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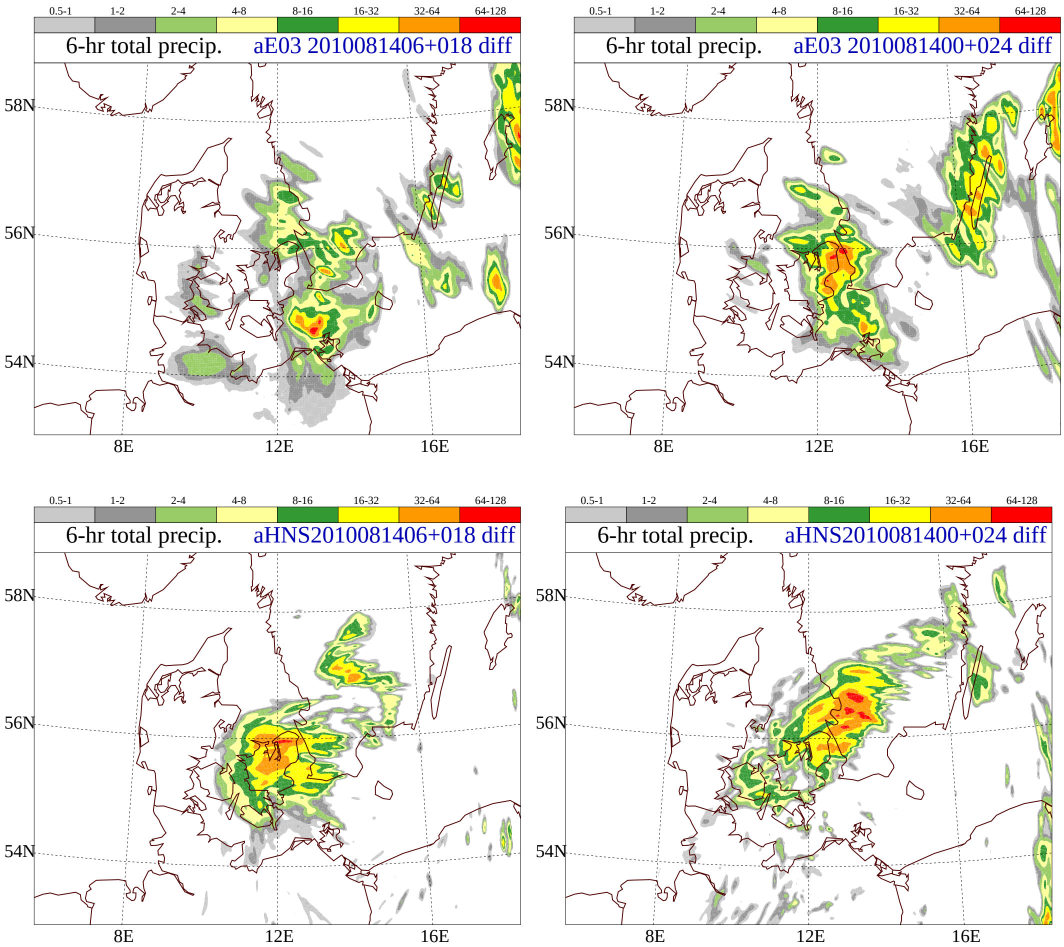
HIRLAM versus HARMONIE: An Intercomparison Study

Niels Woetmann Nielsen, Xiaohua Yang, Kristian Pagh Nielsen and Bjarne Stig Andersen



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Abstract

1. Introduction

A new numerical weather prediction model (NWP) system named HARMONIE (Hirlam Aladin Regional Meso-scale Operational NWP in Europe) has been adapted by the HIRLAM community. Extensive work on and test of the system has taken place during the HIRLAM-A project terminating at the end of 2010. The aim is to make the HARMONIE system operational at DMI (Danish Meteorological Institute) during the HIRLAM-B project beginning 1 January 2011. Before the HARMONIE system is ready to replace DMI-HIRLAM, which is the operational NWP system at DMI (from 23 November 2010 based on the HIRLAM reference system, version 7.3), it must perform at least as good as the present DMI-HIRLAM system in terms of verification scores and in terms of case evaluations primarily focusing on extreme weather such as for example heavy precipitation and strong winds. The intercomparison should be as fair as possible. Ideally this requires that observations available for the analysis, lateral boundary conditions, domain and horizontal and vertical resolution should be identical for the model systems in the intercomparison.

During the last months of 2010 several experiments have been performed with the main purpose of comparing the quality of HIRLAM and HARMONIE forecasts for selected periods in 2010. It has not been possible to run experiments that totally fulfil the ideal conditions. One group of experiments is done for October and November. Verification results for these experiments together with a brief description of each experiment are presented in subsection 2.1.

Subsection 2.2 compares results from different versions of DMI-HIRLAM running on the S03-domain.

Another group of experiments with conditions closer to the ideal than those in subsection 2.1 has been done for the period 10 to 23 August. Verification results from these experiments as well as a brief description of the experimental setups, named DMI-HIRLAM-S03L65, DMI-HIRLAM-S03L65NOUA, HARMONIE-1 and HARMONIE-2 (see Table 1 and Table 2), are given in subsection 2.3.

The period 10 to 23 August contained three extreme precipitation events in Denmark. Section 3 gives a brief description of the meteorological conditions spawning these events together with an intercomparison and discussion of DMI-HIRLAM-S03L65, DMI-HIRLAM-S03L65NOUA, HARMONIE-1 and HARMONIE-2 precipitation forecasts for these events.

Finally, concluding remarks are given in section 4.

2. Verification results

In this section verification results for a number of experiments with HARMONIE as well as DMI-HIRLAM-S03L65NOUA, DMI-HIRLAM-S03L65 and DMI-HIRLAM-S03 are discussed. Results for the period 1 October to 25 November are presented in subsections 2.1 and 2.2 and in the following subsection 2.3 results for a shorter summer period (10 to 23 August) are presented. In the latter subsection results from HARMONIE-1/HARMONIE-2 and DMI-HIRLAM-S03L65-NOUA are of particular interest, since this is the first preliminary intercomparison between the present operational system and the most recent version (36h1) of a future operational system based on HARMONIE.

2.1 DMI-HIRLAM versus HARMONIE: Period October-November 2010

Some of the HARMONIE (AROME) experiments reported here have been done on the ECMWF platform, while others have been done on the DMI platform. Roughly, the experiments performed on the ECMWF platform were all based on the main HARMONIE development branch called trunk, with source code based on cycle CY36T1 issued from Meteo France (the French Meteorological Institute). An AROME (Application of Research to Operations at Meso-scale) model configuration has been used in the currently reported studies, in which the physical parameterization is based on a convection-permitting meso-NH (non hydrostatic) physics scheme developed at Meteo France.

Three different model domains, named NORTHSEA, AROME-2.5 and DENMARK have been used in different tests, all with 2.5 km grid spacing and centered around Denmark. The NORTHSEA-domain with a grid-mesh of 1000x750x65 is closest to the DMI-HIRLAM-S03-domain, AROME-2.5 with 800x800x65 is somewhat smaller and DENMARK has the smallest domain with 384x400x65 grid points. The latter domain is used in daily real-time HARMONIE runs at DMI's own platform. In the present report experiments run on the AROME-2.5-domain are not discussed.

A number of configuration differences do exist comparing the runs done for the DENMARK-domain on the two platforms. On the DMI platform, the current HARMONIE-35h1 run is based on configuration 35h1, using DMI-HIRLAM as initial and lateral boundaries, whereas on the ECMWF platform, the runs are based on 36h1 with numerous changes in the AROME physical parameterization, and using blended ECMWF forecast in upper air blending and lateral boundary coupling, the latter being similar to the current DMI-HIRLAM-S03. On the DMI platform HARMONIE-35h1 was nested to ALADIN-35h1, running with about 10 km horizontal resolution. The latter model was nested to DMI-HIRLAM-T15 with a horizontal resolution about 15 km and running on a large domain, covering the entire North Atlantic region. Experiments run on the AROME-2.5-domain are not discussed in the present report.

Several alternative configuration experiments have been performed using the DENMARK- domain as part of the validation study coordinated in HIRLAM-A program, many of these with a purpose to investigate forecast quality sensitivity on various configuration feature such as analysis and coupling method, vertical resolution and levelling. Some of these results have been used in this report to illustrate typical variability of the AROME model, for which an optimal configuration is yet to be established.

Table 1: Model configurations and domains for the August 2010 runs.

Model version	**DMI-HIRLAM 7.3**	**HARMONIE-1 cy36h1**	**HARMONIE-2 cy36h1**
Model name	S03L65NOUA(aE03)	HARMONIE-1(HNS)	HARMONIE-2 (aHNS)
Area	"S03" (NW Europe)	NORTHSEA	NORTHSEA
Resolution	$\approx 0.03°$	$\approx 0.025°$	$\approx 0.025°$
Vertical levels	65	60	65
Boundaries	IFS cy36r1	IFS cy36r1	IFS cy36r1
Forecast length	24h	24h	24h
Analysis (u.air)	No upper air analysis	No upper air analysis	No upper air analysis
Blending	with ECMWF	with ECMWF	with ECMWF
Analysis (sf.)	Surface analysis	No surface analysis	Surface analysis

Table 2: Model configurations and domains for the October-November 2010 runs.

