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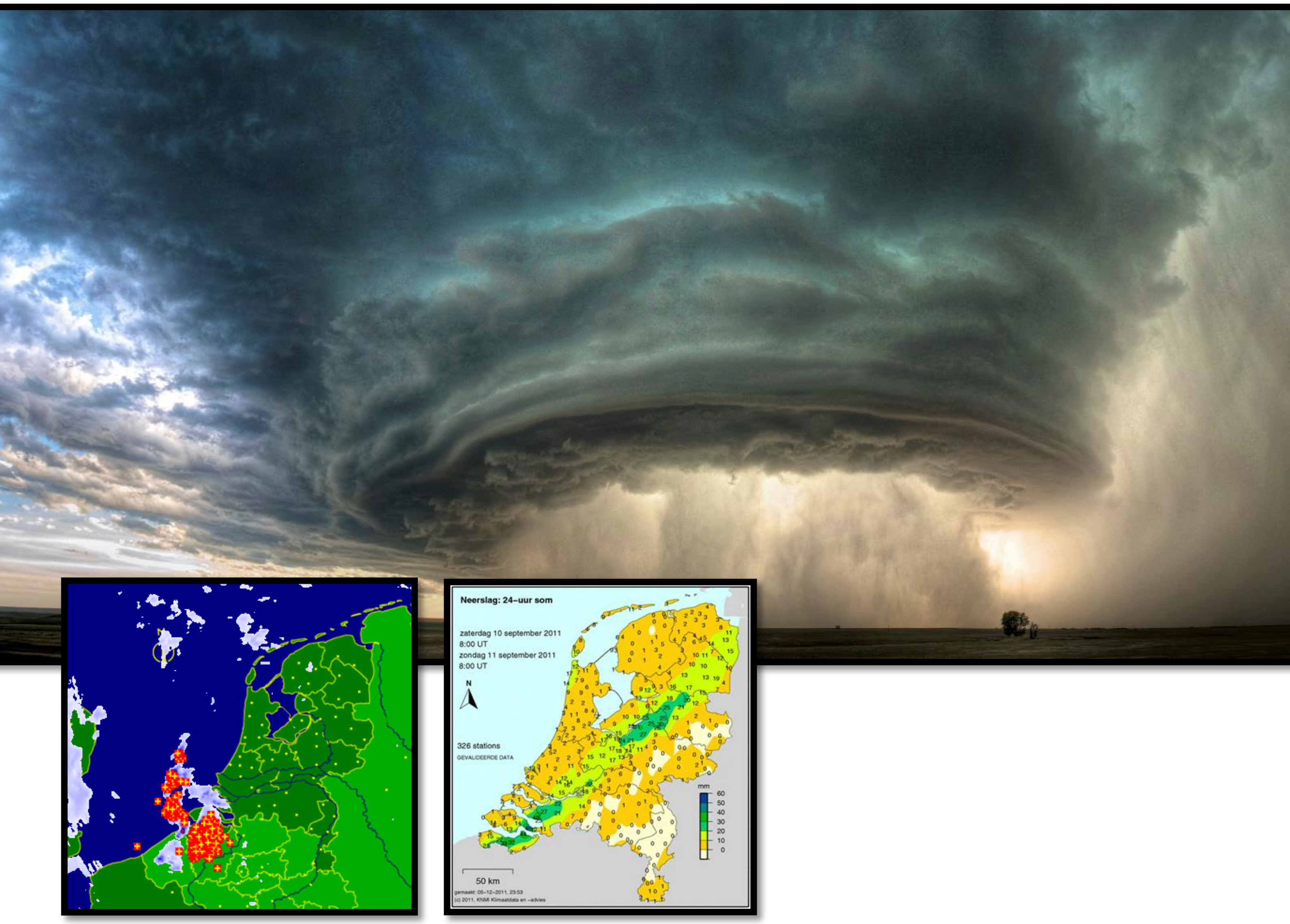

Severe weather events: sensitivity to horizontal resolution and microphysics for HARMONIE

MSc Thesis

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Abstract

On 10 September 2011, a supercell storm travelled from Southwest to Northeast across The Netherlands leading to excessive precipitation, lightning and severe wind gusts. This severe weather event has been investigated with the non-hydrostatic numerical weather prediction model HARMONIE. The case has been run with two versions of the HARMONIE model with increasing horizontal resolution up to 100 m and altered microphysics and turbulence settings. A large factor 10 difference in cloud ice is observed between the two model versions. The new model version shows cloud ice concentrations that are comparable to observations. The overprediction of spots with high amounts of precipitation is hereby reduced. A "sanity check" experiment resulted in a correct inner domain model environment and the removal of a bug in the HARMONIE nesting procedure. The nesting of two HARMONIE environments results in counterintuitive behaviour of the model. At 100 m resolution, almost nothing is left of the original precipitation pattern. Rain intensity increases with increasing resolution and is consistent with existing literature. A higher rain evaporation rate leads to less precipitation reaching the surface at 100 m resolution. A new turbulence scheme (HaRatu) does not show a large impact. At larger scale (2.5 km), a higher evaporation rate also leads to new triggered convection, resulting in more precipitation. The new turbulence scheme results in a decreased accumulated precipitation and is not entirely consistent with earlier tests. Runs with HARMONIE at 100 m resolution are possible, but a lot more work has to be done to be able to use it in operational meteorology.

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1. Introduction

Numerical weather prediction (NWP) has improved remarkably over the past decades, following the increase of computing power. However, there are still limitations in NWP models, due to deficient data assimilation, coarse resolutions, and incomplete or inaccurate representation of atmospheric physics (Roebber, 2004). In recent years, horizontal resolution for limited area models has increased to values of 2-4 km, which made it possible to explicitly resolve deep convection without extra parameterization (Seity et al, 2011, Hong & Dudhia, 2012). These high resolution models are already widely used by national weather services for operational weather forecasting. For example, the Royal Dutch Meteorological Institute (KNMI) uses HARMONIE (2.5 km horizontal resolution) since March 2013, while Météo-France uses the AROME model (2.5 km) since December 2008 (Seity et al, 2011), and the Deutscher Wetterdienst (DWD) uses the COSMO-DE model (2.8 km) since April 2007 (Baldauf et al, 2011). Moreover, Météo-France has a 1.3 km version of the AROME model in operational mode since the beginning of 2015 (Seity et al, 2014).

High resolution models, such as the ones mentioned above, have proven to be rather good in capturing small-scale convective systems. These convective systems are, especially in summer time, important extreme weather phenomena that can lead to excessive precipitation, lightning and severe wind gusts threatening human life and the environment. For example, Groenland et al (2010) describe a bow echo event that occurred on the 14^{th} of July 2010 in The Netherlands leading to two casualties. Researchers strive for more accurate forecasts of these specific convective systems, but due to the non-linear nature of convective processes, it is still a challenge to predict these small-scale convective systems with the desired accuracy. Many studies have shown that deep convection is better reproduced when using a higher horizontal resolution. Verrelle et al (2015) show that a higher resolution represents the convective structures better for a practical weather forecast of organized convective systems. Bryan et al (2003), and Bryan & Morrison (2012) state that the improved representation of convection is due to the fact that sub-kilometer simulations can develop a broader spectrum of convective motions. Azorin-Molina et al (2014) captured sea breeze convective showers in Spain that were previously not forecasted by the operational coarser HIRLAM model. Although, a higher resolution may increase the representation of convective systems, it does not necessarily improve the accuracy of the forecast. It is therefore important to know how large the model errors are at different horizontal resolutions (Bryan & Morrison, 2012). Weisman et al (2008), showed that no overall improvement could be observed in terms of timing and location of significant convective outbreaks in a comparison between a high-resolution model and a coarser operational model. This implies that increasing the model resolution can only improve the accuracy of forecasts of convective precipitation, if also physical parameterizations become more advanced. Fiori (2010) supports this view by showing that a non-hydrostatic model cannot simply have its horizontal resolution increased to simulate deep convection without also changing the turbulence closure scheme to a scheme based on LES.

Recently, a new version of HARMONIE has been released (cy38h1.2; www.hirlam.org) for research purposes and eventually for use in operational weather forecasting. This new version contains new features, mainly concerning data assimilation, microphysics and ensemble prediction (EPS). For this study, the differences in representation of microphysical processes is most important. Harmonie-38h1.2 includes an option where the deposition/evaporation rates of various ice particles are reduced to better represent observations, OCND2. A more detailed description of this OCND2 option can be found in section 2.2.5.

The first aim of this study is to investigate the differences between HARMONIE versions cy38h1.1 and cy38h1.2 for a supercell event in the Netherlands. On top of that, it is a sensitivity study to examine the effects of increasing the horizontal resolution and changing the microphysics settings. The potential of very high resolution (VHR) modelling with HARMONIE will be tested and the role of rain evaporation and a different turbulence scheme will be evaluated under these different resolutions. To reach this, the following main research question will be answered:

- What is the potential of HARMONIE under very high resolution for a specific severe weather case?

To answer this research question, several subquestions need to be addressed:

- What is the difference between Harmonie38h1.1 and Harmonie38h1.2 in forecasting a severe weather case?

- What is the effect of changing the model resolution to sub-kilometer scales (up to 100 m) for this case?

- What is the effect of changing the microphysics representation?

- How do microphysics change with increasing the model resolution?

- How do model data compare to upper-air measurements from Cabauw?

-To what extent is HARMONIE capable of doing 100m simulations?

- What is the effect of implementing a new turbulence scheme into HARMONIE for this case?

The report is organized as follows: Chapter 2 briefly describes the severe weather case, model and experimental set-up. The results will be shown in Chapter 3 and will be thoroughly discussed. Conclusions and recommendations are presented in Chapters 4 and 5, respectively. Furthermore, various aspects that were touched upon in this study are more extensively described in the Appendices.

2. Methodology

2.1 Case description

On 10 September 2011, weather in the Netherlands was dominated by a cyclone located northwest of Ireland (Figure 2.1). On the 9th of September, the warm front passed. Warm, moist and unstable air was transported towards the Netherlands, which resulted in temperatures between 22 and 28 °C on 10 September 2011. The cold front reached the Belgian-French border at around 18 UTC on that day and some thunderstorms started to develop. One of these thunderstorms developed rapidly into a supercell traveling from Zeeland to Drenthe (Figure 2.1). This supercell resulted in a large amount of lightning (up to 800 discharges in 5 min.), very large hail (up to 3 cm) and severe wind gusts (exceeding 25 m/s). The KNMI issued warnings for extreme weather (code orange) in Zeeland, Noord-Brabant, and Zuid-Holland. Later Utrecht and Gelderland were added. The supercell resulted in a distinct SW-NE directed band of precipitation with maximum values up to 45 mm (Figure 3.2; right panel).

