.al [2]), 11-23 August 2011. In the verification the first two days are excluded to allow for some spinup time for the model.

All experiments are run with three hour cycling since this gave better results as shown in section 2, but also since the model needs to be updated frequently to utilize the full potential of radar data. At the analysis times 00, 06, 12 and 18 forecasts was run up to 30 hours lead time and for the intermediate times only a short 3 hour forecast was run to create a new analysis.

5.2.1 Radar reflectivity

In Figures 12-14 the same verification as in Figures 1-3 is shown but with the radar reflectivity experiment included. The pressure level displayed is 850 hPa. The reason for this is that the lowest elevation was excluded in the radar data. In these figures the six hour cycling experiment is presented in blue, the RUC reference run is in red and the RUC experiment including radar reflectivities is presented in green.

It can be seen that the impact is fairly small but in most cases positive. The strongest impact can be seen around 500 hPa which is the region where there was a clear negative impact of three hour cycling compared to six hour cycling. This indicates that the radar data compensated for the lack of high altitude observations and improved the forecasts in the area where this was a problem.

The RUC reference experiment shows improvement compared to the six hour cycling experiment in both Sweden and Norway, but when adding radar data there are differences. The Kuiper skill score (for more information about the verification scores, see Køltzow et.al [2]) for precipitation indicates that in Sweden (Figure 15 upper panel) there is a neutral or a slightly positive improvement when adding radar data. In Norway on the other hand (Figure 15 lower panel) the Kuiper Skill score shows lower scores (worse result) when radar data is added compared to the reference run (for thresholds above 0.5 mm). The model benefits from more rapid updates, but the model experiences problems when including radar data. The reason for this could be due to the more complex terrain in Norway, and to the interpretation of the data and different quality flags such as beam blockage etc. This needs to be investigated further.

5.2.2 Radar reflectivity and radial winds combined

Adding the radial wind data in the assimilation did not add any skill to the forecasts at this time (tested but not shown). Before including the radial winds a good quality check, including de-aliasing, needs to be performed. Until this is done it is very hard to draw any conclusions since assimilating wrong data will have randomly positive or negative effect.

6 Conclusions

Mesoscale models need to be updated with high resolution observations and these updates must be made frequently in time in order to give good results. The results from the experiments in this report confirm that three hourly cycling gives better results than six hourly cycling, and that assimilation of radar observations in addition to the conventional observations shows improvement compared to the experiments without radar data. For most of the model variables the adding of radar reflectivities resulted in a positive impact. The magnitude of the impact varied of course between variables and altitude. The biggest difference was seen where the reference RUC experiment using only conventional observations experienced problems at high altitudes, around 500 hPa. Since there are more analyses made without observations from radiosondes, and to some extent aircraft data, in the reference RUC experiment, the RUC with radar reflectivity gave better results in this area.

There were also some regional differences between Sweden and Norway. A slightly negative impact can be found in Norway for some cases when adding radar data. That might be explained by the more complex terrain in Norway. There is thus a greater need for correct treatment of the radar data in such areas. The results of the radar data assimilation has shown to be very sensitive to the quality of the data. For the experiments in this report for example, the entire lowest elevation for all radars was excluded. For specific radars it might even be necessary to exclude the two lowest elevations but this need to be investigated further.

No verification results for forecasts where the experiment also includes radial winds in the assimilation are presented here. The reason is that there was no good quality control for radial winds available at the time the experiments were made. For radial winds there is especially a need to do de-aliasing of the radial wind before using it. In future versions of the BALTRAD toolbox this quality control method will be included. New experiments will be run for another period which includes strong winds.

7 References

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8 Figures and tables

Figure 1. RMSE and BIAS for an experiment using three hour cycling (red) and an experiment using six hour cycling (green). Upper panel shows vertical profile of temperature and the lower panel shows relative humidity.

Figure 2. RMSE and BIAS for the same experiments as in Figure 1 using three hour cycling (red) and six hour cycling (green). The upper panel shows temperature at 925 hPa and the lower panel shows temperature at 500 hPa as a function of forecast length.

Figure 3. Same as Figure 2 but for relative humidity

Figure 4. Radar reflectivities from the lowest elevation of the radar in Hudiskvall, Sweden. Upper panel shows the original echoes and the lower panel shows the resulting reflectivities after quality control using the BALTRAD toolbox.

Figure 5. Same as Figure 4 but for the radar in Vara, Sweden.

Figure 6.The four cases of moisture assimilation. F is when the model indicates precipitation but there is no corresponding observation, while M is the other way around. For case H there are precipitation in both model and observations while for Z there is no precipitation in either one.

Figure 7. Observed reflectivites compared to reflectivites simulated by the model. Upper panel shows all observations entering the model, while the lower panel shows the observations that is actually used in the minimisation, i.e. what is left after the screening and thinning.

Figure 8. Upper panel: Pseudo observations of humidity corresponding to the reflectivity observations in the lower panel of Figure 7. The lower panel shows the same observations but compared to the resulting analysis.

Figure 9. Upper panel shows observed reflectivity in dBz at 20110819_06 and the lower panel shows the corresponding retrieved pseudo observation of relative humidity.

Figure 10. Model precipitation from a six hour forecast valid at 20110819_06 (the same time as in Figure 9) .

Figure 11. Difference between the analysis including radar reflectivities and the analysis without, for the same time as Figure 10, at 0110819_06. The displayed field is specific humidity at level 55, solid line means adding humidity, and dash-dotted means removing humidity

Figure 12. RMSE and BIAS for two experiment without radar using three hour cycling (green) and six hour cycling (blue). The red line represents an experiment with radar reflectivity included. Upper panel shows vertical profile of temperature and the lower panel shows relative humidity. The two experiments without radar are the same as in Figure 1.

Figure 13. RMSE and BIAS for temperature at 850 hPa (upper panel) and 500 hPa (lower panel). The two experiments without radar (three hour cycling in green and six hour cycling in blue) are the same as in Figure 2. The red line represents an experiment with radar reflectivity included..

Figure 14. The same as in Figure 13, but for relative humidity.

Figure 15. Kuiper skill score for two experiments without radar; three hour cycling (green) and six hour cycling (blue) and one experiment using three hour cycling with radar reflectivity included (red). Verification against Swedish stations are shown in the upper panel and against Norwegian stations in the lower panel.