Model version	**DMI-HIRLAM 7.3**	**HARMONIE cy36h1**	**HARMONIE cy35h1**
Model name	S03L65(bE03)	AROME36-08	HARMONIE-35h1
Area	"S03" (NW Europe)	DENMARK	DENMARK
Resolution	$\approx 0.03°$	$\approx 0.025°$	$\approx 0.025°$
Vertical levels	65	65	65
Boundaries	IFS cy36r1	IFS cy36r1	IFS cy36r1
Forecast length	24h	24h	24h
Analysis (u. air)	Upper air analysis	No upper air analysis	No upper air analysis
Blending (u. air)	with ECMWF	with ECMWF	with ECMWF
Analysis (sf.)	Surface analysis	Surface analysis	No surface analysis

2.2 Results from HARMONIE-35h1 and different versions of DMI-HIRLAM: Period October-November 2010

DMI-HIRLAM-S03L65 versus DMI-HIRLAM-S03. In connection with the operational upgrade at DMI 23 November 2010 runs were made on the ECMWF platform with the purpose of comparing the quality of the forecasts from the new operational system, DMI-HIRLAM-S03L65, based on the HIRLAM reference system 7.3 (supplemented with specific DMI features) with the forecast quality of the operational system, DMI-HIRLAM-S03, prior to the upgrade.

The intercomparison showed that the verification scores (bias and st.dev.) based on the EWGLAM (European Working Group on Limited Area Modelling) list of observations were almost equal for V10m (wind speed at 10 m height) and T2m (temperature at 2 m height) and clearly better in DMI-HIRLAM-S03L65 for mslp (mean sea pressure) and specific humidity, as shown in Figure 1 (left and right, respectively). The specific humidity was significantly better in DMI-HIRLAM-S03L65 throughout the period. The improvement is mainly due to a correction of specific humidity at the surface in the diagnostic calculation of Q2m in the current operational system.

DMI-HIRLAM-S03L65 versus HARMONIE-35h1. Figure 2 shows hit rate and false alarm rate for accumulated precipitation in mm/12 hours for 7 specified intervals/classes (C1:< 0.1; C2: 0.1-0.3; C3: 0.3-1.0; C4: 1.0-3.0; C5: 3.0-10.0; C6: 10.0-30.0; C7: 30.0-100.0) verified against 22 stations in Denmark. Black and red symbols are for DMI-HIRLAM-S03L65 and HARMONIE-35h1, respectively. For the three lowest intervals DMI-HIRLAM-S03L65 had a higher hit rate, but also a higher false alarm rate than HARMONIE-35h1. However, for the next two intervals (1.0-3.0; 3.0-10.0) HARMONIE-35h1 had the highest hit rate and for the interval 1.0-3.0 also the lowest false alarm rate. There was no precipitation events in the two highest classes. Verification scores (BIAS and STDV error) for surface parameters mslp, V10m, Vd10m and RH2m were best in DMI-HIRLAM-S03L65, whereas Q2m scores were equaly good. The BIAS of T2m was best in HARMONIE-35h1 and the STDV error equaly good.

2.3 DMI-HIRLAM versus HARMONIE-1/HARMONIE-2: Period 10 to 23 August 2010

For this period all the HARMONIE runs were based on cycle 36h1. The period is too short for obtaining general representative statistics and the results obtained must be considered as preliminary. Nevertheless, they may point to potential problems, which must be investigated. More results than originally intended are presented. It was decided to run HARMONIE on the ECMWF platform under conditions as close as possible to the operational DMI-HIRLAM-S03L65 at DMI. However, the experiment, named HARMONIE-1, diverged more than intended from HIRLAM-S03L65.

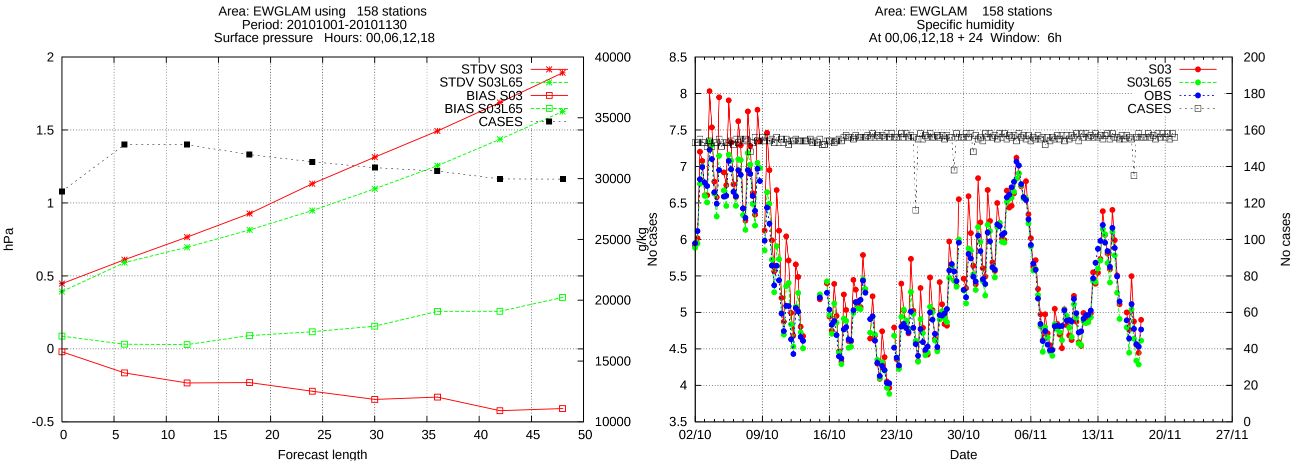

Figure 1: Left: Bias (lower curves) and standard deviation (STDV) of mean sea level pressure (mslp) as function of forecast lead time for DMI-HIRLAM-S03 (red) and DMI-HIRLAM-S03L65 (green). Right: Time series (6 hour intervals) of 24 hour forecasts of specific humidity (Q2m) 2 m above the surface (red: DMI-HIRLAM-S03 and green DMI-HIRLAM-S03L65) together with observed values (blue). Both figures are for the October-November period and observations are from the EWGLAM list.

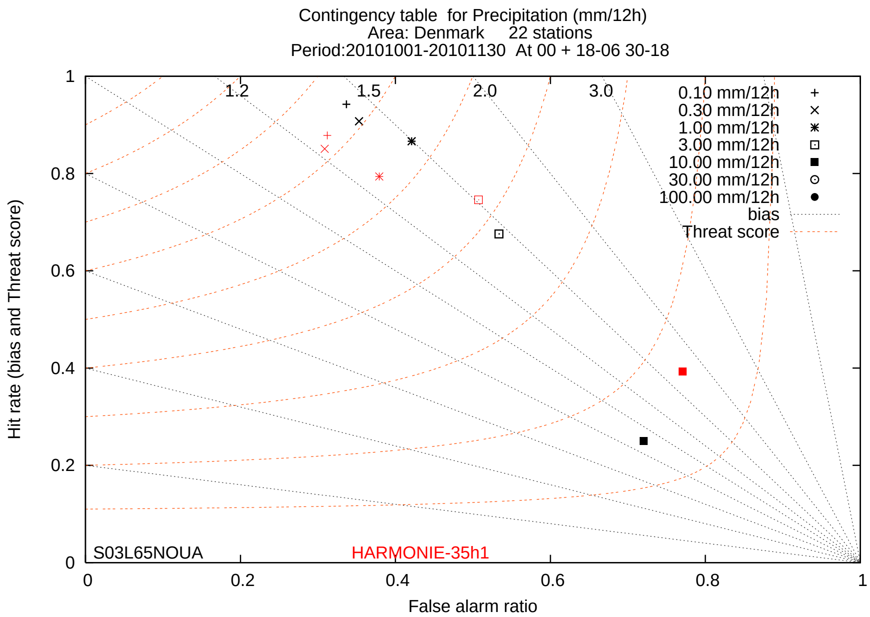

Figure 2: Wilson diagram for 12 h accumulated precipitation. Shown are differences between 18 and 6 h and 30 and 18 h forecasts in HARMONIE-35h1 and DMI-HIRLAM-S03L65NOUA from analysis time 00 UTC. Verification against stations in Denmark. Period 1 October to 25 November 2010.

According to Table 1 both models were run with approximately the same horizontal (about 2.5 km in HARMONIE-1 versus 3 km in DMI-HIRLAM-S03L65) and vertical (60 versus 65 levels) resolution and used the same lateral boundary values. Further, no upper-air analysis was done in any of the models, but unintentionally surface analysis was switched off in the HARMONIE-1 runs.

DMI-HIRLAM-S03L65NOUA versus HARMONIE-1. Undoubtly, the verification results for the HARMONIE-1 runs were influenced by the missing surface analysis, most likely with a negative influence on the results, as also indicated by Figure 3 (left), showing higher 24 hour predicted T2m in HARMONIE-1 (green) than in S03L65NOUA (red). The distribution for the observations (magenta) was in between the distributions for DMI-HIRLAM-S03L65NOUA and HARMONIE-1, reflecting a negative and positive T2m bias in the respective models. In Figure 3 the verification is done for the EWGLAM stations within the DENMARK-domain. Verification against Danish stations gives a similar result. Figure 3 (right) shows that the 24 hour prediction of Q2m was clearly best in S03L65NOUA both in terms of bias and root mean square error (rmse). This also holds if the verification is done against Danish stations. Verified against EWGLAM as well as Danish stations the same conclusion can be drawn for the surface parameters mslp, wind direction (Vd10m), dew point temperature (Td2m) and relative humidity (RH2m) at 2 m height. For total cloud cover (Ccov) both models had a small negative bias, but the root mean square error (RMSE) was somewhat higher in HARMONIE-1.

DMI-HIRLAM-S03L65NOUA versus HARMONIE-1 and AROME36-08. The verification results based on verification against Danish stations were mixed. The bias was numerically smallest for mslp, Td2m and Q2m in DMI-HIRLAM-S03L65NOUA and largest for Vd10m, Td2m and Q2m in HARMONIE-1 and largest for mslp in AROME36-08. The STDV was smallest for Vd10m, T2m, Td2m, RH2m, Q2m and Ccov in DMI-HIRLAM-S03L65NOUA and largest for Vd10m, Td2m, RH2m and Q2m in HARMONIE-1 and largest for mslp in DMI-HIRLAM-S03L65NOUA.