2.2 Model description

The model used in this study is HARMONIE. It is a non-hydrostatic numerical weather prediction model that is developed by the HIRLAM and ALADIN consortia, two research cooperations consisting of several European meteorological institutes (www.hirlam.org). HARMONIE is a meso-scale model with a 2.5 km horizontal resolution and 65 vertical levels. Due to this high resolution it is assumed that deep convection will be resolved by the model itself, but shallow convection must still be parameterized (de Bruijn, 2012). HARMONIE has adopted many of the physical parameterizations from the AROME model (see Seity et al (2011) for a detailed description of AROME). Some of these parameterizations, important for this study, are described in more detail below. Surface components, like natural land surface, urban areas, lakes and oceans are described by various physical models, merged in the so-called SURFEX land surface module (SURFEX, 2009). This module can also be used for assimilation of (near) surface variables.

2.2.1 Microphysics

The microphysics in HARMONIE is represented by a three-class ice parameterization scheme, called ICE3 (Pinty and Jabouille, 1998). It is coupled to a Kessler scheme for warm cloud pro-

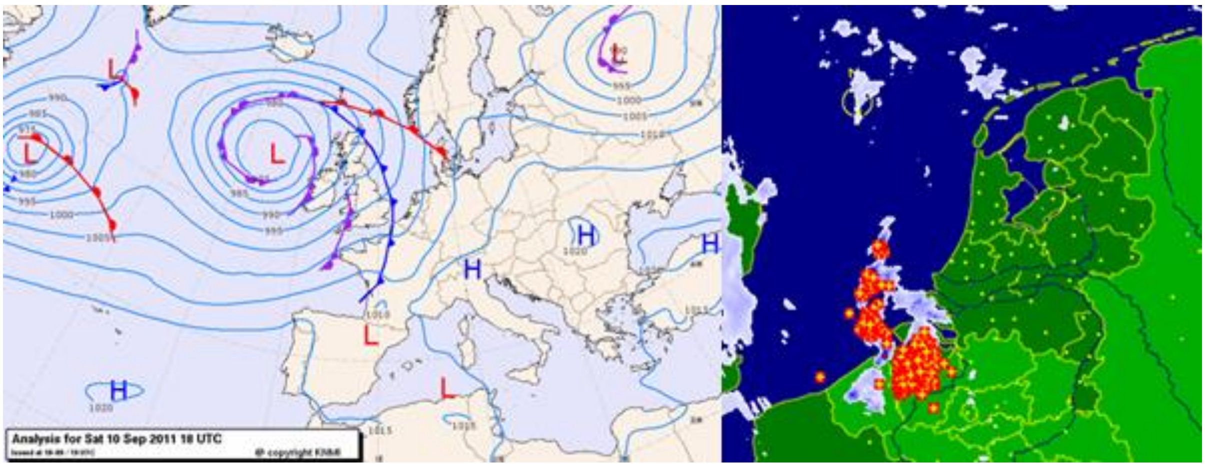


Figure 2.1. The synoptic situation for 10 September 2011 at 18 UTC (left) and the developed supercell above Zeeland (right).

cesses. Besides describing the evolution of water vapor content (qv), the scheme describes five more water species: cloud droplets (q_c), rain drops (q_r), ice crystals (q_i), snow (q_s) and graupel (q_g). Hail is not included as a separate water species in ICE3, but is assumed to behave like large graupel particles. The size distribution of the hydrometeors is assumed to follow a generalized γ-distribution, which is simplified into a more classical exponential (Marshall-Palmer) distribution. Simple power laws are used for linking size with mass and terminal velocity. The ICE3 scheme also includes a subgrid condensation scheme and a probability density function based sedimentation scheme. The condensation scheme allows a more gradual course between cloudy and non-cloudy cells, based on the variance of the departure from saturation inside the grid box which is diagnosed by the turbulence scheme (Bechtold et al, 2009; Seity et al, 2011). The sedimentation scheme is implemented to improve the numerical efficiency of the microphysics computation with relatively long time steps.

2.2.2 Shallow convection

To parameterize shallow convection, a combined eddy diffusivity mass-flux scheme (EDMF-m) is used. This scheme, developed at KNMI, follows the EDMF approach (Siebesma, 2007). This approach combines the ED (eddy-diffusivity: successful in representing a neutral boundary layer and surface layer in general) and MF (mass-flux: used for parameterization of shallow and deep moist convection) approaches and is presented for the dry convective boundary layer. Optionally, the EDKF scheme can be chosen. This scheme mainly differs from EDMF-m in terms of the convection scheme (MF). The EDMF-m convection scheme is based on the dual mass flux framework by Neggers et al. (2009) that accounts for both dry and moist updrafts which can coexist simultaneously. Dry updrafts are responsible for internal mixed layer (ML) transport, whereas the moist updrafts are responsible for transport out of the ML, coupling the cloud and subcloud layer. To allow both types of updrafts to coexist, a gradual transition to and from shallow cumulus convection is possible. The main difference between EDMF-m and this framework is the parameterization of lateral mixing (de Rooy and Siebesma, 2008, 2010, 2011). It takes, in contrast to other mass-flux schemes including EDKF, the cloud-height dependence into account (deeper cloud layers ask for smaller detrainment rates). Also the influence of the environmental relative humidity and updraft properties on detrainment rates are taken care of by this new parameterization.

2.2.3 Turbulence

The 1D prognostic Cuxart-Bougeault TKE scheme (Cuxart et al, 2000), originally developed for the Meso-NH research model, is used to represent turbulence in HARMONIE. This scheme uses the Bougeault and Lacarrere mixing-length (Bougeault and Lacarrere, 1989), which calculates the potential maximum displacement of parcels lifted upwards and going downwards. The distance traveled by the parcel is related to its initial kinetic energy at its starting level. The parcel will stop when it has lost all of its initial kinetic energy. The 1D approach is sufficient for the default resolution of 2.5 km, since at these resolutions it can be assumed that vertical gradients and turbulent fluxes are much larger than in horizontal directions (Bechtold, 2009). A 3D turbulence scheme is actually necessary for model simulations at higher resolutions (Seity et al, 2014).

2.2.4 Data Assimilation

The model contains a 3D-VAR data assimilation technique, by which the initial conditions are determined. In earlier small-scale numerical studies, initial conditions were taken from a coarser NWP model (e.g. HIRLAM or ALADIN) in combination with a spin-up mode (Brousseau et al, 2011, 2014). This data assimilation technique uses regional observations and a previous high-resolution model forecast valid for the same analysis time as the new forecast. Observation-error covariances and background variances are used to perform corrections to different model variables. The extent to which corrections are performed depends on, among others: the model itself, its resolution, geographical area, weather regime, and the density of the observation network. For this specific study, 3D-VAR is not used.

2.2.5 OCND2 option

A large difference between the two model versions, which are used in this study, is the *OCND2* option (Ivarsson, 2014). This option mainly concerns the ICE3-cloud- and stratiform condensation scheme in the AROME model (which contains the underlying physics of Harmonie) and can be set to *TRUE* or *FALSE*. In the new HARMONIE version (cy38h1.2) this option is *TRUE* by default.

The updates that come with *OCND2=TRUE* have been incorporated in this model version to improve cloud forecasts over Northern Europe and other cold regions in wintertime. Several aspects of cloud forecasts were addressed, like the underestimation of low level clouds (LLC) in moderate cold winter conditions and an overestimation of LLC and fog under severe cold conditions. The underestimation can be connected to a too active growth of ice particles and too quick release of water vapor. The overestimation is mainly caused by an overprediction of cloud ice water.

A more realistic forecast of clouds is reached by reducing the deposition/evaporation of snow and graupel with a factor of 0.1 and 0.25, respectively. The deposition/evaporation rate of cloud ice water is also reduced, by deriving it from the Bergeron-Findeisen process. This process occurs in the conversion from vapor to ice and has been tuned. Furthermore, a parameterization of the effect of non-spherical ice crystal characteristics is included as well as a collision factor which is based on the Stokes number (a measure for the particle characteristics in a flow). An ice-cloud cover parameterization is derived and is related to the extent to which cloud ice water and relative humidity are saturated with respect to ice. For more details on all the alterations and tuning, see the documentation by Ivarsson (2014).

2.3 Experimental set-up

Figure 2.2 shows a graphic representation of the experimental set-up for this study. Two default runs (model version 38h1.1 and 38h1.2) are carried out with the default 2.5 km horizontal resolution and 65 vertical levels on an 800x800 grid centered at De Bilt, The Netherlands (red dot in Figure 2.3). Initial and 3-hourly boundary conditions are taken from a coarser ECMWF model (for more information see www.ecmwf.int). No data assimilation is performed prior to the actual forecast (a ''cold start''), resulting in a forecast starting directly from ECMWF fields. The time step is set to 60 seconds, which is the default value.

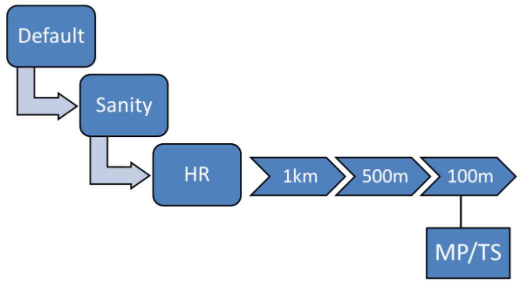


Figure 2.2. A graphic representation of the experimental set-up (HR = high resolution, MP=microphysics, TS= turbulence scheme).

In order to test the envisaged experimental set-up for higher resolutions, a so-called "Sanity Check" is performed to check whether the nesting procedure works properly. The "Sanity Check" is an experiment with a 400x400 domain at 2.5 km nested into the default 800x800 domain at 2.5 km. The inner domain uses 1-hourly HARMONIE boundaries instead of the 3-hourly ECMWF boundaries for the outer domain. To examine the sensitivity of the model to changing horizontal resolution, three resolution changes have been applied to the default run of 38h1.2 (1 km, 500 m and 100 m). The corresponding domains are shown in Figure 2.3. This is not done for version 38h1.1. These high resolution runs are also carried out on an 800x800 grid and 65 vertical levels. The time step is lowered to 20 and 5 seconds for 500 m and 100 m resolution, respectively. For these high resolution runs, a 3D turbulence scheme would actually be required. As this is not implemented yet, a 1D turbulence scheme was used for all experiments in this study. Two sensitivity tests are performed for the 100 m runs. The first test concerns microphysics, where the rain evaporation is increased by 50% and decreased by 50%. For the second test, the RACMO turbulence scheme is implemented into HARMONIE (HaRatu; HARMONIE-RACMO turbulence). The RACMO turbulence scheme is, most likely, the scheme that will be used operationally by the KNMI in the near future. Therefore, the default 1D-TKE scheme in HARMONIE is replaced by the RACMO scheme. A brief description of the main runs is shown in Table 2.1. For a more elaborate description of the specific settings for every run, see Appendix A.

Table 2.1. Brief description of the main model runs.