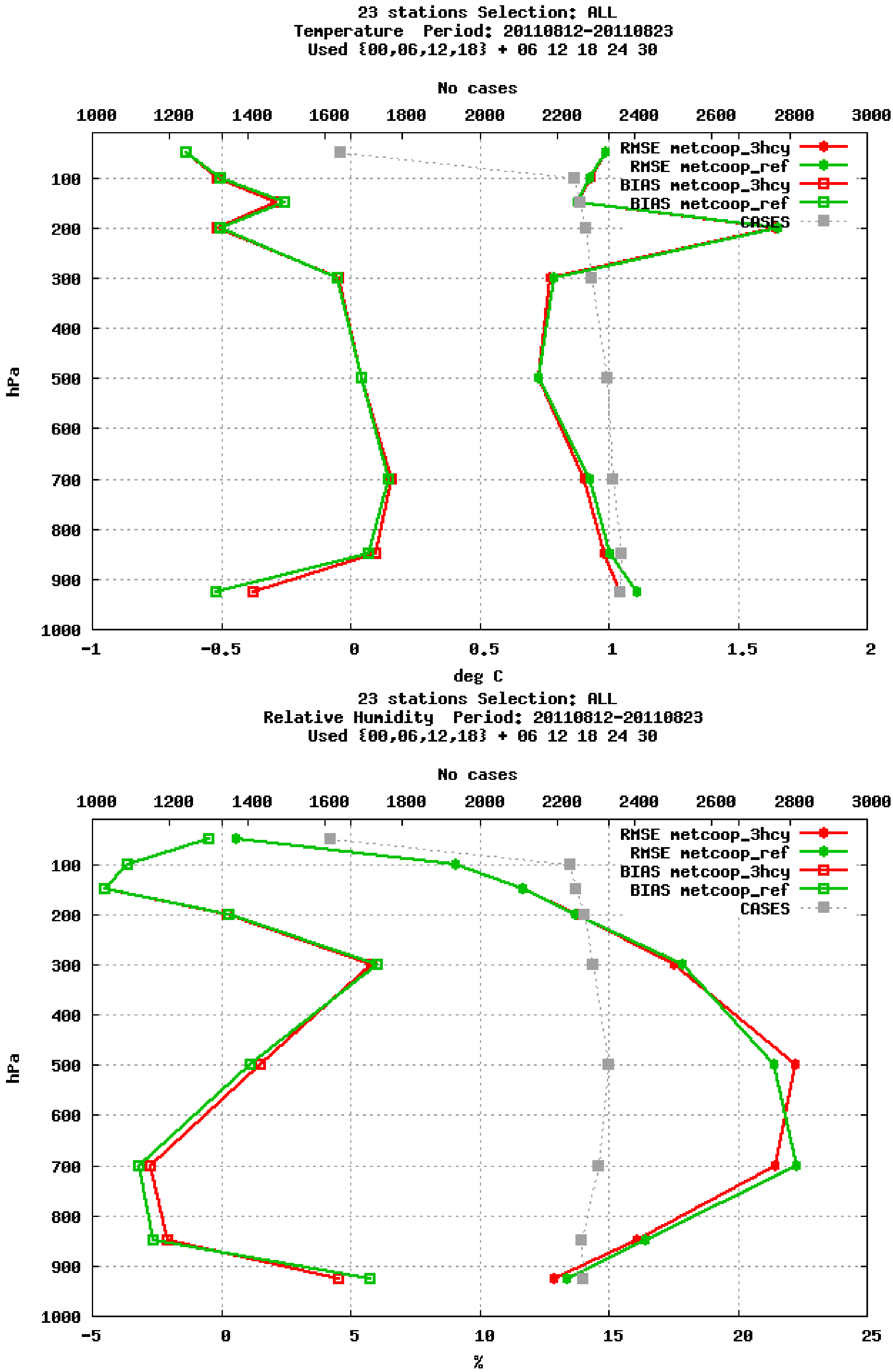


Figure 1. RMSE and BIAS for an experiment using three hour cycling (red) and an experiment using six hour cycling (green). Upper panel shows vertical profile of temperature and the lower panel shows relative humidity.

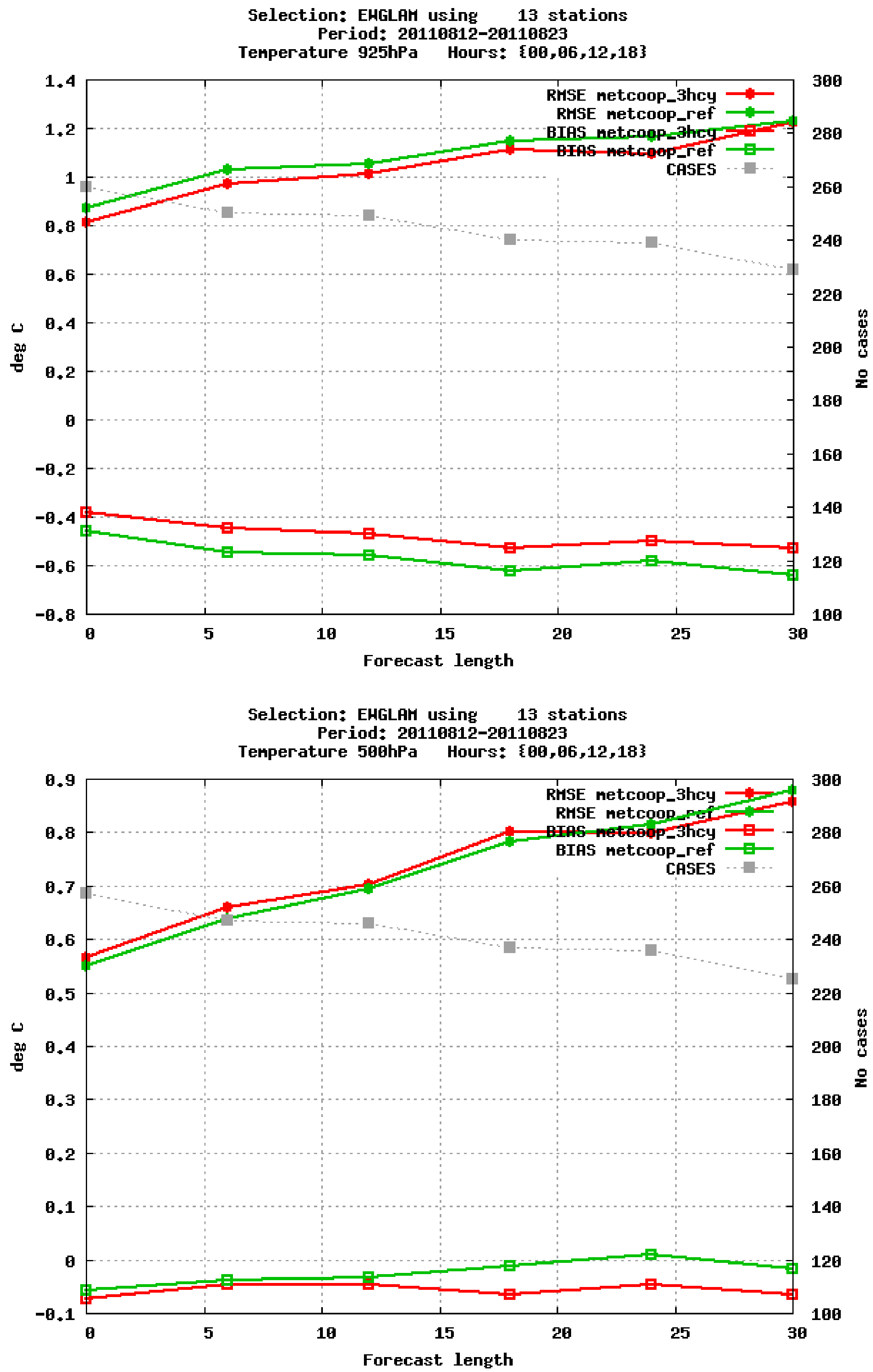
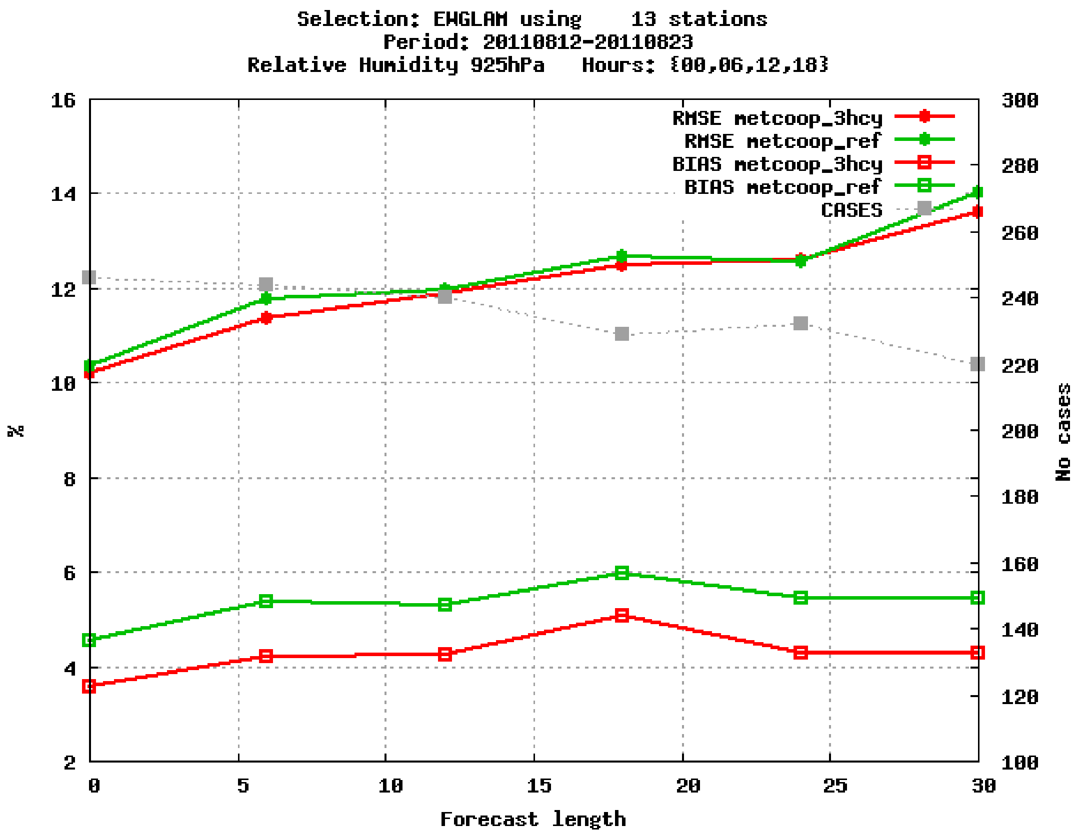


Figure 2. RMSE and BIAS for the same experiments as in Figure 1 using three hour cycling (red) and six hour cycling (green). The upper panel shows temperature at 925 hPa and the lower panel shows temperature at 500 hPa as a function of forecast length.