For accumulated precipitation the results are shown by the Wilson diagrams in Figure 4. The precipitation classes are the same as in Figure 2. The diagrams to the left and right show results based on the Danish stations and the EWGLAM stations within the DENMARK-domain, respectively. Compared to the verification against the Danish stations there is a clear preference for lower hit rate and higher false alarm rate in the verification against the EWGLAM stations, most likely due to a negative impact of predicted precipitation in the boundary zone of the domain. Both for EWGLAM and Danish stations DMI-HIRLAM-S03L65 had the highest hit rate, but also the highest false alarm rate for the four lowest precipitation classes C1 to C4, except for a little lower false alarm rate than in AROME36-08 for the EWGLAM stations. HARMONIE-1 and DMI-HIRLAM-S03L65 had the highest hit rates in C5 for the Danish and the EWGLAM stations, respectively and AROME36-08 had the highest false alarm rates. The number of observations in C6 and C7 was too small for a meaningful discussion.

If HARMONIE-1 is compared with AROME36-08 the verification against the EWGLAM stations shows that HARMONIE-1 has both a higher hit rate and a lover false alarm rate for C1 to C4. For C5 the models have the same hit rate, but HARMONIE-1 the lowest false alarm rate. Verification against the Danish stations gives or more mixed picture with only clearly better HARMONIE-1 scores for C2 and C5. Again this points to a negative impact of the predicted precipitation in or close to the boundary zone of the DENMARK-domain used in AROME36-08. No observations from or near the boundary zone of the larger NORTHSEA-domain are in the list of observations for the DENMARK-domain, which means that the predicted precipitation in or near the boundary zone in the NORTHSEA-domain does not influence the verification results in HARMONIE-1.

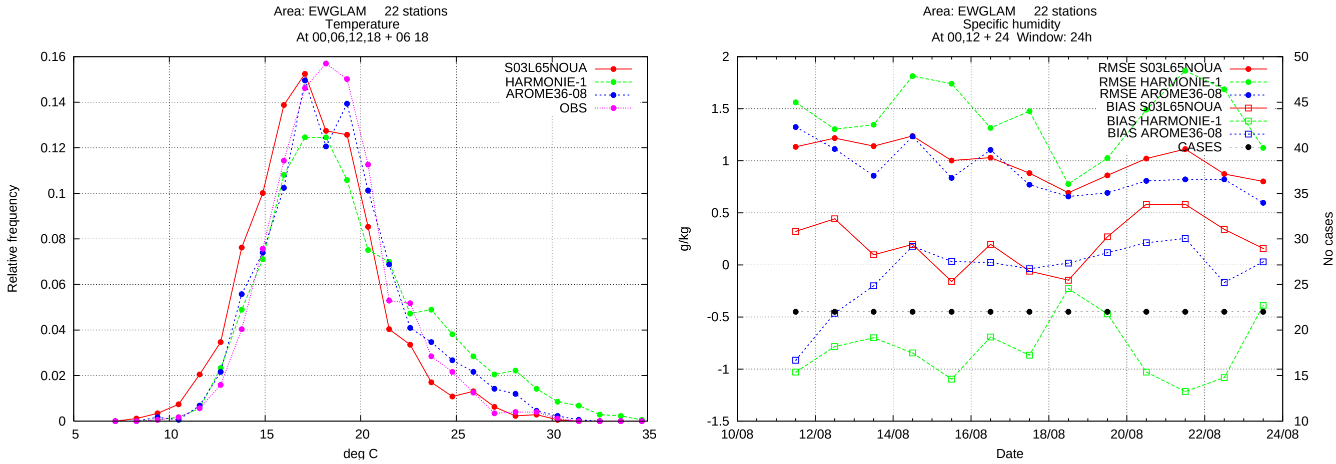

Figure 3: Left: Frequency distribution of 06 and 18 hour predicted T2m from analysis times 00, 06, 12 and 18 UTC. Red: S03L65, green: HARMONIE-1, blue: AROME36-08 and magenta: observed T2m. Right: Daily variation of bias (lower curves) and root mean square error (rmse) of Q2m 24 hour forecasts from 00 and 12 UTC. For both figures forecasts are compared with observations from the EWGLAM list within the DENMARK-domain and the considered period is 10 to 23 August.

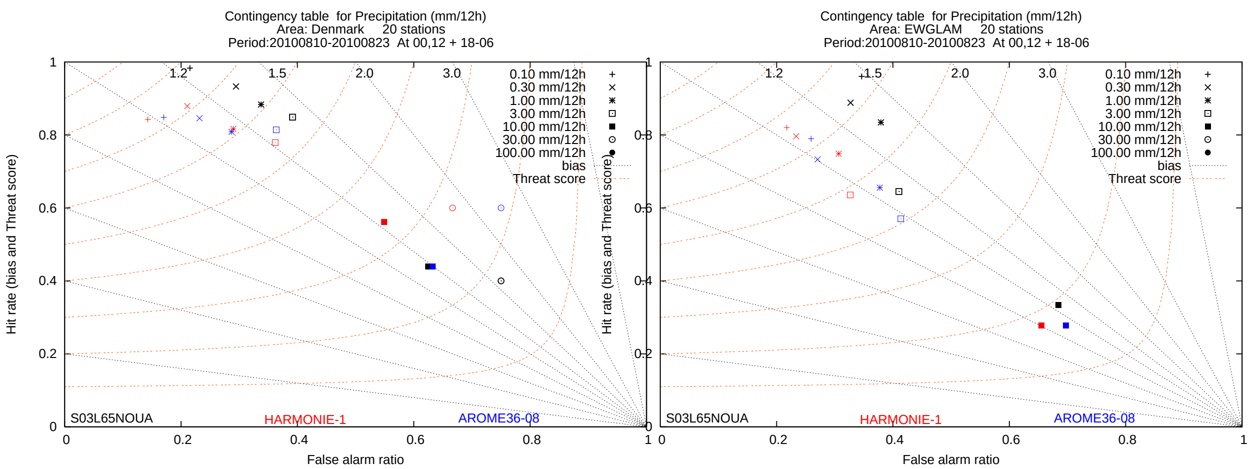

Figure 4: Wilson diagrams for predicted 12 hour accumulated precipitation (18-06 UTC) in forecasts from 00 and 12 UTC. Period: 10 to 23 August. Verification is against observations within the DENMARK-domain - left: only Danish stations, right: EWGLAM stations. Results are for DMI-HIRLAM-S03L65NOUA (black), HARMONIE-1 (red) and AROME36-08 (blue).

Table 3: **BIAS for 10 - 23 August 2010**: Model with the best and poorest BIAS is marked by + and -, respectively. The sign of the BIAS is shown in parenthesis. Double plus (++) and double minus (--) means that the BIAS is almost equal and best and poorest, respectively. The statistics are based on EWGLAM stations.

Parameter	**HARMONIE-1**	**HARMONIE-2**	**S03L65NOUA**	**S03**
mslp	- (< 0)		++ (≈ 0)	++ (≈ 0)
V10m		- (> 0)		+ (< 0)
Vd10m	- (> 0)		++ (≈ 0)	++ (≈ 0
T2m		++ (< 0)	++ (>0)	- (< 0)
Td2m	- (< 0)	+ (< 0)		
RH2m	- - (< 0)	++ (< 0)	++ (> 0)	- - (> 0)
Q2m	- (< 0)	+ (< 0)		
Ccov		+ (≈ 0)		- (<0)
Acc. precip.	- - (< 0)	+ (≈ 0)		- - (> 0)

Table 4: **STDV for 10 - 23 August 2010**: Model with the best and poorest STDV is marked by + and -, respectively. Double plus (++) and double minus (–) means that the STDV is almost equal and best and poorest, respectively. The statistics are based on EWGLAM stations.

Parameter	**HARMONIE-1**	**HARMONIE-2**	**S03L65NOUA**	**S03**
mslp	-	+		
V10m	-			+
Vd10m	-		++	++
T2m	-	++	++	
Td2m	-		+	
RH2m	-			+
Q2m	-	++	++	
Ccov	-		++	++
Acc. precip.	+			-

It was decided to rerun HARMONIE (with name HARMONIE-2) on the ECMWF platform, this time with 65 levels and with inclusion of surface analyzes, which brings the configuration as close as possible to that of DMI-HIRLAM-S03L65.