Run	Description
ZL1.1	Default 38h1.1 run
ZL1.2	Default 38h1.2 run
ZL1.2f	38h1.2 run LOCND2=FALSE
Sanity Check	“sanity check”
ZL1000	1 km run
ZL1000n	1 km run nested in HARMONIE
ZL500n	500 m run nested in HARMONIE
ZL100n	100 m run nested in HARMONIE
HaRatu	100m with RACMO TS
EVAPx1.5	100m with increased evaporation
EVAPx0.5	100m with decreased evaporation

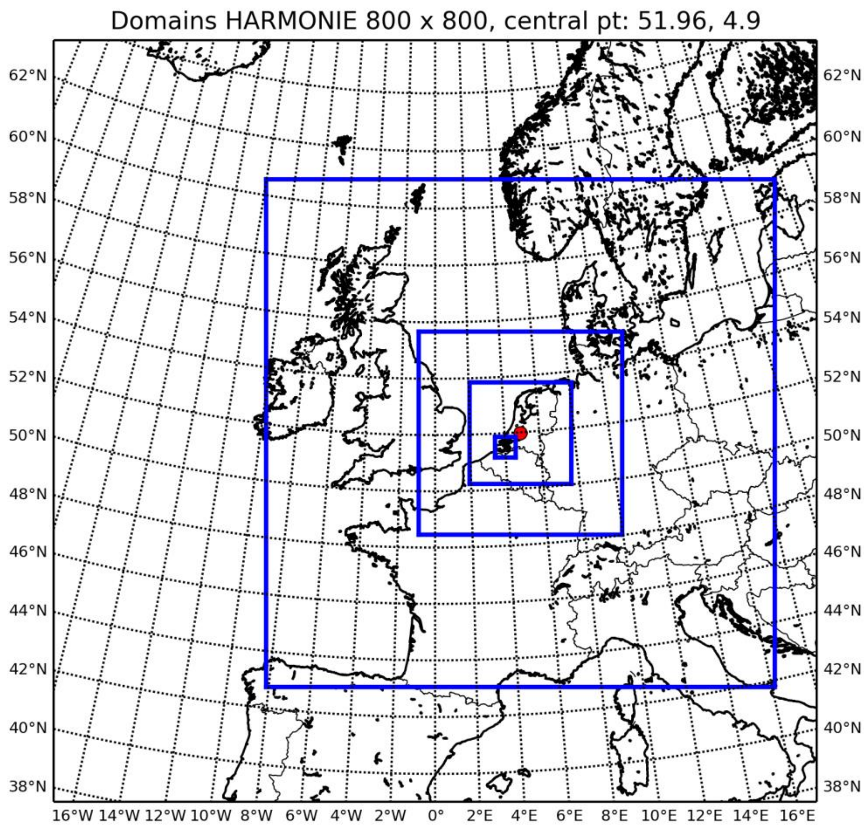


Figure 2.3. The 4 model domains comprising 800x800 grid points used in the HARMONIE experiments. The 2.5 km, 1 km and 500 m domains are centered at De Bilt, The Netherlands (red dot). The smallest (100 m) domain is centered at Zeeland.

3. Results & Discussion

This chapter gives an overview of the results. Section 3.1 starts with the results of the default 2.5 km model runs and continues with the Sanity Check in section 3.2, and higher resolution runs (1 km, 500 m and 100 m resolution) in section 3.3. The fourth section contains results on the sensitivity study that was performed for the 100 m runs.

3.1 Default runs

3.1.1 Sensitivity of rainfall to model versions

The base of this study are the two default runs *ZL1.1* and *ZL1.2*, corresponding to the HARMONIE versions cy38h1.1 and cy38h1.2, respectively. It is necessary to first check the model performance based on general parameters like temperature, wind, and precipitation. In general, the model reproduces the observed maximum temperatures of 22 – 28 °C reasonably good and the two model versions do not differ significantly. However, both versions show temperatures that are slightly lower than observed (Table 3.1). This is especially true for Maastricht with up to 1.3 °C difference for *ZL1.1*. Maximum wind speeds of up to 25 m/s (at station De Bilt) were observed on 10 September 2011 during the convective showers. Both model versions underestimate the maximum wind speed, with values up to 21 m/s (lower for the specific stations in Table 3.1). However, *ZL1.2* seems to do a better job, especially for the stations Westdorpe and Terneuzen.

Both model runs capture the convective precipitation that develops near the French-Belgian border on 10 September 2011 at 15 UTC and travels in a NE direction over The Netherlands (Figure 3.1). The convective cells are well captured by both model versions. At 18 UTC the first thunderstorms reach the south of Zeeland, which corresponds to observations. However, both runs seem to show some more precipitation over land than over sea compared to the observations (not shown). The extent of precipitation seems to be larger than observed, especially at 20 UTC. The area over sea travels much faster Northwards, causing the precipitation area to become stretched. The red area in the far South of The Netherlands, develops even more in time and corresponds to the highest rain intensities (up to 30 mm/hr). Both location and amount of precipitation can differ significantly for modeled and observed data in case of convective precipitation (double penalty) due to the very small scale of this type of event. Westdorpe, for example, received 2.2 mm of rain during the day instead of the 10.8 and 12.2 m predicted by ZL1.1 and ZL1.2, respectively (Table 3.1). Terneuzen received a lot more precipitation than modeled. This does not indicate a priori that the model is performing badly. Also notice

Table 3.1. Observed and modeled maximum temperatures, 24-hr precipitation and wind for 4 meteorological station in The Netherlands.

Location	Observed			ZL1.1			ZL1.2		
	T (°C)	P (mm)	Wind (m/s)	T (°C)	P (mm)	Wind (m/s)	T (°C)	P (mm)	Wind (m/s)
De Bilt	25.4	11.7	25	25.1	6.5	12	25.1	4.2	12
Maastricht	27.8	0.8	12	26.5	1.7	6	26.8	0.0	5
Westdorpe	26.5	2.2	15	25.9	10.8	10	25.9	12.2	15
Terneuzen	26.5	32.4	15	26.0	9.4	10	25.9	16.7	17

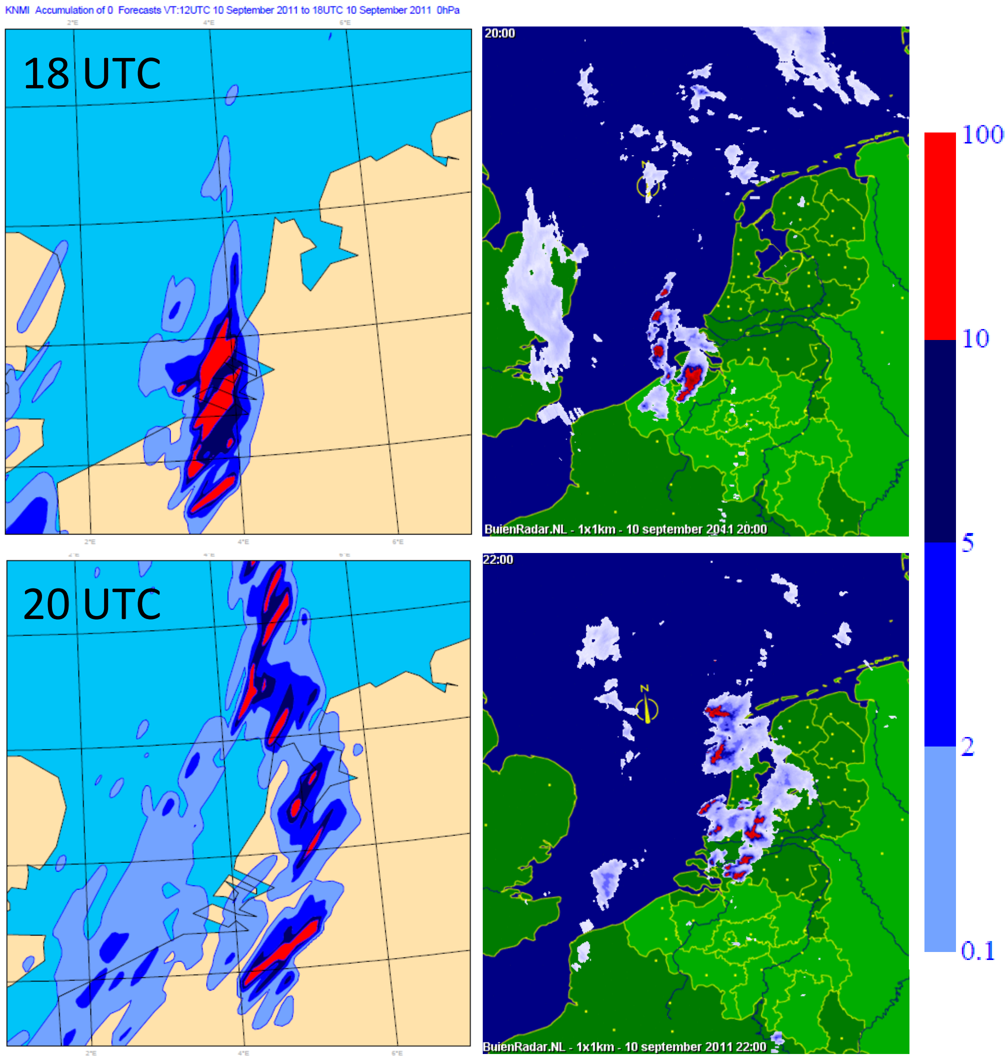


Figure 3.1. Precipitation in mm/hr for ZL1.1 (left) and observations (right) for 18 UTC (top) and 20 UTC (bottom).

the difference in observed precipitation between Westdorpe and Terneuzen, two stations that are only 10 km apart. It illustrates that routine verification of precipitation forecasts is difficult due to the double penalty phenomenon.

When looking at the accumulated precipitation, the precipitation patterns of both model runs look very similar (Figure 3.2; left and middle panel). Two distinct bands of precipitation are visible, one located over the southeast in a southwest (SW) to northeastern (NE) direction and one along the coast in a northerly direction. In the observations, this distinct band of precipitation over the southeast is clearly visible with maximum values of 45.2 mm in Zeeland. Accumulated amounts are comparable to observations, with maximum values mostly between 30 and 40 mm for both model runs. One peak value is present located South of Zeeland of almost 70 mm in ZL1.1 (Table 3.2). A second band located along the coast is not very clearly visible, but some higher values can be noticed from observations. Especially ZL1.1 shows more precipitation over land along the coast. Concerning the location of this band of precipitation, there is a small shift to the southeast compared to observations (more for ZL1.2 than ZL1.1). However, overall model output is comparable to observations.

Table 3.1. Domain average, minimum and maximum values of accumulated rain for observations, ZL1.1 and ZL1.2.

Experiment	Avg	Min	Max
Observed	-	0	45.2
ZL1.1	1.64	0	68.3
ZL1.2	1.50	0	44.1

3.1.2 Sensitivity of cloud ice/cloud water

Initially, no cloud ice is observed on any level for both model runs. At the first output step (after 1 hour), there is cloud ice present from level 31 to 10 (3.5-12 km height) for *ZL1.1* and from level 26 to 10 (4.8-12 km height) for *ZL1.2* (not shown). During the forecast, this remains almost the same. When the thunderstorms are developing further, cloud ice already appears at levels 6 or 7 (approx. 15 km height). Values are reaching 2-3 g/kg of cloud ice for *ZL1.1*, with maximum values being attained between levels 10 and 15. Values are reaching 0.2-0.3 g/kg of cloud ice for *ZL1.2*, which is a factor 10 smaller. This can be attributed to the lower deposition/evaporation rate of cloud ice (a process that happened too fast) in the option by Karl-Ivar Ivarsson (OCND2=true, *see section 2.2.5*). This result is consistent with early tests including this option (CNRM, 2015). However, these tests were performed during winter situations.