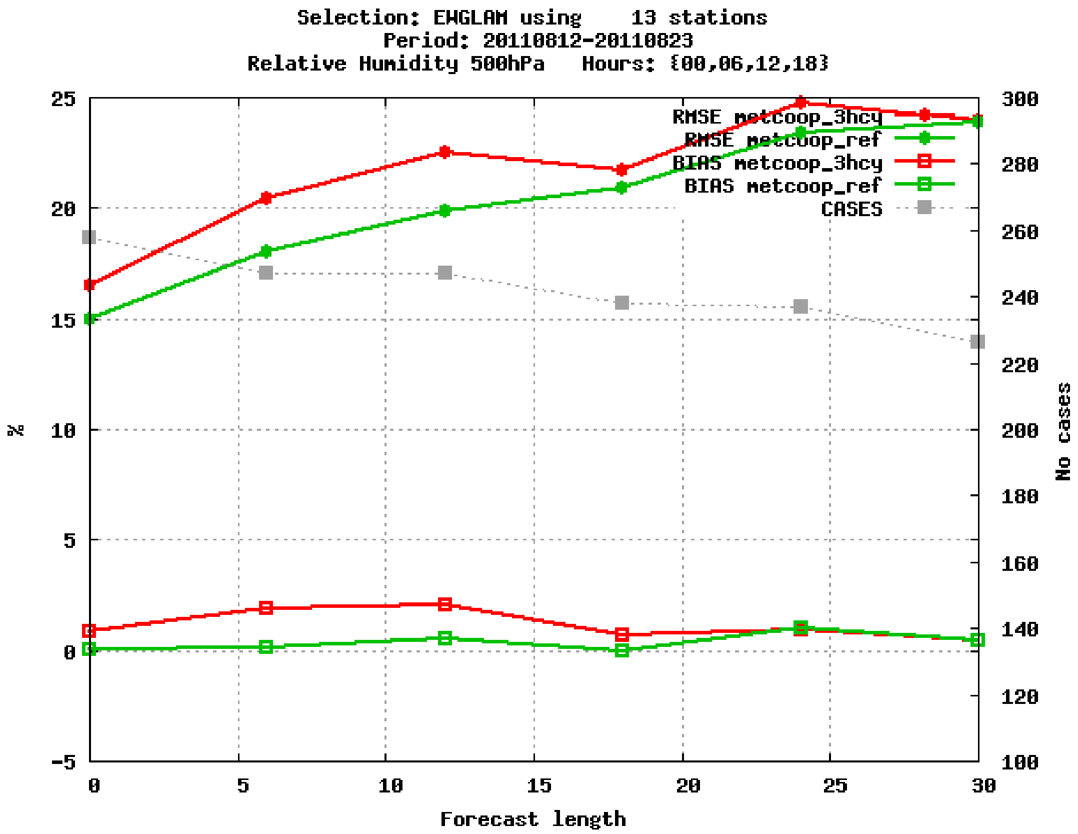


Figure 3. Same as Figure 2 but for relative humidity

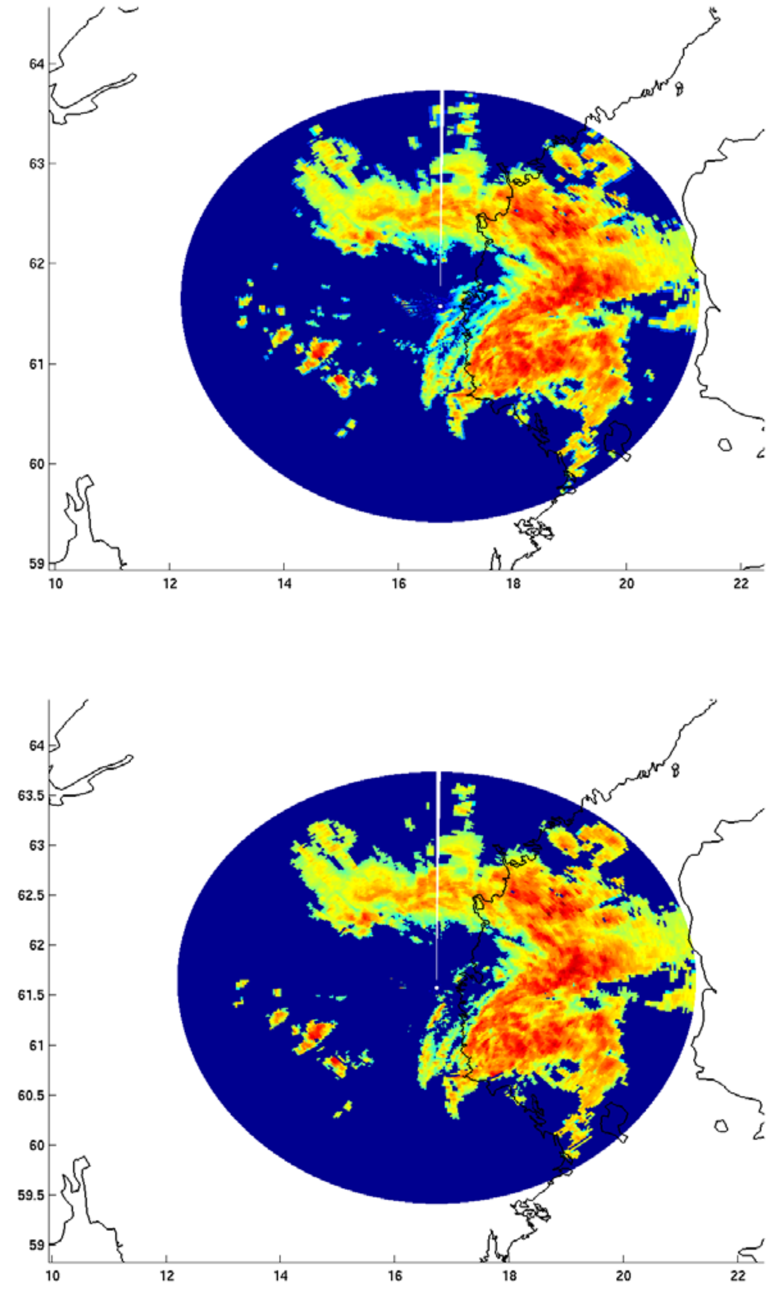


Figure 4. Radar reflectivities from the lowest elevation of the radar in Hudiskvall, Sweden. Upper panel shows the original echoes and the lower panel shows the resulting reflectivities after quality control using the BALTRAD toolbox.