DMI-HIRLAM versus HARMONIE. This set of experiments involved runs with DMI-HIRLAM-S03L65NOUA, HARMONIE-1, HARMONIE-2 (see Table 1) and DMI-HIRLAM-S03 (the operational model prior to the most recent update 23 November 2010) and the forecasts were verified against the EWGLAM stations located within the NORTHSEA-domain. In contrast to the other models DMI-HIRLAM-S03 has the advantage of including variational analysis (3DVAR). The latter model is also somewhat less influenced by boundary values from the ECMWF model, since it is running on a larger domain with boundary values from DMI-HIRLAM-M09. The verification results in terms of bias (BIAS) and standard deviation (STDV) are summarized in Table 3 and Table 4, respectively. Table 3 shows that HARMONIE-2 and DMI-HIRLAM-S03L65NOUA have the numerically smallest bias for most of the considered surface parameters. However, it can be noted that the bias of mslp, V10m and Vd10m (wind direction at 10 m height) is numerically smallest in the DMI-HIRLAM models. According to Table 4 the STDV error for most of the shown parameters was lowest in DMI-HIRLAM-S03 and DMI-HIRLAM-S03L65NOUA and highest in HARMONIE-1. Exceptions were: 12 h accumulated

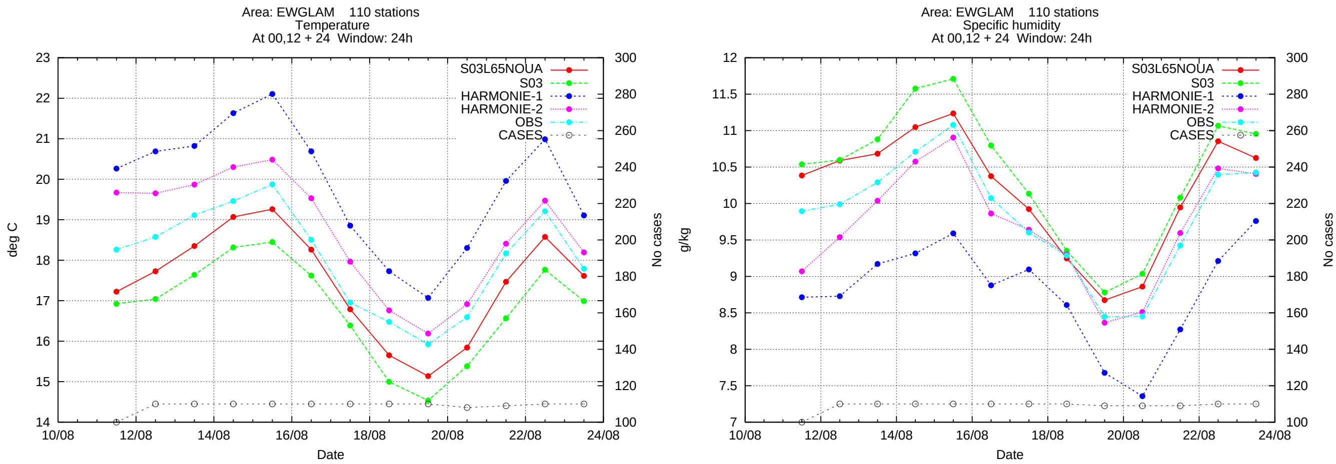

Figure 5: Time series of daily 24 hour predicted T2m () and Q2m () from initial times 00 and 12 UTC for the period 10 to 23 August 2010 verified against EWGLAM stations within the NORTHSEA-domain. HARMONIE-1: dark blue, HARMONIE-2: magenta, DMI-HIRLAM-S03L65NOUA: red, DMI-HIRLAM-S03: green and observations (OBS): light blue.

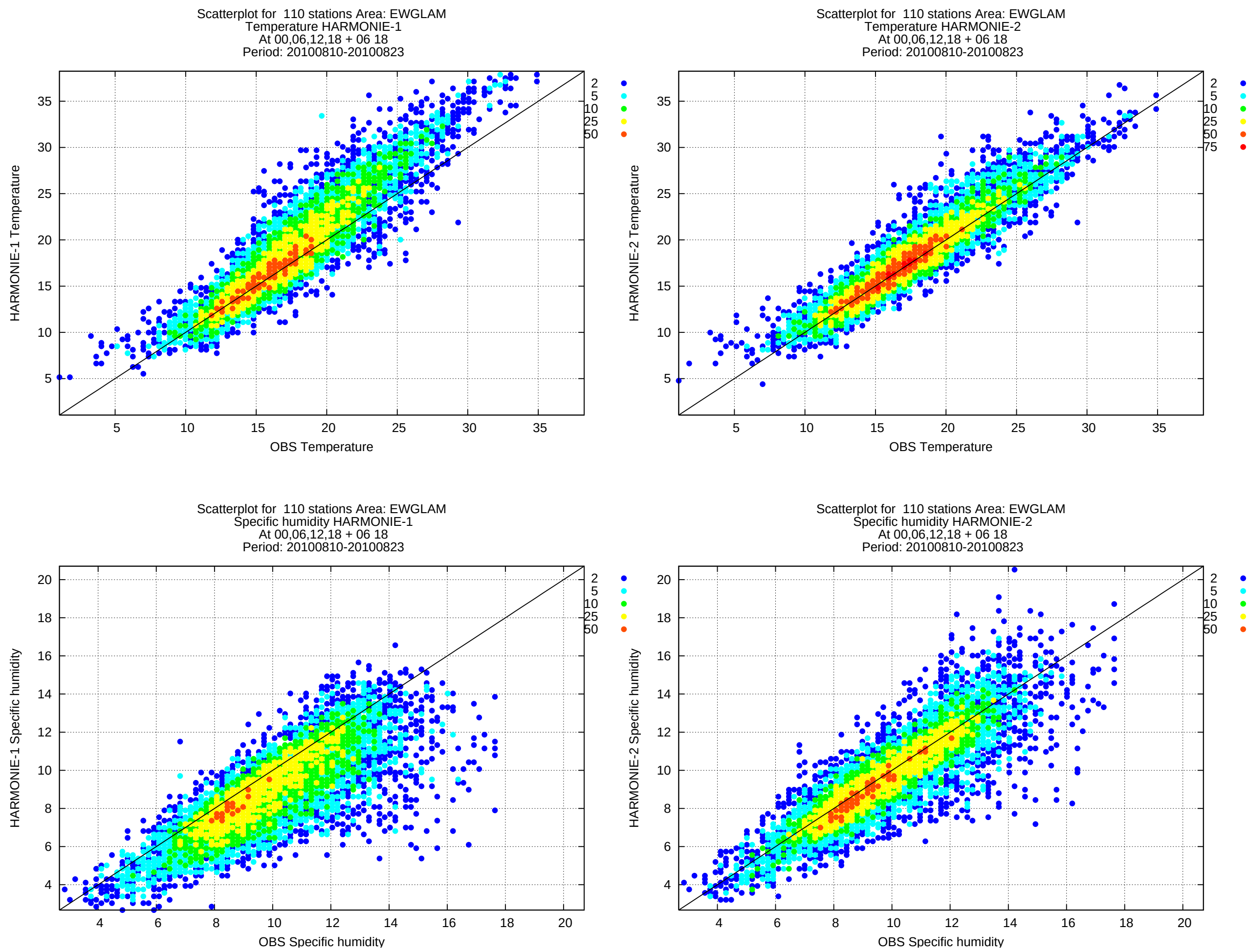

Figure 6: Scatter plots of T2m (top row) and Q2m (bottom row) for HARMONIE-1 (left) and HARMONIE-2 (right) for the period 10 to 23 August 2010. Abscissa: observations, ordinate: 6 and 18 h forecasts from initial times 00, 06, 12 and 18 UTC.

precipitation, which had the lowest and highest STDV error in HARMONIE-1 and DMI-HIRLAM-S03, respectively, and mslp, which had the lowest STDV error in HARMONIE-2. Supplementary to the BIAS statistics the time-series of T2m and Q2m in Figure 5 show that 24 hour forecasts from initial times 00 and 12 UTC of T2m averaged for the NORTHSEA-domain on a day to day basis is higher than observed in HARMONIE-1 and HARMONIE-2 and lower than observed in in the DMI-HIRLAM models. Largest deviations from the observed values occurred in HARMONIE-1 and DMI-HIRLAM-S03. Similarly, the Q2m predicted by HARMONIE-1 and DMI-HIRLAM-S03 had lower and higher values than observed, with the largest (and negative) deviations from observed values in the former model. Q2m predicted by HARMONIE-2 and DMI-HIRLAM-S03L65NOUA was fairly close to the observations (mostly a little higher in DMI-HIRLAM-S03L65NOUA and a little lower in HARMONIE-2.

HARMONIE-1 versus HARMONIE-2. Table 3 and Table 4 show that the verification statistics in terms of BIAS and STDV error clearly is in favor of HARMONIE-2. The main reasons for the improved results in the latter model are that it in contrast to HARMONIE-1 has been running with surface analyzes and a canopy form drag switched on. The improved results for HARMONIE-2 are also evident in the scatter plots for T2m and Q2m shown in Figure 6. HARMONIE-1 has a rather strong tendency to predict higher temperatures than observed, particularly in warm weather conditions and has also in the entire range of observed specific humidity a clear tendency to predict lower specific humidity than observed. The scatter points in HARMONIE-2 are much closer to the diagonal and with a smaller spread than in HARMONIE-1.

3. Discussion of extreme precipitation events in Denmark in August 2010: How did DMI-HIRLAM and HARMONIE perform?

The 3 episodes considered here occurred within a 5 day period in August. For convenience the episodes are named The Copenhagen case (14 august, main precipitation period: 17 to 21 UTC, location: 55.8 N, 12.5 E), the Bornholm case (17 August, main precipitation period: 02 to 04 UTC, location: 55.1 N, 15.1 E) and the Billund case (18 August, main precipitation period: 6 to 10 UTC, location: 55.7 N, 9.2 E).

In all the episodes the general weather conditions had several features in common. The surface air was relatively warm and moist with relative humidities above 90% and dew point temperatures around $15°\mathrm{C}$ in the Billund case and from about 17 and $19°\mathrm{C}$ in the other cases. Soundings (not shown) in the area had a deep troposphere with tropopause levels roughly from 200 to 300 hPa, lowest in the Billund case, and relatively small deviations from a moist adiabatic lapse in the troposphere above the planetary boundary layer (PBL). The soundings were much like a Miller "type II" (Bluestein, 1993) with a depth of the troposphere typical for the subtropics. Lightning, which often is associated with deep convection, was reported in all the cases.