From theory, it is known that the precipitation process really starts to get going when cloud grow higher and contain more cloud ice (Lin, 2007). However, no large differences in the 24-hr accumulated precipitation are observed between the two forecasts (section 3.1). Overall, the same precipitation pattern is visible. The largest difference between the two default runs is the peak value of 70 mm that is not present anymore in *ZL1.2*. This is consistent with the earlier tests with summer convection and the OCND2 option, where there is a less "spotty" behavior with very intense precipitation in certain grid points. Over-prediction of very high precipitation amounts is reduced, probably due to the slowing down of cloud ice generation (Ivarsson, 2014). Since there is no large difference in precipitation amounts visible, there has to be a balance between cloud ice and cloud water that results in the same amount of cloud particles (ice, water) for both runs.

Initially, also no cloud water is observed on any level for both model runs. At the first output step, cloud water is present from level 20 to 33 and 41 to 52 for *ZL1.1* and from level 15 to 33

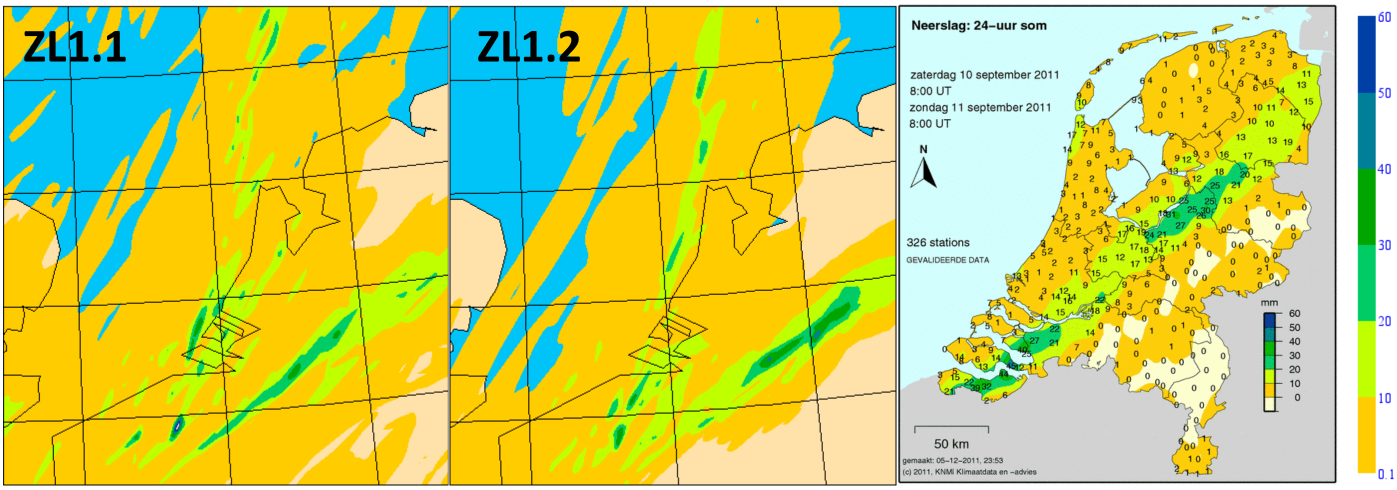


Figure 3.2. Accumulated precipitation between 10 September 2011 8 UTC and 11 September 2011 8 UTC for ZL1.1 (left panel), ZL1.2 (middle panel) and observations (right panel).

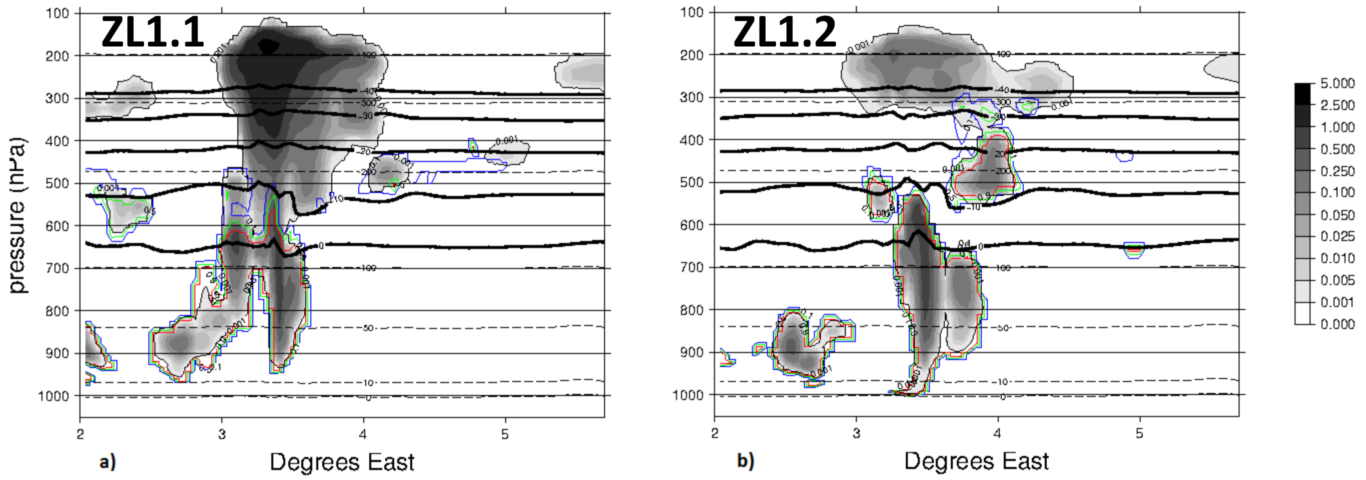
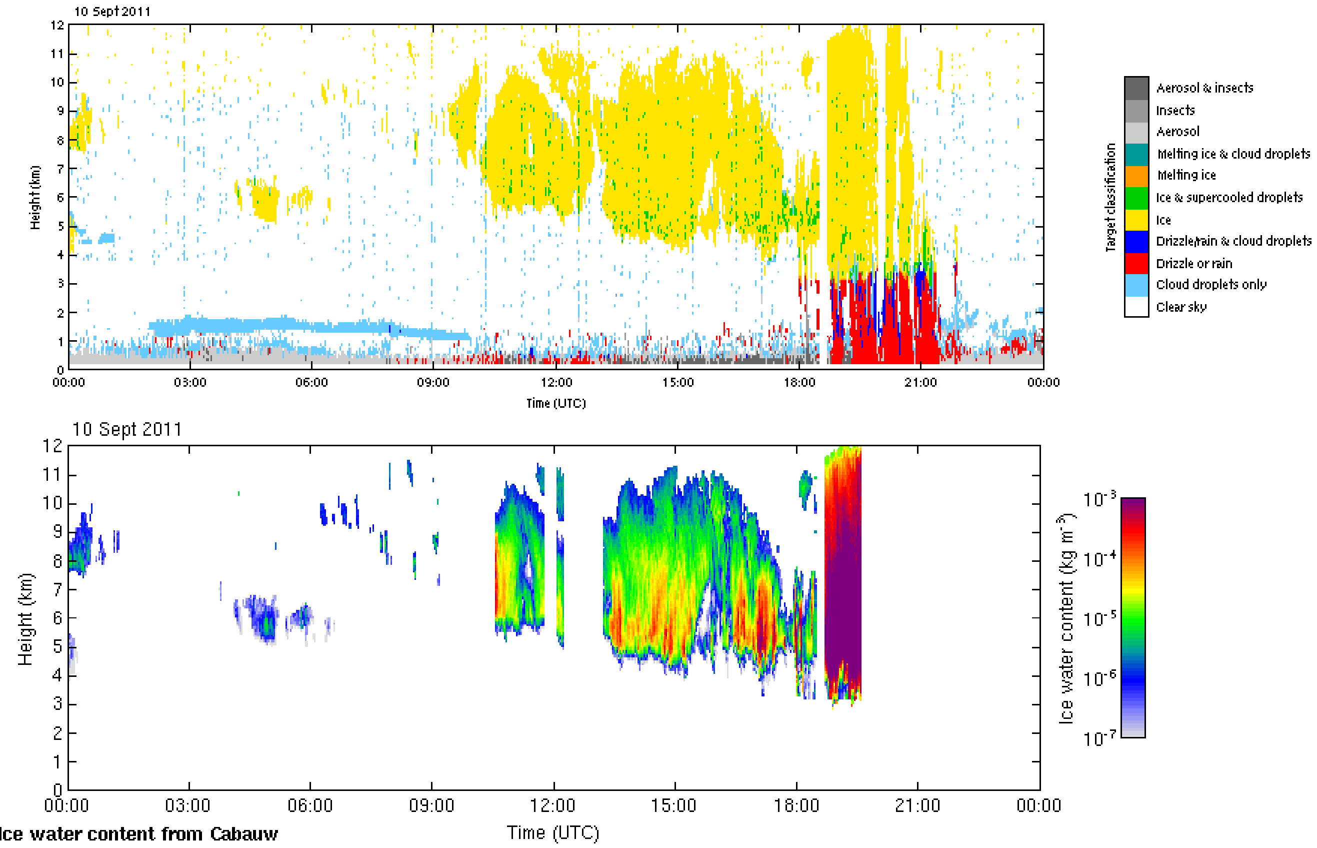


Figure 3.3. Vertical cross-section at 51ºN of cloud ice/cloud water for a) ZL1.1 and b) ZL1.2 at 17 UTC. Concentrations of cloud ice/cloud water are shown in grey (shaded; g/kg). The fraction of cloud water is shown by the colored lines (blue indicates 0.1, green indicates 0.5, red indicates 0.9).

and 41 to 52 for *ZL1.2* (not shown). This makes the upper cloud water layer of *ZL1.2* thicker. Since mainly the upper boundary of the cloud water layer differs between the two runs, the OCND2 option mainly appears to have an effect on the upper cloud layers (where of course cloud ice is present). Maximum values are in the order of 0.01 or 0.02 g kg^{-1} for *ZL1.1* and are a factor 10 higher for *ZL1.2*. This indicates that there is a new balance between cloud ice and cloud water (more cloud ice means less cloud water). Cloud water is present at lower levels than cloud ice, and the cloud water layers are shallower than the cloud ice layer. When the showers have formed, the cloud water layer reaches from level 20 to level 65 for *ZL1.1* and from level 15 to level 65 for *ZL1.2*. Maximum values during the showers are in the range of 0.5-0.7 g kg^{-1} for both model runs.