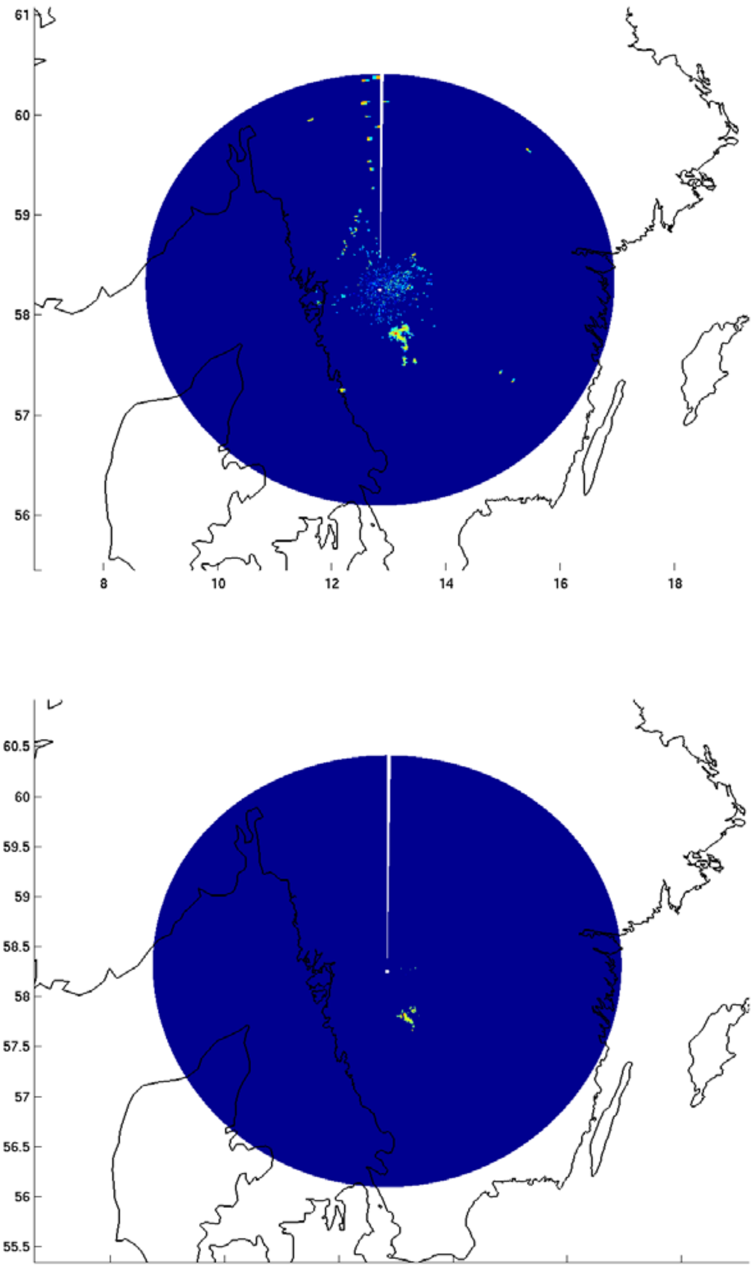


Figure 5. Same as Figure 4 but for the radar in Vara, Sweden.

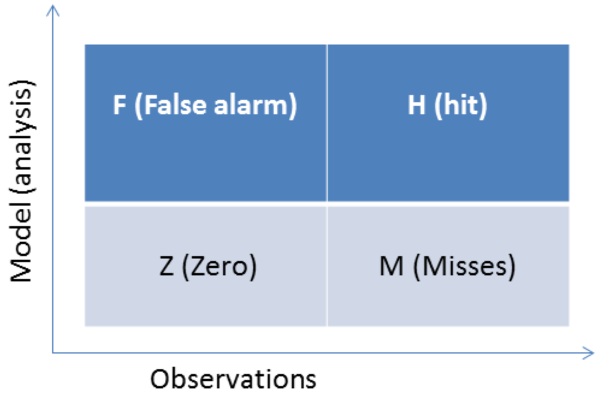


Figure 6.The four cases of moisture assimilation. F is when the model indicates precipitation but there is no corresponding observation, while M is the other way around. For case H there are precipitation in both model and observations while for Z there is no precipitation in either one.

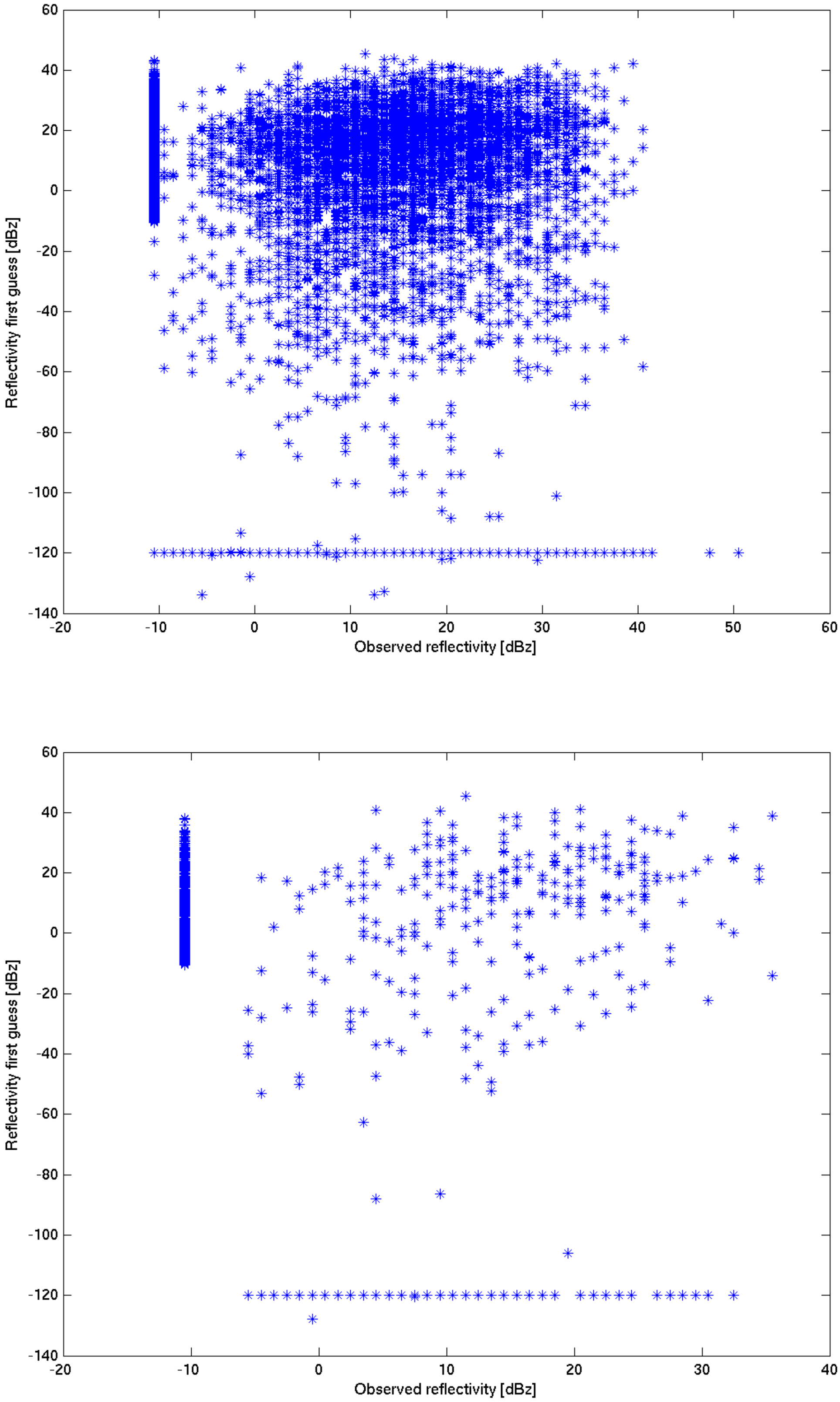


Figure 7. Observed reflectivites compared to reflectivites simulated by the model. Upper panel shows all observations entering the model, while the lower panel shows the observations that is actually used in the minimisation, i.e. what is left after the screening and thinning.