In the Copenhagen and Billund cases observations showed that the heavy precipitation occurred in a rather weak cyclonic surface circulation with a radius of no more than 100 km (shown by the forecasted V10m (wind velocity at 10 m height) in Figure 8, Figure 9, Figure 11, Figure 12 top and middle row and Figure 13 middle and bottom row, and confirmed by observations (not shown)). Observations also indicate that a cyclonic surface circulation on a somewhat larger scale than in the other cases was present in the Bornholm case (Figure 10, Figure 12 bottom row and Figure 13 top row). In the latter case the satellite image in Figure 4 (top right) indicate that convection may have been triggered by forced ascent in a near-surface convergence band associated with a frontal zone over the western Baltic Sea. Apparently the convection in the Billund cases was triggered by forced ascent in the cyclonic circulation below a lowered tropopause and Figure 7 (bottom row) indicates that a cluster of convection cells developed in the region. Figure 7(top left) indicates in the Copenhagen case that the intense convection developed underneath a transition zone in the upper troposphere between the slot of dry intrusion air and moist air in the cloud-head of the cyclonic circulation. The most likely triggering mechanism for the convection was in all cases release of potential instability by forced ascent. A rather deep troposphere with large amounts of vertically integrated water vapor (figure not shown) undoubtly contributed to the large amounts of precipitation in the considered cases. Further, evaporation from the nearby sea may have supplied additional moisture to the convection (Gustafsson et al., 2010), particularly in the Copenhagen and Bornholm cases. The fairly high intensity of the convective precipitation points to high precipitation efficiency, which is the ratio of total precipitation to total available moisture for a convection cell. In the considered cases the vertical wind shear was relatively weak, the cloud base low and the mixing ratio high at cloud base, all supporting relatively high efficiency.

The absence of dry air below the cloud base also counteracts development of significant wind gusts generated in individual cell downdrafts and may have been the main reason for the observed relatively weak wind gusts.

Figures 8 to 13 show that all the models in the experimental runs for the considered heavy precipitation episodes had difficulties in predicting correctly the amount of precipitation, its location and at which time it occurred.

In the Copenhagen case (Figure 8, Figure 9 and Figure 12 top and middle row) the 3 hour accumulated precipitation in the Øresund area was best predicted by S03L65NOUA (aE03 in the figures) and HARMONIE-1 (HNS in the figures) was the least accurate of the forecasts. At Sjælsmark, a little north of Copenhagen, the recorded accumulated precipitation was 76 mm from 17 to 21 UTC with a maximum intensity of 35.6 mm from 17 to 18 UTC. Unofficial reports indicate higher intensities in the Copenhagen area.

The experiments also showed sensitivity to the initial state. It was not always the case that the shortest range forecasts of the episodes gave the best prediction. This is illustrated by the Copenhagen case. The precipitation forecasts from 14 august 12 UTC were less accurate than the forecasts from 12 hours earlier (Figure 8 and Figure 9).

The figures also show that inclusion of upper-air observations in the analyzes does not always improve the precipitation forecasts. An example is shown by the Bornholm case (Figure 10), where the precipitation episode was somewhat better predicted in the DMI-HIRLAM-S03L65NOUA (aE03) system without inclusion of upper air observations in the analysis than in the DMI-HIRLAM-S03L65 (bE03) system, where upper air observations were included in the analysis. In HARMONIE-1 (HNS in Figure 10), which is also running without upper-air analysis the predicted accumulated precipitation on Bornholm was in fact fairly close to the observed 78 mm from 01 to 04 UTC in Nexø with a maximum intensity of 46.1 mm from 02 to 03 UTC. On the other hand in the Billund case the precipitation at Billund (92 mm from 06 to 12 UTC with a maximum intensity of 48.6 mm from 07 to 08 UTC) was best predicted by the system S03L65, which included upper-air analysis.

Further, Figure 12 and Figure 13 show a sensitivity to the combined effect of increasing the number of model-levels from 60 to 65 and including surface analysis. In the shown cases the precipitation forecasts are improved somewhat in HARMONIE-2 (aHNS), the model with 65 levels and inclusion of surface analysis. It is most likely the surface analysis that is responsible for the improvement.

The presented cases illustrate that the predicted convective precipitation is sensitive to the initial

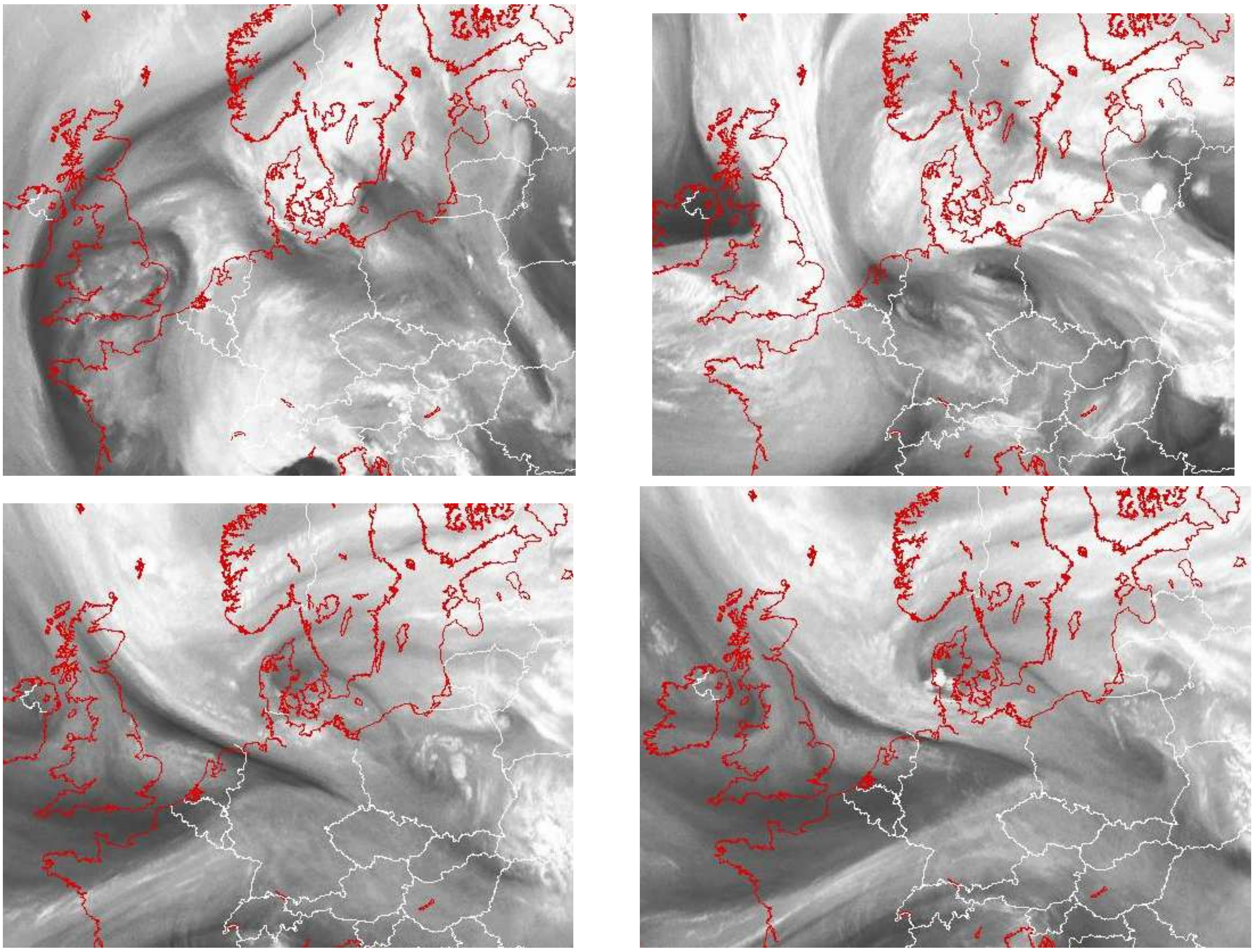

Figure 7: Meteosat Second Generation (MSG) water vapor channel 5 satellite images. Top left: Copenhagen case 14 August 18 UTC, top right: Bornholm case 17 August 02 UTC, bottom left and right: Billund case 18 August 03 and 06 UTC, respectively.

state in the sense that even small changes in the state may lead to significant changes in the precipitation pattern and its evolution in time.

The significant variation in the convective precipitation pattern from analysis to analysis is an illustration of the strong convective response to changes in the atmospheric state due to analysis (which tends to smooth wind, temperature and moisture), updated lateral boundary values and blending. In other words, the subsequent evolution of trigger-regions for deep convection varies substantially from one analysis time to the next. This behavior is related to the limited predictability of convective precipitation. This type of precipitation typically originates from convective cells with horizontal and vertical scales of the order of 10 km and a life cycle normally less than one hour. A convective cell develops when and where a threshold for convection is exceeded, Once a cell has developed it may trigger new cells in the environment by interaction with the environmental wind field (through linear and nonlinear perturbation pressure gradients, e.g. Rotunno and Klemp, 1982) or by forced ascent at the gust front, where the downdraft air from the cell replaces environmental air. Thus the precipitation pattern that develops from a single cell depends on the environmental state, which in turn depends on the initial state. The latter also has an influence on the locations where new cells form independently of other already existing cells or multi-cell systems. This points to a predictability of deep convection (i.e. convection with cloud tops near the tropopause) that is