Figure 3.3 shows a vertical cross-section of cloud water/cloud ice from west to east at 51ºN for a) ZL1.1 and b) ZL1.2 at 17 UTC. The colored lines show the fraction of cloud water where blue, green and red indicate that 10%, 50% and 90% of the cloud particles is cloud water, respectively. In both cases the storm is located at the same position (approximately 3.5 degrees East). However, there is a large discrepancy in the amount of cloud ice between the two runs. This is mainly caused by the addition of the OCND2 option in *ZL1.2*, where changes have been made concerning the evaporation and deposition rates of cloud ice, snow and graupel to improve the quality of cloud forecasts (see section 2.2.5 for a more elaborate description of this option). Much more cloud ice is present in *ZL1.1*. Cloud ice concentration reaches values of up to 2.5 g kg^{-1}, whereas for *ZL1.2* values only reach up to 0.25 g kg^{-1} which is a factor 10 difference. Another striking difference between the two runs is the fact that there is only cloud ice (and no cloud water) present from around 500 hPa (approx. 5 km) and higher for *ZL1.1* and from 300 hPa (approx. 9 km) and higher for *ZL1.2*. Observations from the Cabauw meteorological site (Figure 3.4) indicate that cloud ice already occurred at heights of approximately 5 km, but mixed with super cooled droplets and some cloud water, which makes *ZL1.2* closer to observations. Moreover, *ZL1.2* shows a more physical behavior reminiscent of the *Wegener-Bergeron-Findeisen* process (Wegener, 1911;



Figuur 3.4. CloudNet classification product from Cabauw indicating the presence of several cloud particles in time (top panel, yellow indicates cloud ice) and the associated concentrations (bottom panel), *CloudNet (2015)*.

Bergeron, 1935; Findeisen, 1938). This widely accepted process is responsible for the growth of several precipitation elements in clouds and reaches its maximum at approximately -12°C (where the difference between the water vapor pressure with respect to water and the one with respect to ice is largest). Above the -20°C level, many cloud droplets are already turned into ice. Above the -40°C level, everything is converted into ice. *ZL1.2* follows this process pretty accurately, with some cloud water still present between the -20°C and -40°C levels and no cloud water above the -40°C level. *ZL1.1* does not show any cloud water particles anymore above approximately the -15°C level. Concentrations of cloud ice in *ZL1.1* are a lot higher compared to observations (factor 10). Due to the OCND2 option, cloud ice concentrations in ZL1.2 better represent the observations. The observations show values around 10^{-4} kg m^{-3}, which make the model values of the same order of magnitude as observations.

3.2 Sanity Check

Changing the horizontal resolution in high resolution numerical weather prediction models is not as straightforward as one might think. Just lowering the value from 1 km to 500 m resolution is in most cases not ideal. The default 2.5 km runs in this study obtain boundary conditions from the ECMWF model. By increasing the HARMONIE resolution below 1 km, the resolution difference between the ECMWF model and HARMONIE may lead to unwanted features in the forecast. In this way, the HARMONIE model domain may be too small to be able to capture the hydrostatic environment. Therefore multiple nesting is required, by which a smaller HARMONIE domain with higher resolution is placed into the default 2.5 km domain instead of the ECMWF model. The

2.5 km run will provide the lateral boundary conditions for the higher resolution runs.

Before embarking on higher resolution experiments, it is necessary to check whether such a nesting experiment gives the expected output. Therefore, a so-called "sanity check" is performed. The sanity check is an experiment with a 400x400 domain at 2.5 km nested into a larger (800x800) domain at 2.5 km. The inner domain uses 1-hourly HARMONIE boundaries instead of the 3-hourly ECMWF boundaries for the outer domain.

It is expected that the nested 400x400 domain will yield quite similar output as the output from the default 800x800 experiment in terms of basic parameters like temperature (T), specific humidity (Q) and the two wind components U and V. This is based on the fact that two domains of the same HARMONIE model environment are involved in the nesting procedure. Figure 3.5 shows vertical profiles of the difference between the default experiment ZL1.2 and the Sanity Check experiment for the parameters T, Q, U, and V at initial state (t=0). The profiles consist of three lines, indicating maximum differences and the average difference between the two domains. They are constructed by subtracting the maximum positive, maximum negative, and average values from the field on every model level (65 levels) from both domains. What can be noticed from the figures is that T is not very different for the two

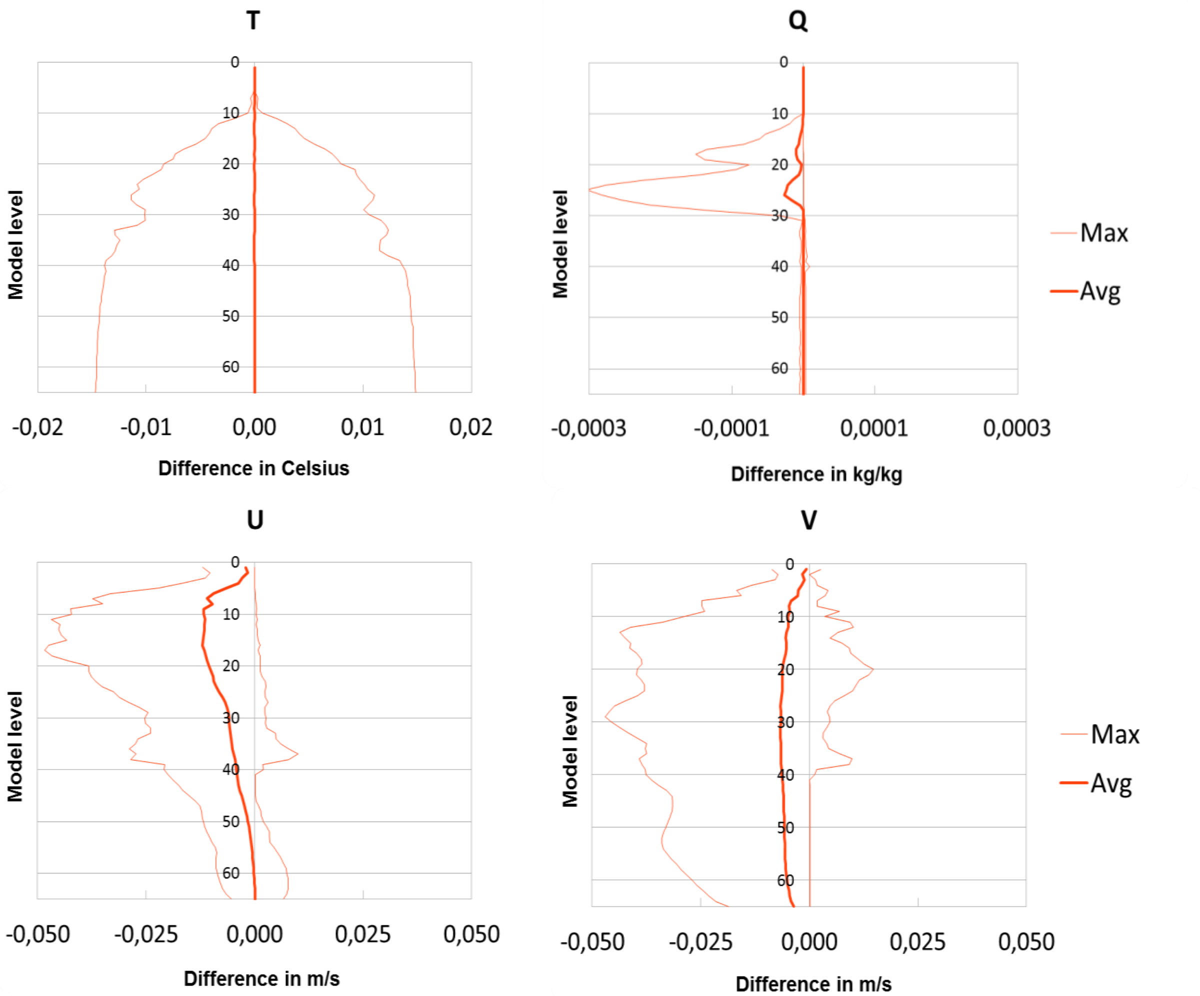


Figure 3.5. Vertical profiles for maximum and average differences between the default ZL1.2 experiment and the "sanity check" experiment over all model levels for the different parameters T, Q, U, and V.

experiments. Maximum differences reach values of up to 0.015 degrees. The average shows a profile around 0, since maximum negative and minimum positive values cancel each other out. The parameters Q, U and V show larger discrepancies between the two domains, where the average profile is negative for the three parameters. Especially the negative difference of Q between model levels 10 and 30 (drying of the upper air) was alarming, which resulted in the absence of high cloud cover and, consequently, too high temperatures at the surface. This means that it is not straightforward to assume that the inner domain receives the right input from the outer domain. The upper air moisture problem eventually turned out to be a bug in the HARMONIE to HARMONIE nesting procedure, which caused concern, because this setting was already in operational mode at some meteorological institutes. The bug concerned the allowance of RH oversaturation and was removed from the model (by Ulf Andrae, SMHI). This resulted in an inner domain with a comparable general output for all model levels between the two runs. More (technical) details on this bug can be found in Appendix B.

3.3 High resolution runs

The next step in this study was to increase the model horizontal resolution. For the runs at high resolution, we applied the process of multiple nesting (as discussed in Chapter 3.2). At 1km resolution, a run employing the default nesting using ECMWF data at the boundaries is also performed. This experiment is denoted as ZL1000. In the process of running simulations