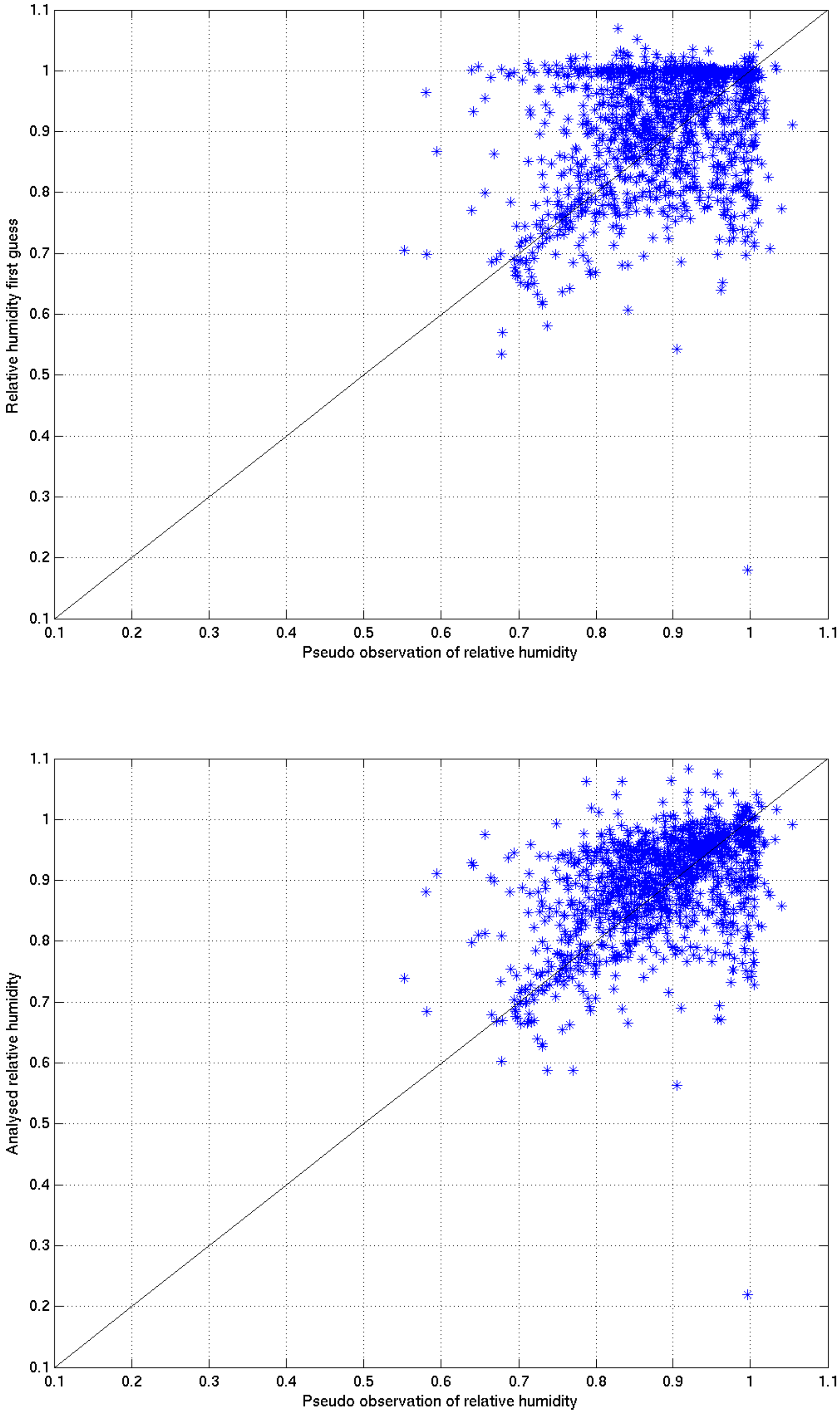
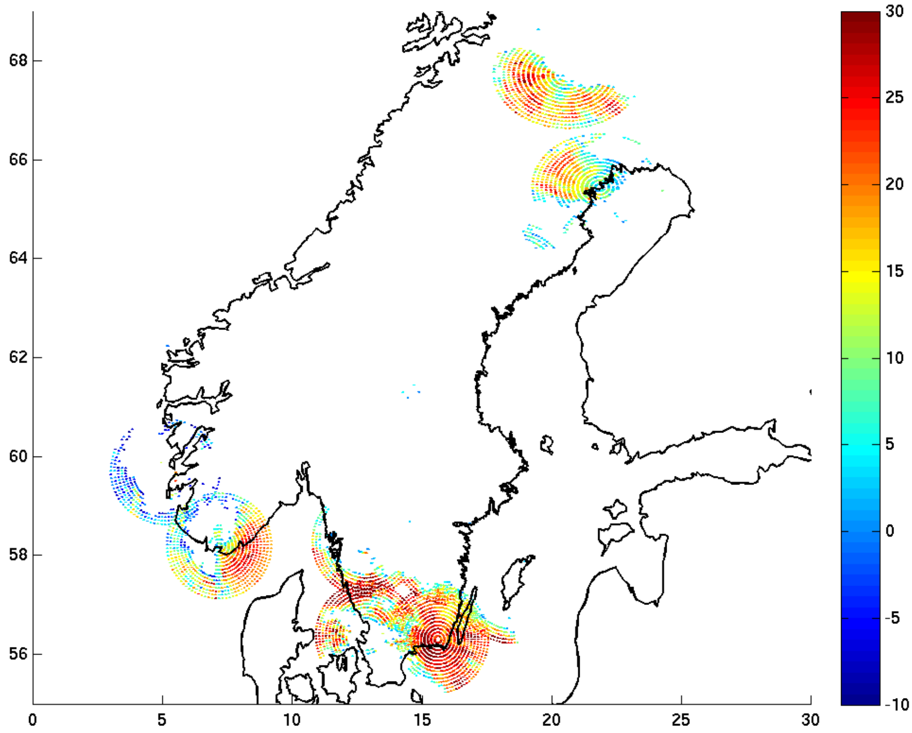


Figure 8. Upper panel: Pseudo observations of humidity corresponding to the reflectivity observations in the lower panel of Figure 7. The lower panel shows the same observations but compared to the resulting analysis.



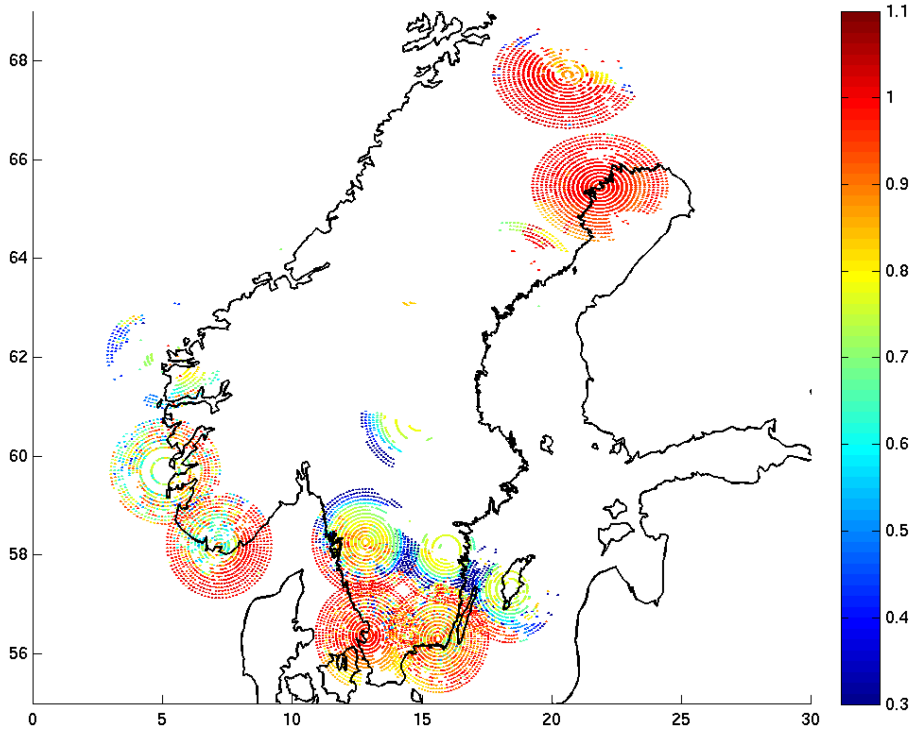


Figure 9. Upper panel shows observed reflectivity in dBz at 20110819_06 and the lower panel shows the corresponding retrieved pseudo observation of relative humidity.