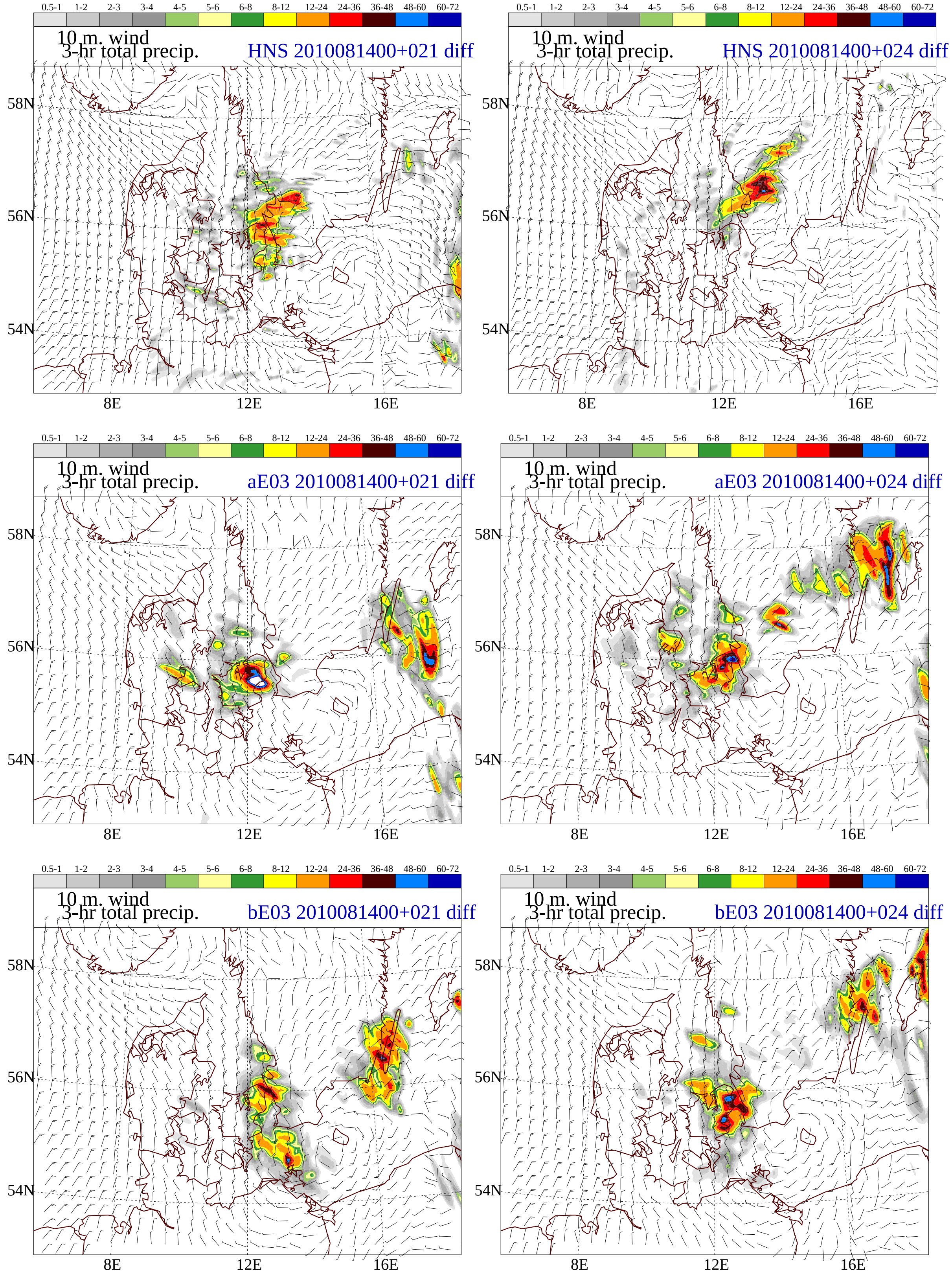

Figure 8: The Copenhagen case (55.8°N, 12.5°E). Forecasts from analysis time 00 UTC 14 August 2010 showing 3 hour accumulated precipitation and 10 m wind speed at valid times 14 August 21 UTC and 15 August 00 UTC. HNS: HARMONIE-1, aE03: S03-L65 without upper air analyzes and bE03: as aE03, but with upper air analyzes.

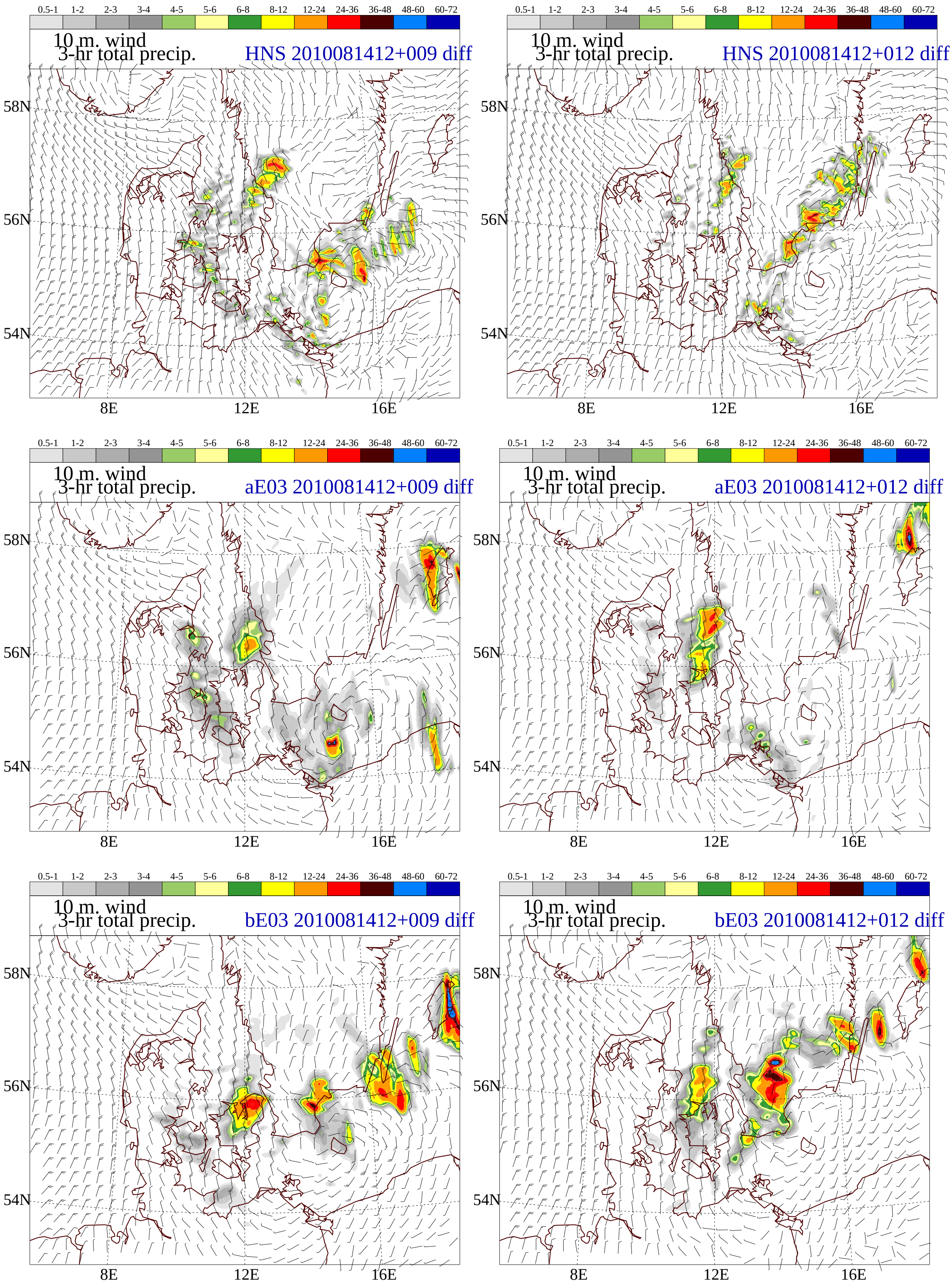

Figure 9: The Copenhagen case (55.8°N, 12.5°E). Forecasts from analysis time 12 UTC 14 August 2010 showing 3 hour accumulated precipitation and 10 m wind speed at valid times 14 August 21 UTC and 15 August 00 UTC. HNS: HARMONIE-1, aE03: S03-L65 without upper air analyzes and bE03: as aE03, but with upper air analyzes.