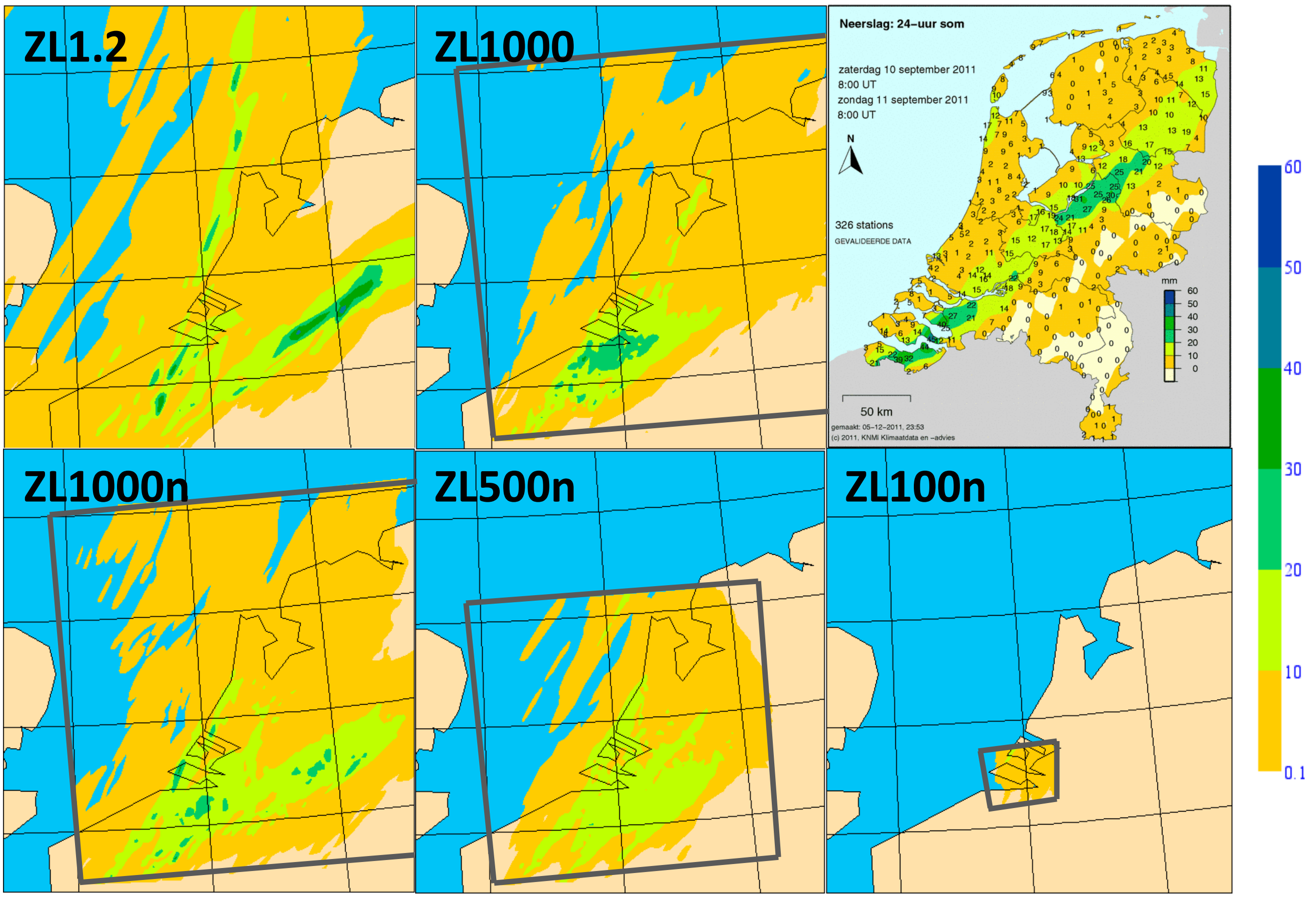


Figure 3.6. Accumulated precipitation between 10 September 2011 8 UTC and 11 September 2011 8 UTC for ZL1.2 (left top panel), ZL1000 (middle top panel), ZL1000n (left bottom panel), ZL500n (middle bottom panel), ZL100n (right bottom panel) and observations (right top panel). Also notice the smaller domains with increasing resolution (the grey boxes indicate the domain).

with sub-kilometer resolutions, HARMONIE experienced instability issues and an LPC scheme was needed in order to complete the forecasts. More on instability and the solution for this can be found in Appendix A.

Table 3.2. Average, minimum and maximum values of accumulated rain for ZL1.2, ZL1000, ZL1000n, ZL500n and ZL100n.

Experiment	Avg	Min	Max
ZL1.2	1.50	0	44.1
ZL1000	2.41	0	33.0
ZL1000n	3.19	0	31.0
ZL500n	3.66	0	21.1
ZL100n	1.48	0	13.5

3.3.1 Sensitivity of rainfall to model settings

There are large discrepancies visible between the accumulated amount of precipitation simulated in the five runs (Figure 3.6). Notice that the domain is getting smaller with increasing resolution (ZL100n only covers Zeeland). For all the runs a comparable large convective system travels from Zeeland to the Northeast, except for the 100 m run where only small showers start to develop (not shown). Precipitation patterns are different for all runs, of which the reference run (ZL1.2) shows the largest similarity to the observations. The default 1km run (ZL1000) shows a more widespread area with precipitation amounts >10 mm, and is mostly located above the Southwest of The Netherlands. The band of higher precipitation along the coast and over the Southeast are not present. Maximum values reach 33 mm of precipitation, which is much less than the 45.2 mm in observations and the 44.1 mm in ZL1.2 (Table 3.2). The 1km run that is nested into the 2.5 km run (ZL1000n) also shows a lower accumulated precipitation. However, it shows more similarity to the reference run than the straightforward 1km run. A band of higher accumulated precipitation from Southwest to Northeast is visible, though with lower maximum values. Maximum values reach to 31 mm for this run, even less than the other 1km run. The 500 m run (ZL500n) shows a similar pattern as the ZL1000 run. Most of the precipitation is located above the Southwest and no clear band of high precipitation is visible. However, the area with values >10 mm is larger than the reference run. Maximum values are only half of the amounts simulated in the reference run. The 100 m run only covers the province Zeeland, due to the domain of only 80x80 km. For this run precipitation is only marginal. Notice that even some areas in Zeeland receive no rain at all. Maxi-

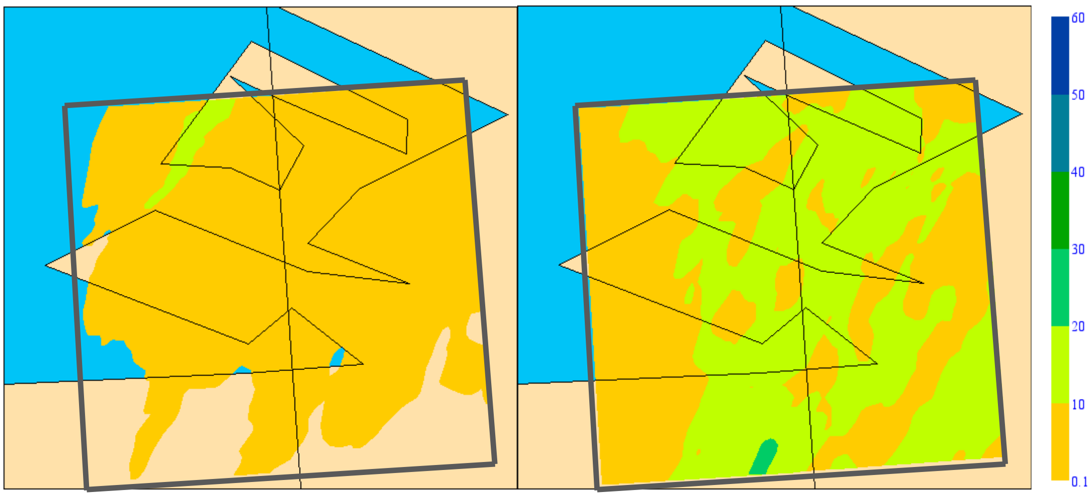


Figure 3.7. Accumulated precipitation between 10 September 2011 8 UTC and 11 September 2011 8 UTC for ZL100n. Left: the original 100 m run. Right: runs with increased additional parameter input.

mum values reach up to only 13 mm. This result is contrary to what several studies on convective cases with increasing resolution state: precipitation intensity increases with increasing resolution (Fiori et al, 2010, 2011; Seity et al, 2014). In the latter paper, it is mentioned that there is also an increase in the amount of individual cells with increase in resolution. This is not the case for this specific study, which results in the more gradual and widespread precipitation. As stated earlier, only small showers develop in the 100 m domain. Several hypotheses were set up to examine why almost all precipitation disappeared in the 100 m run:

- The first being that the step from nesting a 100 m resolution domain in a default 2.5 km domain would be too large (factor 25). However, nesting the same domain in a domain with 500 m resolution yielded comparable results.
- A next step was to increase the frequency of giving boundary input files to the 100 m domain from 1-hourly to every 20 minutes. This step also did not improve the forecast.
- The small domain size for the 100 m runs could be a factor that was limiting here. Decreasing the domain size of the 500 m run (ZL500n) from 800x800 to 400x400 grid points did worsen the forecast significantly and showed comparable results as the 100 m run, indicating that domain size is a limiting factor. This is surprising, because both domains have the same HARMONIE model environment. Therefore, it would seem that not much time is needed for the smaller domain to adapt to the larger one.

Based on the points mentioned above, some additional information given from the mother domain to the smaller domain seems to be missing. By forcing the large domain to give extra information (by more parameter input and starting from a different forecast step; for more details see *Appendix A*) to the inner domain, the forecast showed an area of precipitation as in the lower resolution runs. Showers passed through the domain and did not only develop in the domain itself.

Due to this alteration in experiment settings, the accumulated precipitation for ZL500n and ZL100n has increased remarkably (only ZL100n shown in Figure 3.7). Maximum values reach up to 42.8 and 26.0 mm instead of the 21.1 and 13.5 mm for ZL500n and ZL100n, respectively. The average rain intensity now increases with increasing resolution (Figure 3.8), which is consistent with the existing literature. Especially,

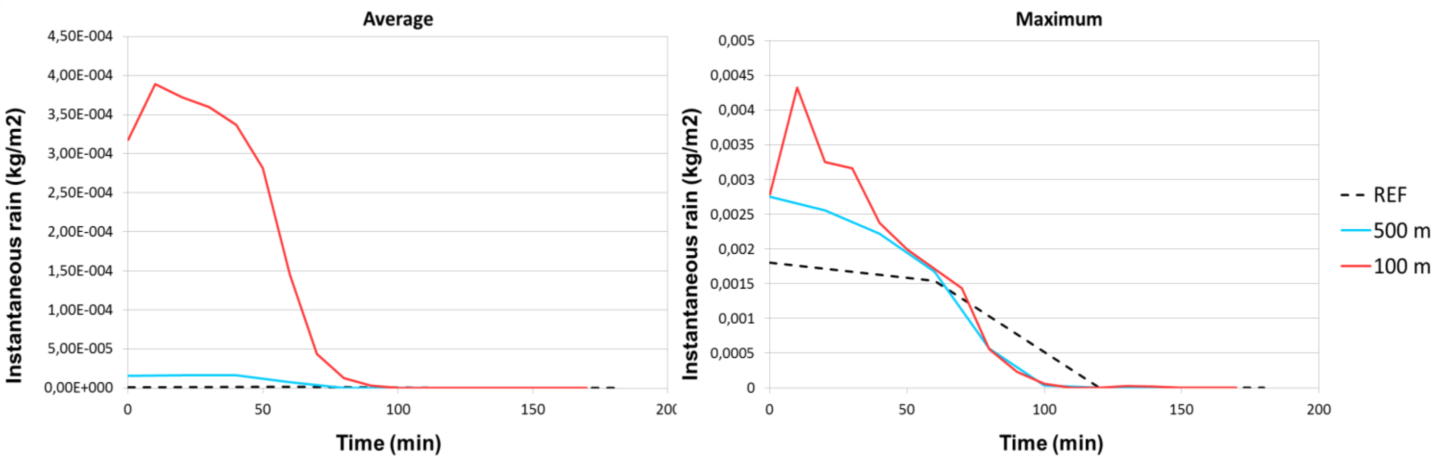


Figure 3.8. The average (left) and maximum (right) rain intensity for the reference run (ZL1.2), 500 m (ZL500n) and 100 m run (ZL100n) over time. The values are calculated over the same domain for all three runs (the domain of the 100 m run).

the average intensity of the 100 m run is significantly higher. It indicates that the ZL100n becomes very active over the whole domain. ZL100n also shows a much higher maximum rain intensity, especially during the first 30 minutes. The fact that rain intensity increases with increasing resolution, does not necessarily indicate that the new, adjusted runs are better. However, the area of rain that passes through the domain is more comparable to the default runs and subsequently the observations. Therefore, the adjusted runs are used for further analysis.