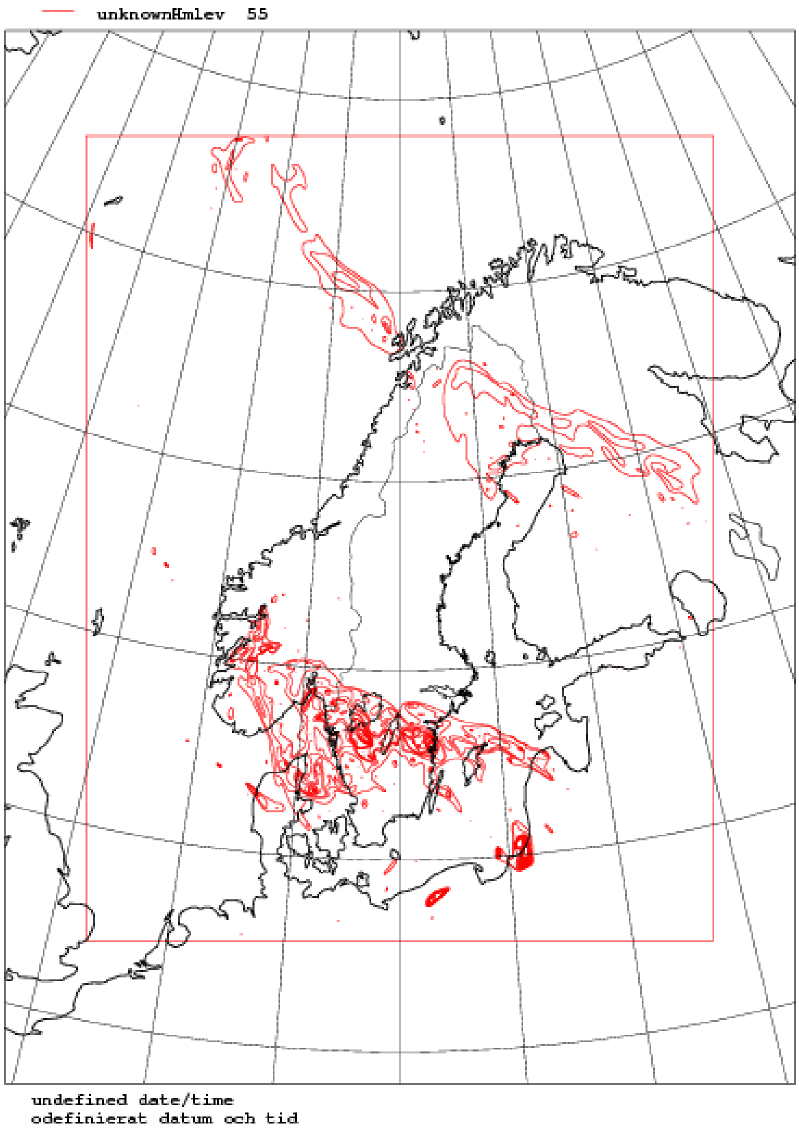


Figure 10. Model precipitation from a six hour forecast valid at 20110819_06 (the same time as in Figure 9) .

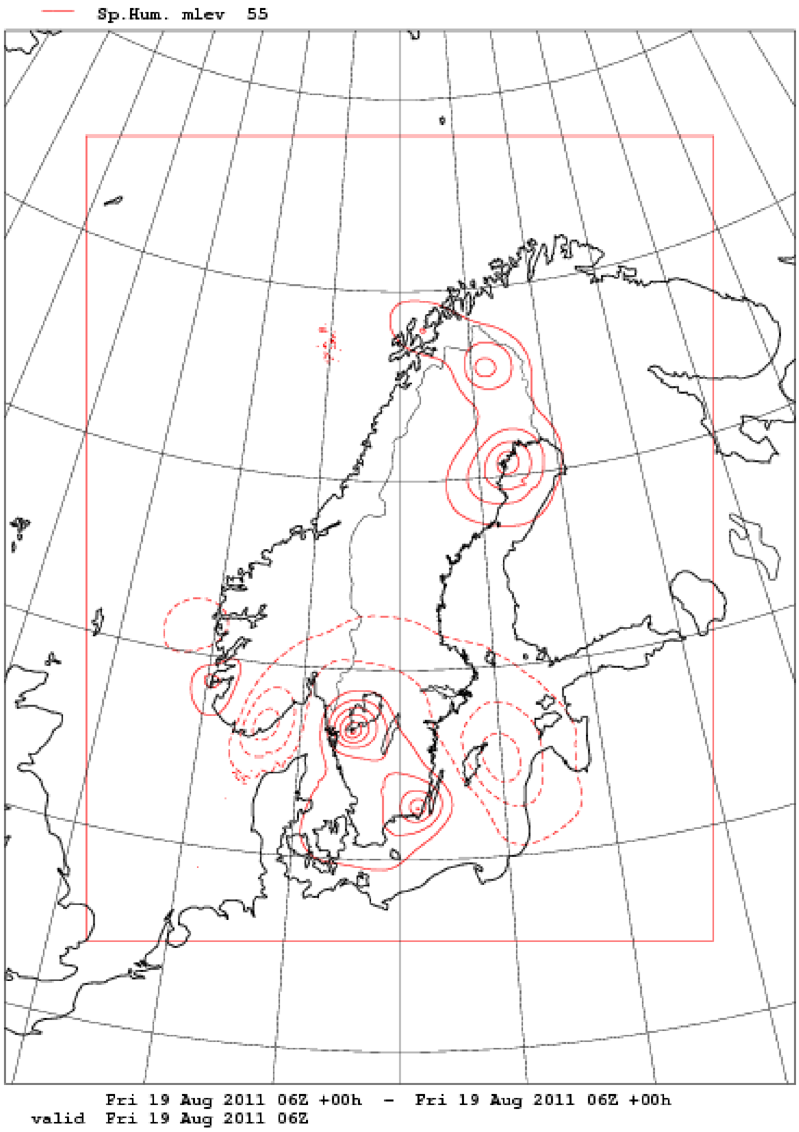
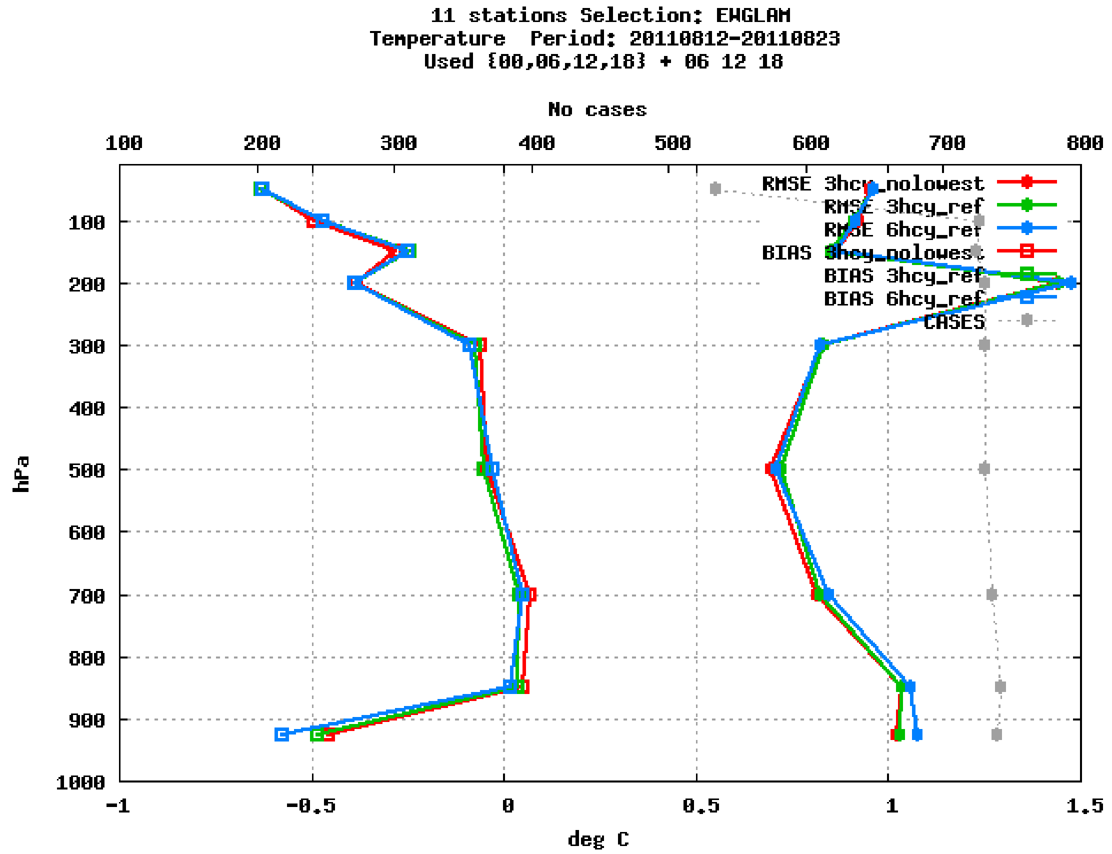


Figure 11. Difference between the analysis including radar reflectivities and the analysis without, for the same time as Figure 10, at 0110819_06. The displayed field is specific humidity at level 55, solid line means adding humidity, and dash-dotted means removing humidity