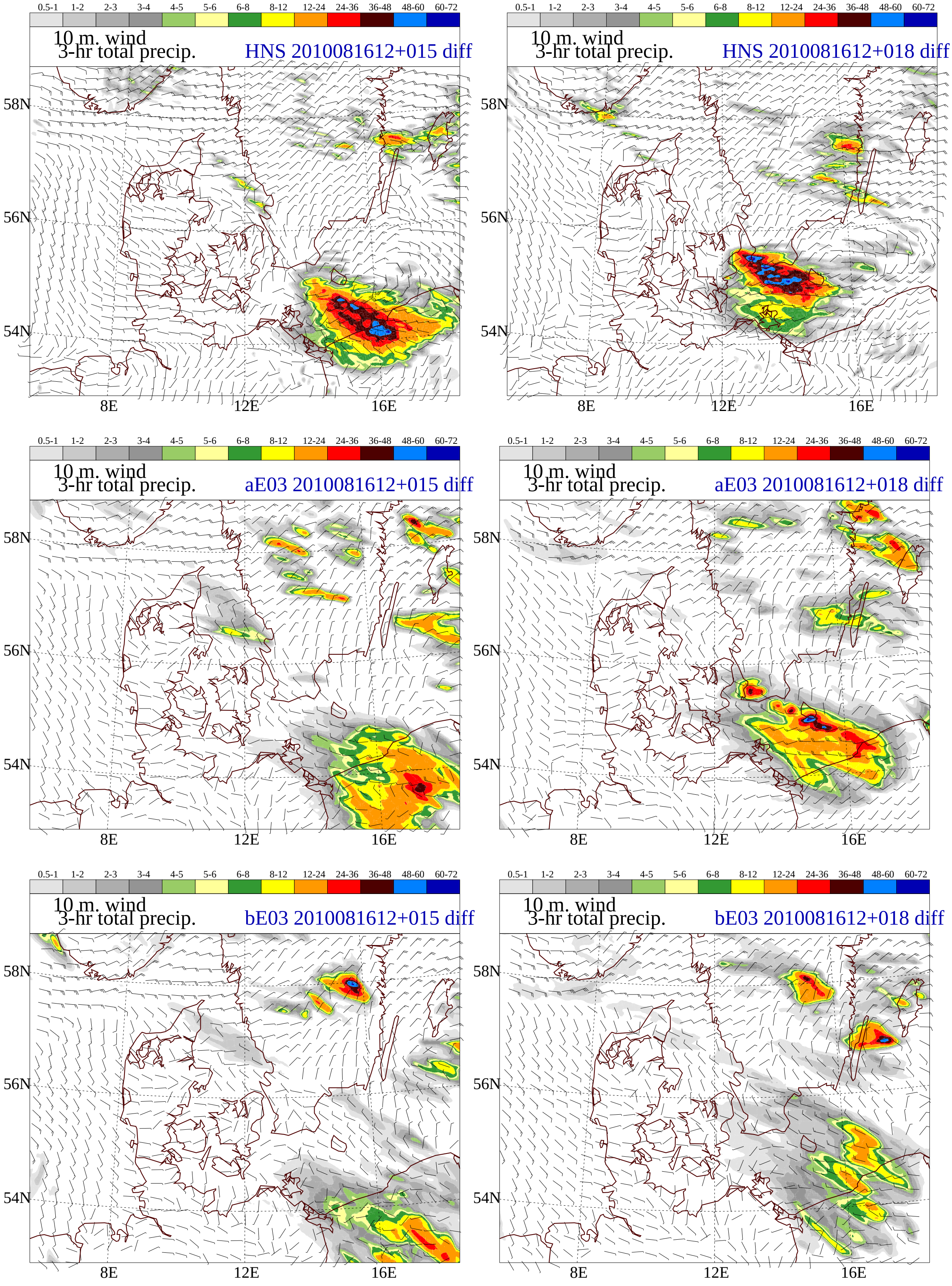

Figure 10: The Bornholm case (55.1°N,15.1°E). Forecasts from analysis time 12 UTC 16 August 2010 showing 3 hour accumulated precipitation and 10 m wind speed at valid times 17 August 03 UTC and 06 UTC. HNS: HARMONIE-1, aE0S: S03-L65 without upper air analyzes and bE03: as aE03, but with upper air analyzes.

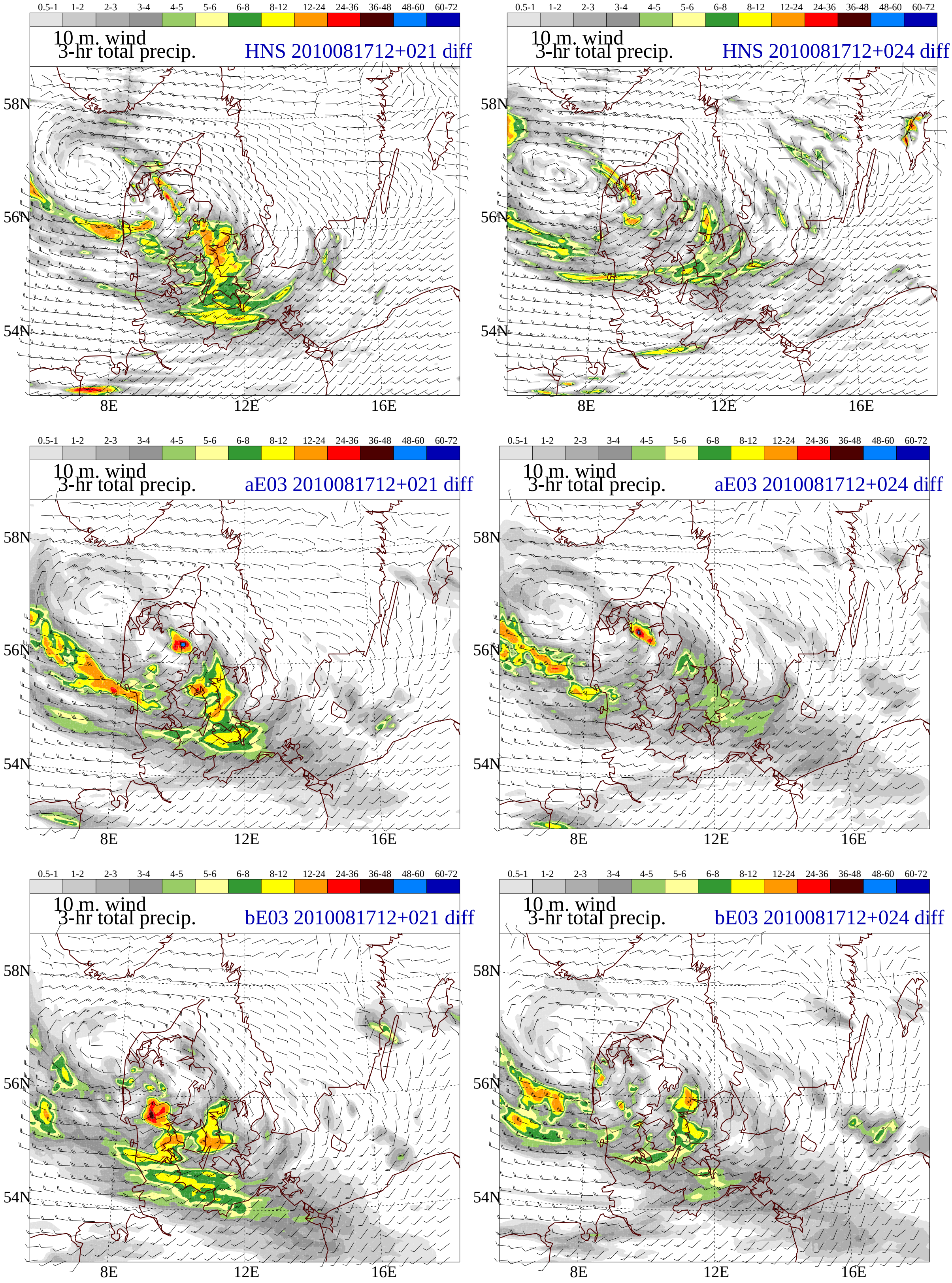

Figure 11: The Billund case (55.7°N, 9.2°E). Forecasts from analysis time 12 UTC 17 August 2010 showing 3 hour accumulated precipitation and 10 m wind speed at valid times 18 August 09 UTC and 12 UTC. HNS: HARMONIE-1, aE03: S03-L65 without upper air analyzes and bE03: as aE03, but with upper air analyzes.

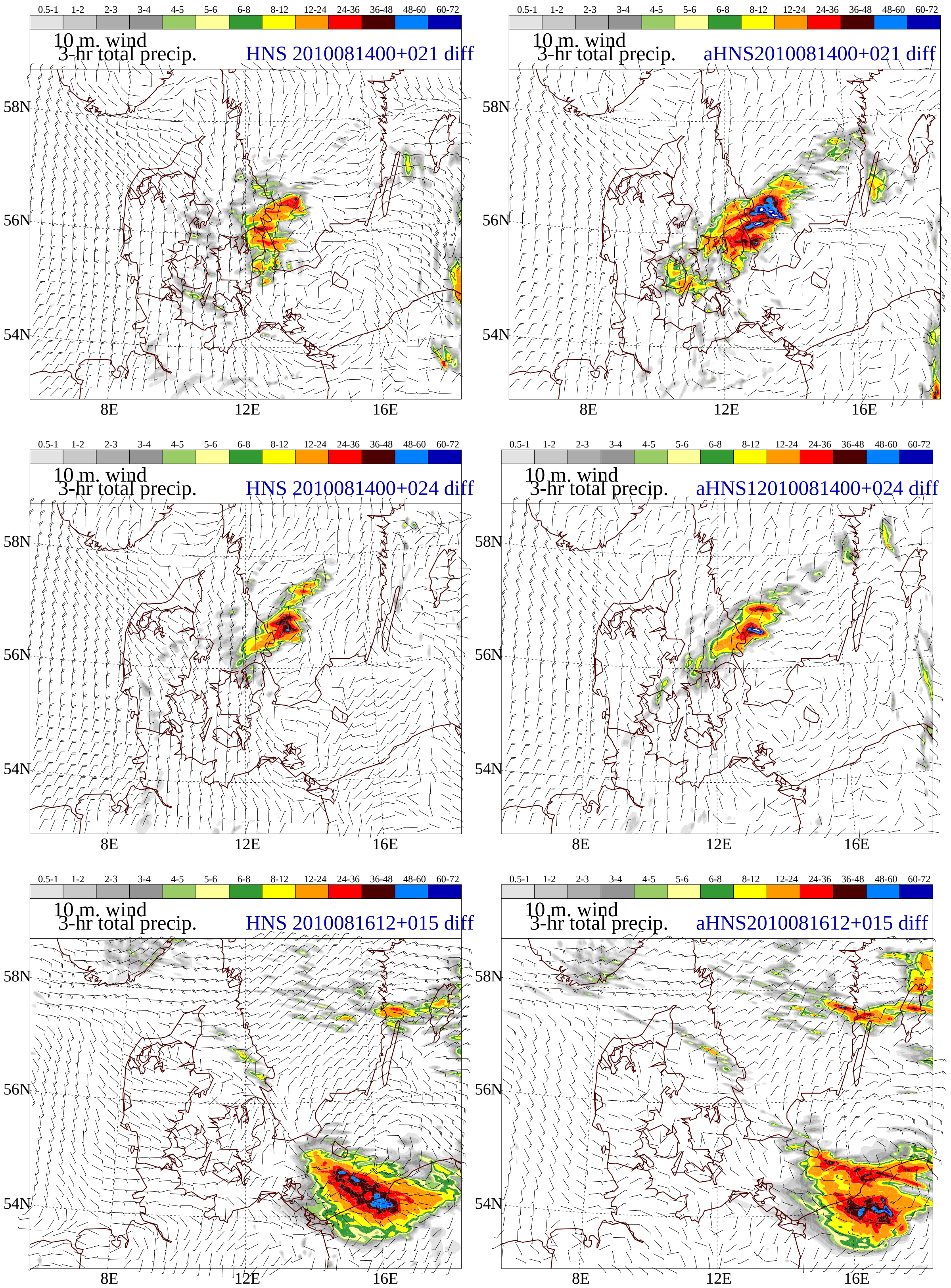

Figure 12: HARMONIE versus HARMONIE. Three hour accumulated precipitation and 10 m wind speed forecasts from HARMONIE-1 (left) and HARMONIE-2 (right). Top and middle: Copenhagen case, valid times 14 August 21 UTC and 15 August 00 UTC, respectively. Bottom: Bornholm case, valid time 17 August 03 UTC.