3.3.2 Sensitivity of cloud ice/cloud water

Vertical cross-sections at 51°N of cloud water/cloud ice for different high resolution runs at 17 UTC are shown in Figure 3.9. The colored lines show the fraction of cloud water. In all cases, the storm is located at approximately the same position (3.5 degrees East). This indicates that the location is a quite constant factor in the model simulations and that it is not sensitive to increasing horizontal resolution. Also the amount of cloud ice and cloud water is not sensitive for changes in horizontal resolution. Large differences in cloud ice concentrations, as observed between ZL1.1 and ZL1.2, are absent. Cloud ice concentration reaches values of up to 0.25 g kg^{-1} for all four simulations. Cloud water concentrations seem to be just slightly higher for ZL1000n, ZL500n, ZL100n, which can possibly be connected to

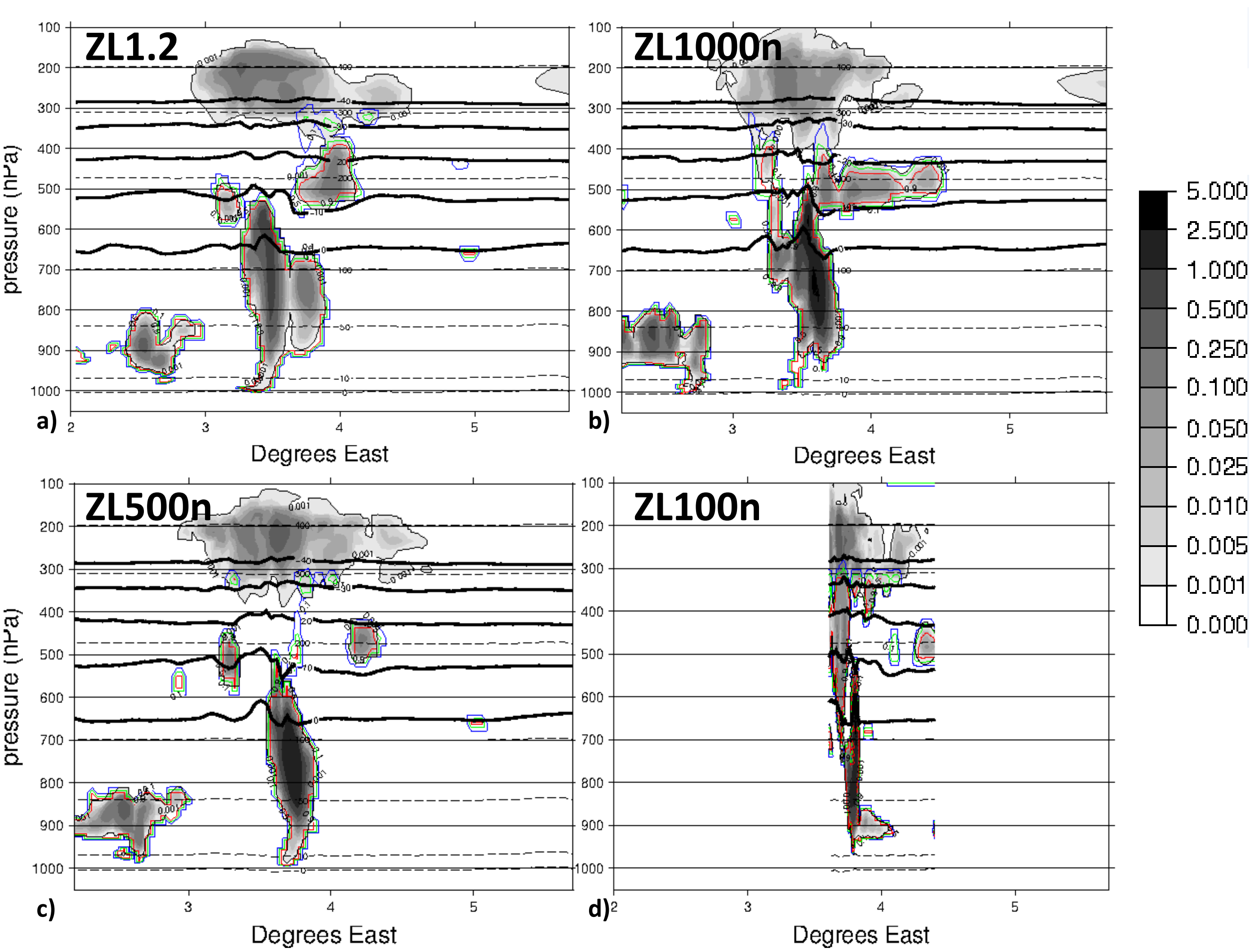


Figure 3.9. Vertical cross-section at 51°N of cloud ice/cloud water for a) ZL1.2, b) ZL1000n, c) ZL500n and d) ZL100n at 17 UTC. Concentrations are shown in grey (shaded; g/kg). The fraction of cloud water is shown by the colored lines (blue indicates 0.1, green indicates 0.5, red indicates 0.9).

the higher precipitation intensity for these three runs. However, the spatial extent of cloud water is larger for the default run (ZL1.2). ZL100n shows a somewhat smaller area of cloud water.

3.4 Sensitivity Analysis

The sensitivity analysis comprises two tests in order to investigate the impact of *i)* a different turbulence scheme (HaRatu) and *ii)* changes in the rain evaporation rate (EVAPx0.5 and EVAPx1.5).

3.4.1 Sensitivity to microphysics settings

For the sensitivity test concerning microphysics, rain evaporation has been both increased and decreased with 50%. This change in evaporation acts in two ways on (deep) convection. A direct impact (and negative feedback) is that due to a higher evaporation rate, less precipitation is reaching the surface. The second impact is due to the cooling of air, because the process of evaporation uses environmental heat. A higher evaporation rate leads to cooler

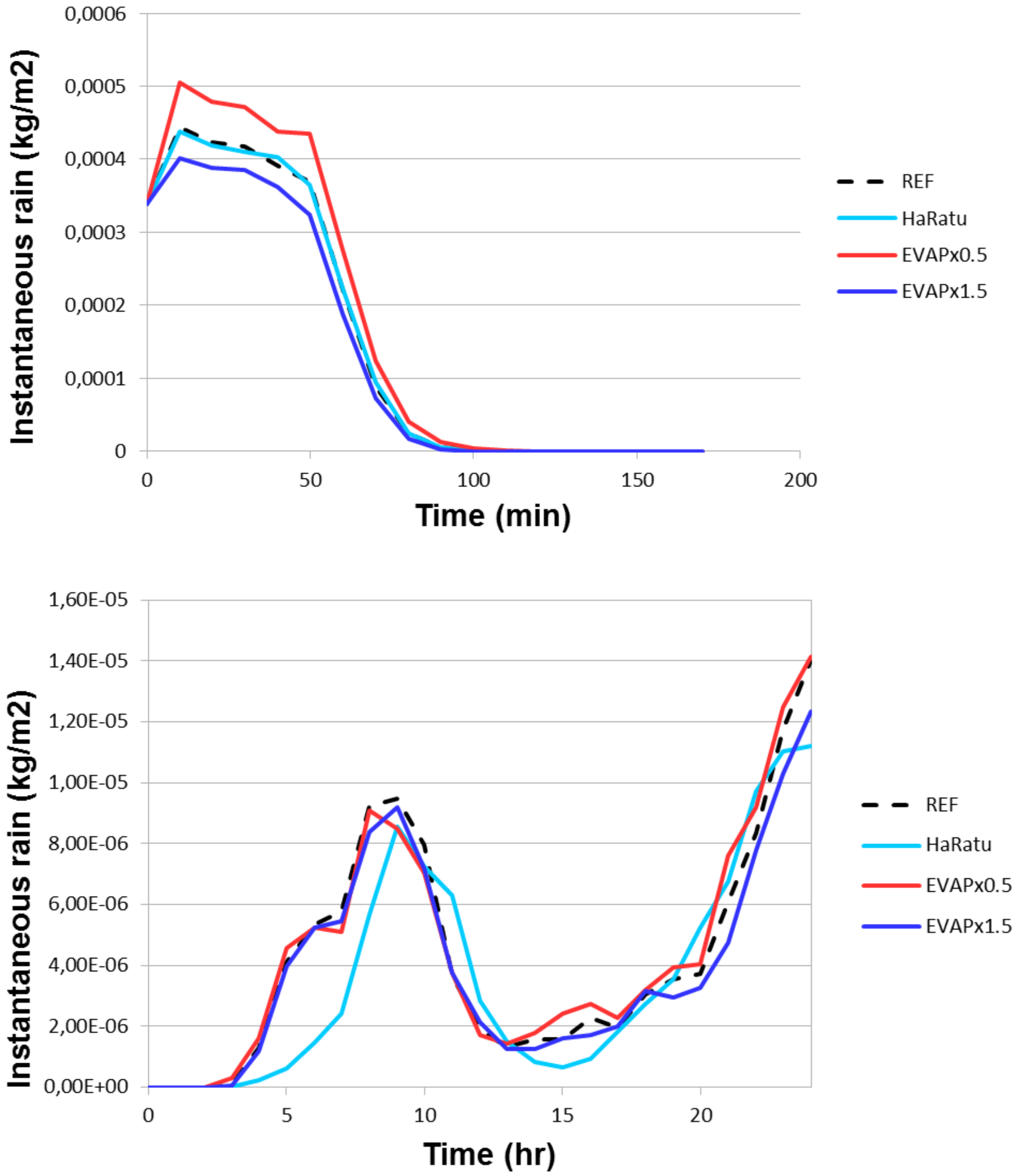


Figure 3.10 Domain averaged precipitation intensity in kg m^{-2} for the reference run ZL100n (top panel) and ZL1.2 (bottom panel) and the perturbation runs HaRatu, EVAPx0.5 and EVAPx1.5.

air that descends more quickly and can therefore trigger more (new) convection, resulting in more precipitation reaching the surface (Tompkins, 2000). This is an indirect impact and a positive feedback. Results of the 100 m runs, show that a higher evaporation rate leads to less precipitation reaching the ground, due to a decreased precipitation intensity (as already mentioned in section 3.1.2, Figure 3.10; top panel). This is expected, based on the direct impact of increasing the evaporation rate and is consistent with a study by Krikken (2012) for convective summertime situations. A decrease in rain evaporation of 50% leads to an increase in rain intensity of approximately 16%. An increase in rain evaporation of 50% leads to a decrease in rain intensity of approximately 10%. With the increase in evaporation, temperatures in the cold pool are slightly lower (approximately 2%) and associated wind speeds are slightly higher (approximately 8%), indicating that more triggering of convection is possible. However, this extra convection is not visible for this specific case at a resolution of 100m, making the direct impact the most important process of the two mentioned. Most probably, the domain size of 80x80 km is limiting and not large enough to show the new triggered convection. Therefore, the same alterations have been performed on the default 2.5 km runs and results are shown in Figure 3.10 (bottom panel). Two peaks are visible, the first one corresponding to the actual supercell event and the second one corresponds to different system not affecting the Netherlands. Both, the run with an increased evaporation,