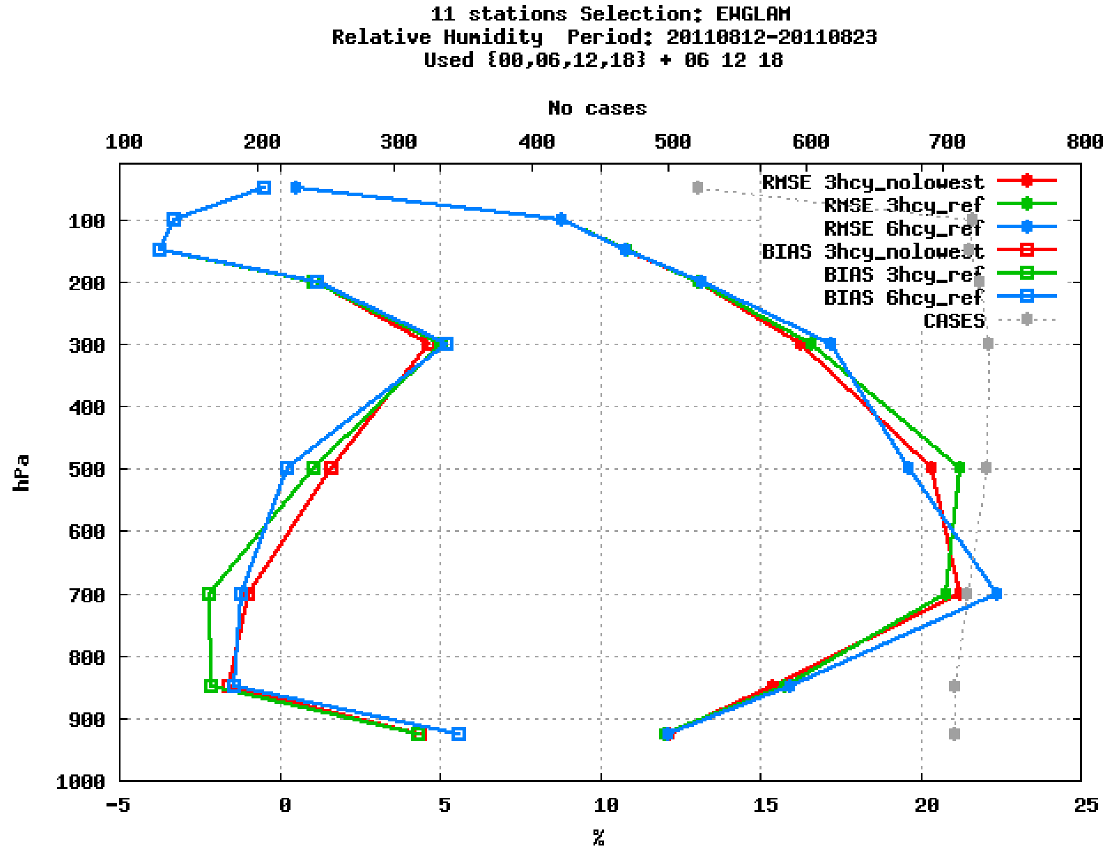
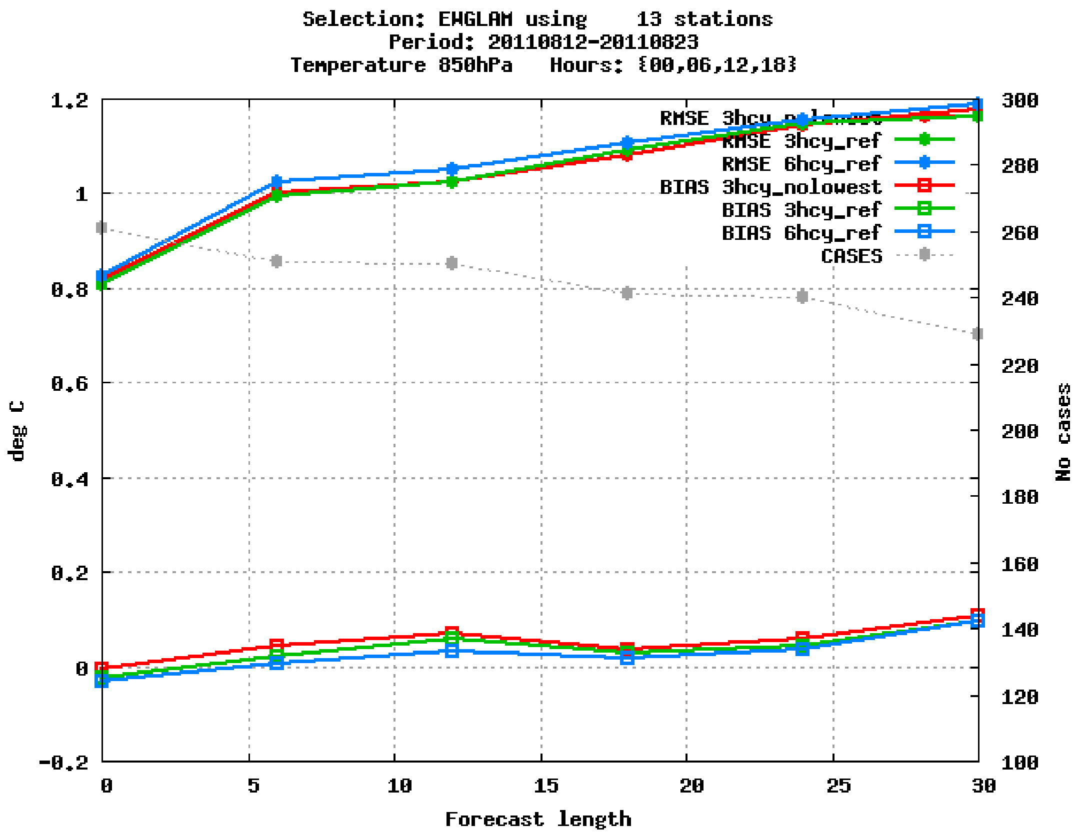


Figure 12. RMSE and BIAS for two experiment without radar using three hour cycling (green) and six hour cycling (blue). The red line represents an experiment with radar reflectivity included. Upper panel shows vertical profile of temperature and the lower panel shows relative humidity. The two experiments without radar are the same as in Figure 1.



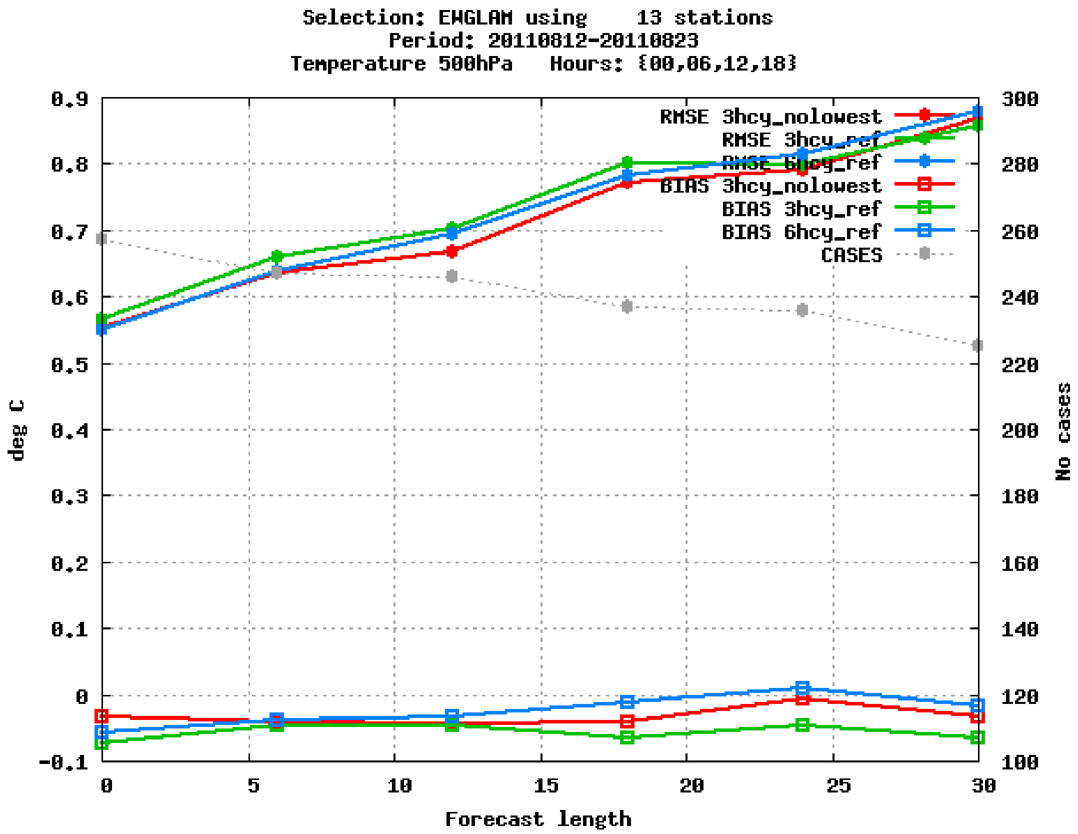


Figure 13. RMSE and BIAS for temperature at 850 hPa (upper panel) and 500 hPa (lower panel). The two experiments without radar (three hour cycling in green and six hour cycling in blue) are the same as in Figure 2. The red line represents an experiment with radar reflectivity included..