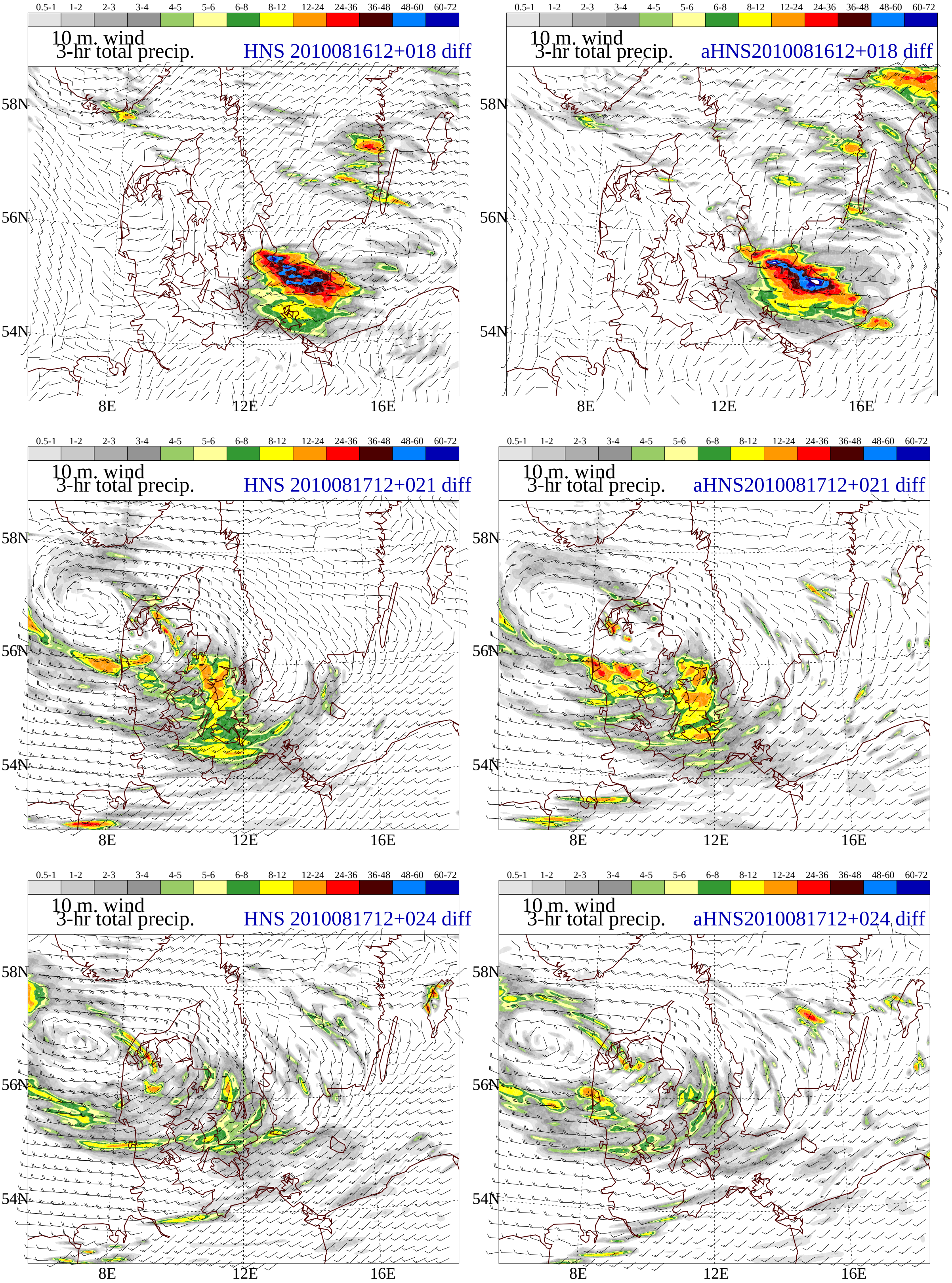

Figure 13: HARMONIE versus HARMONIE. Three hour accumulated precipitation and 10 m wind speed forecasts from HARMONIE-1 (left) and HARMONIE-2 (right). Top: Bornholm case, valid time 17 August 06 UTC. Middle and bottom: Billund case, valid times 18 August 09 UTC and 12 UTC, respectively.

much smaller than the predictability of larger-scale weather systems such as extratropical cyclones. If the deep convection is activated by forced ascent in a weather system with a much larger horizontal scale than the scale of the convective cell it might be expected to be possible to identify the convective regions within the weather system with almost the same predictability as is valid for the weather system. However, the predictability of the precipitation pattern that develops within the convective regions is likely to be much shorter for the reasons discussed above.

4. Concluding remarks

Experiments have been run for a longer Autumn period (1 October to 25 November 2010) and for a shorter Summer period (10 August to 23 August 2010).

Verification results for the Autumn period showed that the present operational DMI-HIRLAM system (DMI-HIRLAM-S03L65), operationalized 23 November 2010, for this period generally performed better than the former operational system DMI-HIRLAM-S03(L40). The intercomparison further showed that DMI-HIRLAM-S03L65 performed better than the HARMONIE-system (HARMONIE-35h1), running preoperationally at DMI. The latter system generates 24 hour forecasts twice a day (from 00 and 12 UTC). The main reason for the inferior results of the HARMONIE-system is likely to be that it is not yet running under optimal conditions for the following reasons: No upper air and surface analysis are done, the code is based on cycle 35h1 instead of the most recent release (cycle 36h1) and a double nesting involving ALADIN-35h1 and DMI-HIRLAM-T15 is applied. It is to be expected that improvements in performance can be obtained by including upper air and surface analysis, switching to cycle 36h1 and possibly also by simplifying the nesting, for example by a direct coupling of HARMONIE (AROME) to ECMWF (European Centre for Medium Range Weather Forecasts) model data. The experiments done for the August period should be considered as a preliminary step in this direction.

Results for the August period showed that improvement in surface parameter verification against EWGLAM observations within the NORTHSEA-domain is obtained in the HARMONIE-system by switching from cycle 35h1 in HARMONIE-1 to cycle 36h1 in HARMONIE-2. It is not clear how much of the improvement was due to the shift in cycle and how much was due to inclusion of surface analysis (unintentionally switched off i the HARMONIE-1 runs) and an increase in the number of levels from 60 to 65. Another important result was that HARMONIE-2 performed almost as good as DMI-HIRLAM-S03L65NOUA. This result is of particular importance, since the latter models were running under nearly the same conditions (same number of levels, nearly same horizontal resolution, surface analysis, no upper air analysis, and nesting plus blending with ECMWF). Conditions differed concerning model domain, since HARMONIE-2 was running on a subdomain (NORTHSEA) of "S03" applied in DMI-HIRLAM-S03L65NOUA as well as in the operational DMI-HIRLAM-S03L65.

The verification results for HARMONIE-2 appear promising, but the considered period is too short for any firm conclusion. The intension is to replace the operational DMI-HIRLAM-S03L65 with an operational HARMONIE system. Before this step can be taken it is necessary to prove that the HARMONIE system performs at least as good as the present operational system. This requires runs with the HARMONIE system with upper air analysis (3DVAR) as well as surface analysis on the DMI platform in parallel with the operational runs. Further, the present domain (DENMARK) in HARMONIE should be increased to meet storm surge demands and experiments with the goal of establishing an optimal configuration should be done on extended periods, perhaps as an ideal minimum two winter and summer periods dominated by a low and high index NAO (North Atlantic Oscillation) circulation, respectively.

In the HARMONIE system extreme weather events should also be predicted at least as good as in DMI-HIRLAM-S03L65. In the present report focus has been on extreme precipitation, exemplified by three events occurring in Denmark within the August period. Case studies of these events showed that both HARMONIE and DMI-HIRLAM in all the cases were able to predict accumulated precipitation amounts comparable to observed amounts. However, the models were not very accurate in predicting where and at what time the heavy precipitation occurred. The fundamental reason for this is probably that the predictability of deep convection is much shorter than the predictability of synoptic-scale systems. Convective precipitation depends strongly on sub-synoptic structures with horizontal scales down to 10 km or less. Accurate analysis of these scales is a huge challenge, and requires both theoretical work and more observations with finer coverage in space and time. Such improvements would undoubtly lead to more accurate very short range (up to about 6 hours) convective precipitation forecasts, but do not change the predictability limit for these events.

With the state-of-the-art analysis and the present availability of observations, the case studies of heavy precipitation indicate that HARMONIE-2 is as good as DMI-HIRLAM-S03L65 in predicting these events. Similar case studies for other extreme weather events have not yet been done.

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