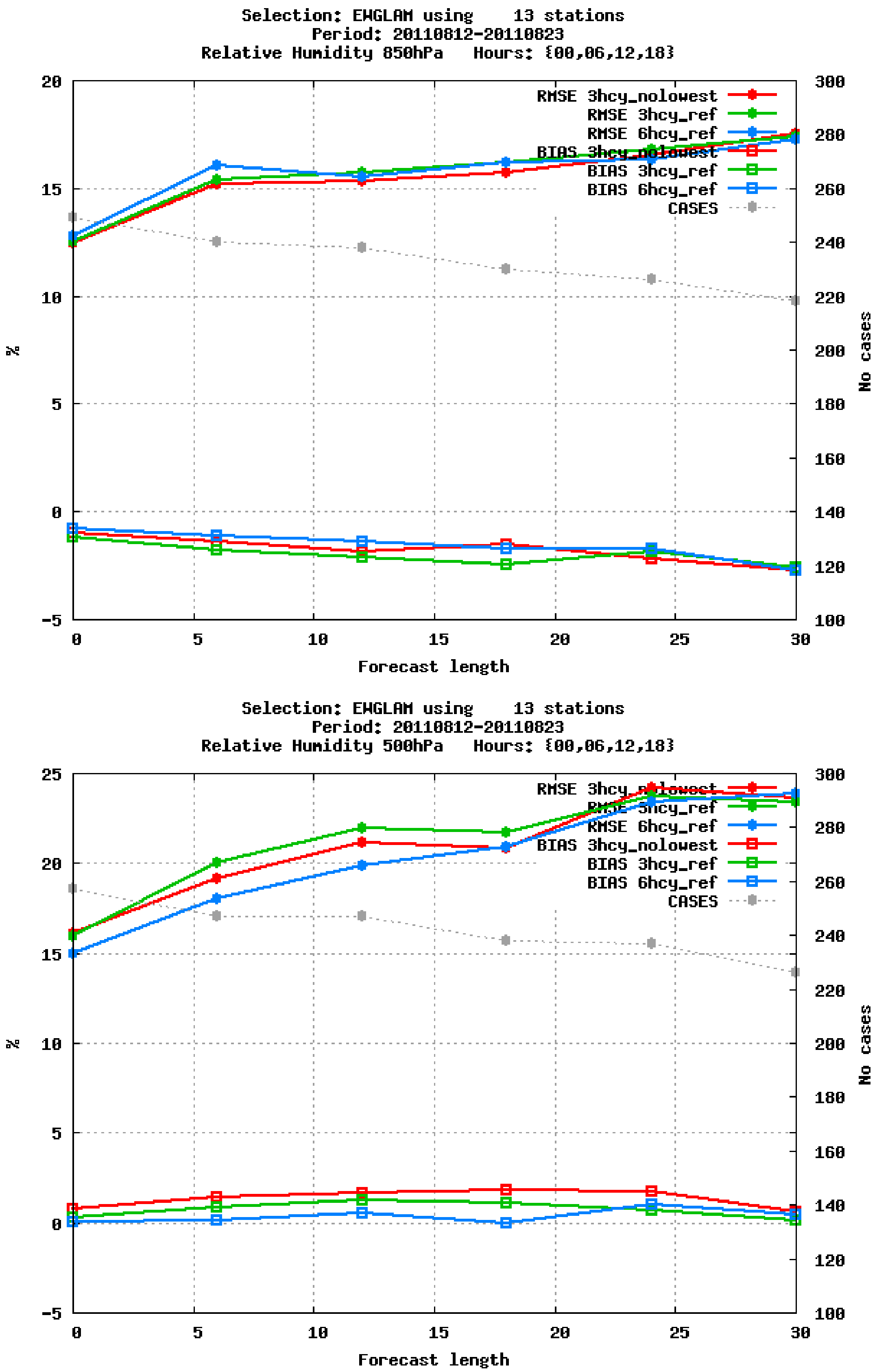


Figure 14. The same as in Figure 13, but for relative humidity.

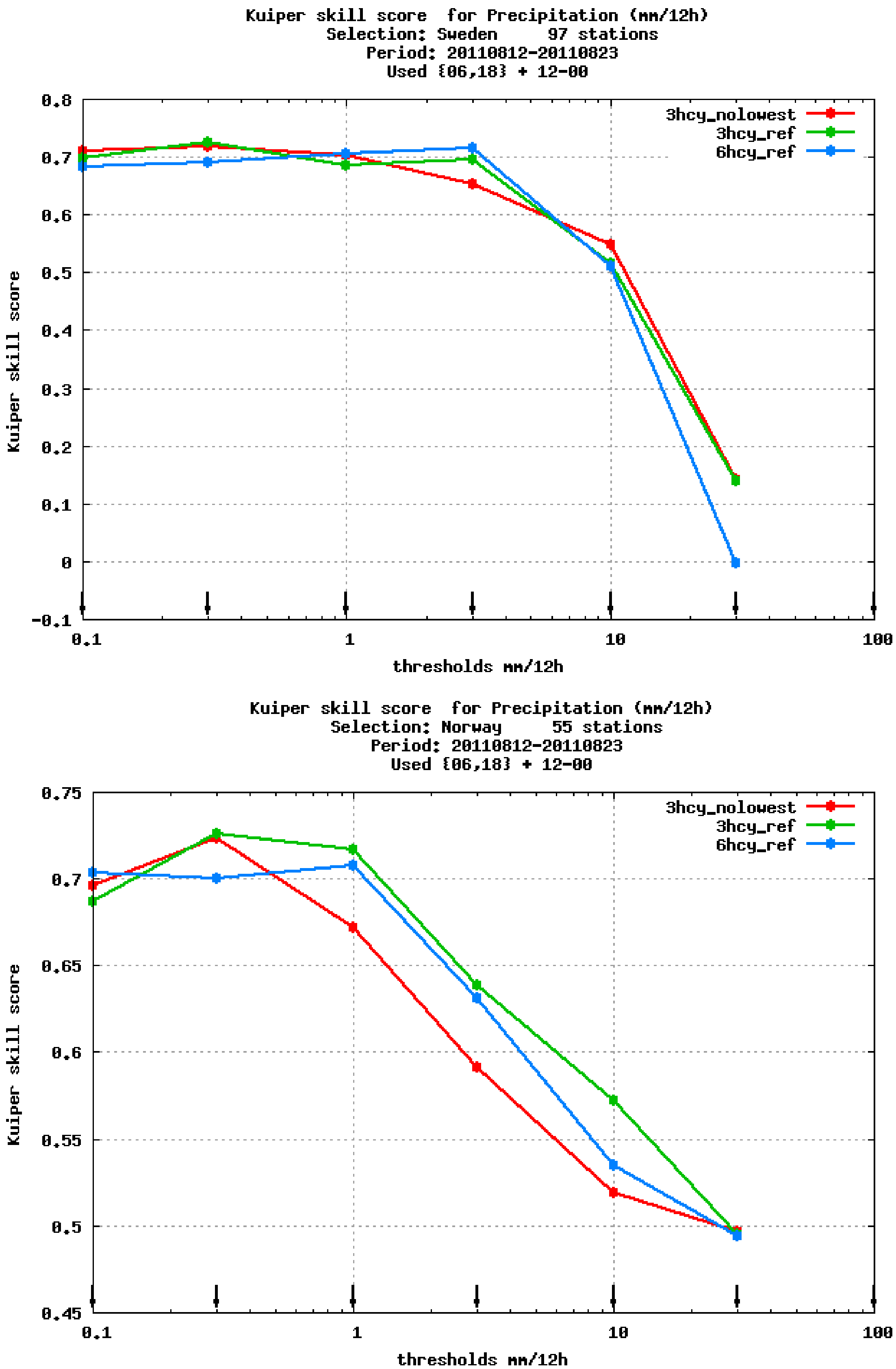


Figure 15. Kuiper skill score for two experiments without radar; three hour cycling (green) and six hour cycling (blue) and one experiment using three hour cycling with radar reflectivity included (red). Verification against Swedish stations are shown in the upper panel and against Norwegian stations in the lower panel.

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