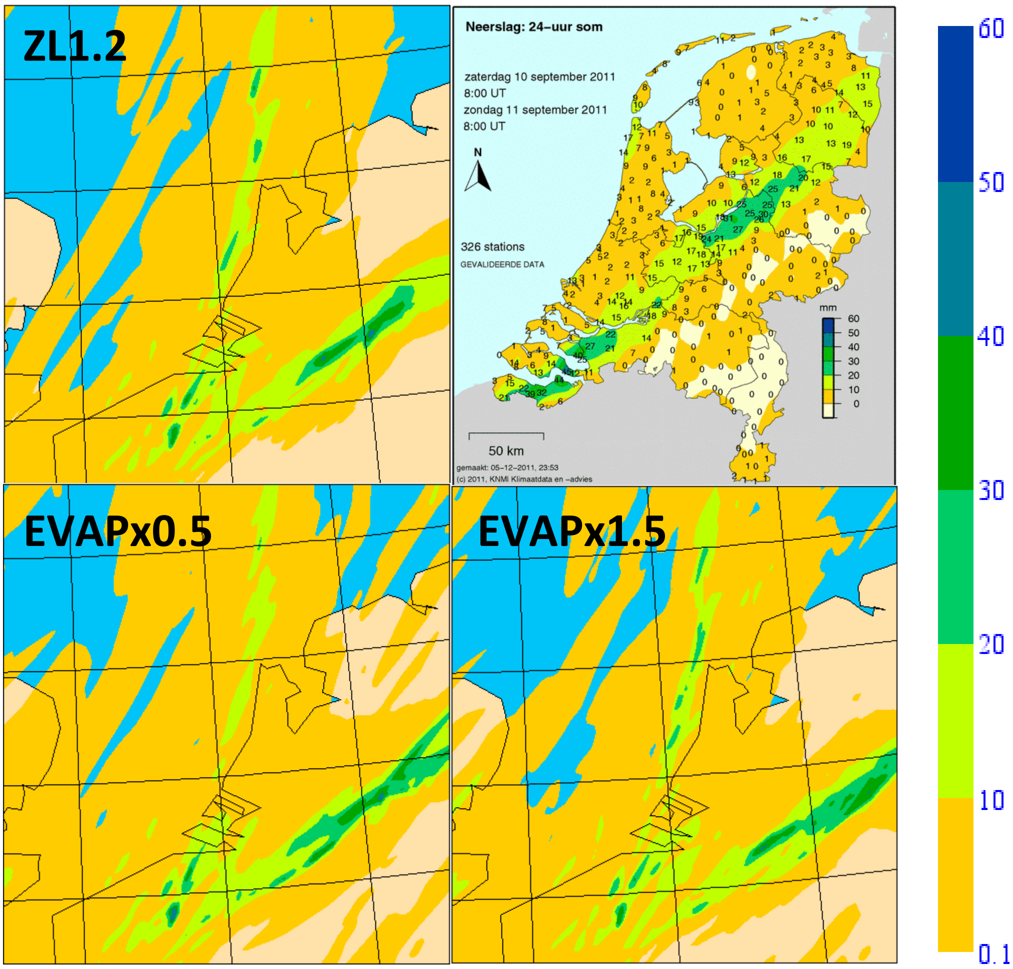


Figure 3.11. Accumulated precipitation between 10 September 2011 8 UTC and 11 September 2011 8 UTC for ZL1.2 (left top panel), EVAPx0.5 (left bottom panel), EVAPx1.5 (right bottom panel) and observations (right top panel).

and the run with a decreased rain evaporation do not differ much from the reference run (in this case *ZL1.2*) for the time of interest. After approximately 12 hours, however, the same behavior is observed as in the 100 m runs (*EVAPx0.5* and *EVAPx1.5*): higher (lower) evaporation leads to less (more) precipitation reaching the ground. Figure 3.11 shows the 24-hr accumulated precipitation for the default 2.5 km run and the runs with increased and decreased evaporation. *EVAPx0.5* shows more precipitation in the bottom left corner as well as for the SW-NE directed band of precipitation (direct impact). However, it shows slightly less precipitation along the coast, which could indicate that there is less triggering of convection due to a weaker cold pool (temperatures are slightly higher and wind speeds lower). Surprisingly, *EVAPx1.5* shows more precipitation along the coast and more widespread precipitation for the SW-NE directed band. This could indicate that the indirect impact (more evaporation, more triggering of convection) is of bigger influence. here.

3.4.2 Sensitivity to turbulence scheme

The 100 m run and the default 2.5 km run are also performed with the RACMO turbulence scheme implemented. This scheme mainly results in increased entrainment at the top of the mixed layer and is in general numerically more stable than the Bougeault and Lacarrere length scale on which it is based (Lenderink and Holtslag, 2004). An overall result of the larger entrainment rate is that the convective inhibition (CIN; the energy needed to lift a parcel vertically and pseudo-adiabatically from its starting level to its level of free convection (Stensrud, 2007)) is broken down faster. In this way, convection is able to take place earlier. Strong buildup of energy is therefore limited, resulting in less intensive precipitation. Experimentation with Haratu in HARMONIE indicated that unrealistic (too strong) precipitation events were removed (Pers. Commun., Lenderink, 2015).

The light-blue line in Figure 3.10 shows the precipitation intensity for the runs with the RACMO turbulence scheme. In contrast to the *EVAP* runs, *HaRatu* shows no significant difference with the reference 100 m run (Figure 3.10; top panel). Probably, this is due to the fact that the model environment needs some time to adapt to the new turbulence scheme. The test with the 2.5 km run including HaRatu does show low values of 24-hr accumulated precipitation as compared to the default 2.5 km runs and observations (Figure 3.12). This is as expected, following the process explained above. Maximum values reach up to 30 mm for *HaRatu* compared to 44.1 and 45.2 mm for

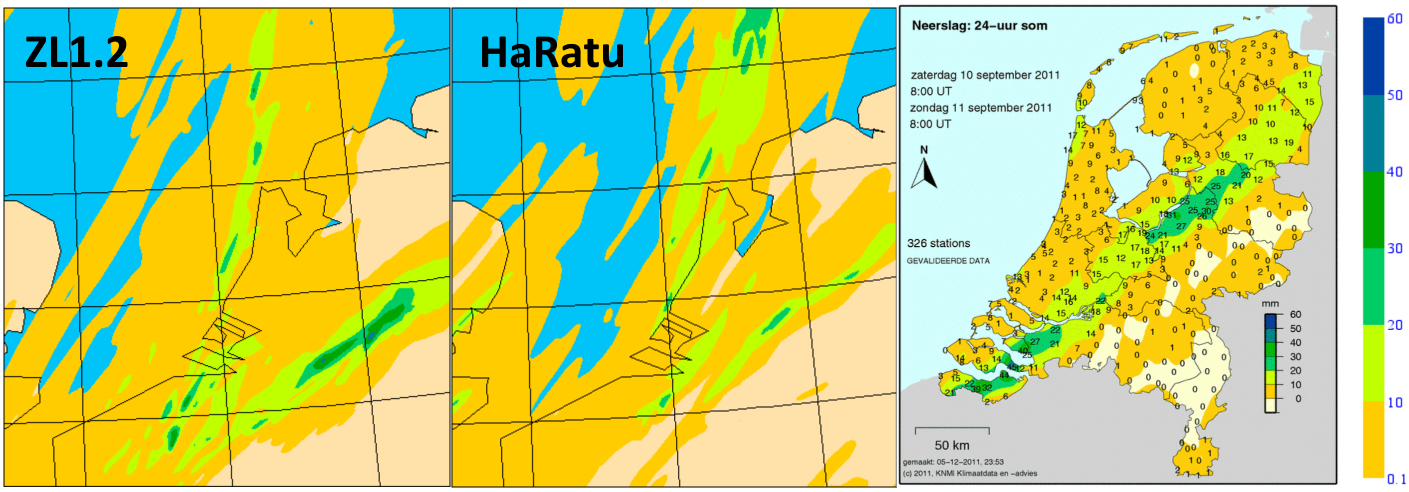


Figure 3.12. Accumulated precipitation between 10 September 2011 8 UTC and 11 September 2011 8 UTC for ZL1.2 (left panel), HaRatu (middle panel) and observations (right panel).

ZL1.2 and observations, respectively. This does not indicate whether the model run is worse than reference runs. For example, the location of the precipitation is better predicted and there is less overestimation of the spatial extent of the showers (which was too large in *ZL1.1*; Figure 3.1). Especially, the SW-NE directed rain band is weaker and the area located North of The Netherlands is more active. This indicates that the hypothesis on CIN does not hold for the entire domain. In Figure 3.10 (bottom panel), the light-blue line clearly shows the lower average rain intensity and peak value as compared to the reference run. After approx. 10 hours, the average intensity for *HaRatu* is higher, corresponding to the more active precipitation located North of The Netherlands. Showers also develop later in *HaRatu* and no increased precipitation is observed before the supercell event occurred. This, one would expect because CIN is broken down faster.

4. Summary and Conclusion

High-resolution model simulations of a severe convective case in The Netherlands on 10 September 2011 have been conducted with HARMONIE, a non-hydrostatic model with a 2.5 km horizontal resolution. This grid resolution is assumed to be sufficient for explicitly resolving deep convection. The differences between two HARMONIE model versions have been investigated. Several runs have been performed ranging from the default 2.5 km to 1 km, 500 m and even 100 m horizontal resolution. This has been done in order probe the potential of HARMONIE with very high resolution runs in case of a severe weather event. The sensitivity to rain evaporation settings and a different turbulence scheme (HaRatu) has been tested.

4.1 Main conclusions

The two model versions (*cy38h1.1* and *cy38h1.2*) are comparable in forecasting the deep convective case, by showing the same precipitation pattern. Although, the older model version (*ZL1.1*) shows more spotty behavior of intense precipitation, due to a too active growth of ice particles. The OCND2 option in the new model version (*ZL1.2*) results in a more realistic growth of ice particles, which leads to cloud ice concentrations that are closer to observations. The intensive "spots" are absent in *ZL1.2*, which is in accordance with earlier experiments performed in Sweden. The 10 times higher cloud ice concentrations in *ZL1.1* do not result in substantial higher precipitation amount, since more cloud water is present in *ZL1.2*. Increasing the model resolution only, does not improve the forecasting quality. In this study, it results in an underestimation of 24-hr accumulated precipitation and a more widespread precipitation area. This underestimation increases for increasing horizontal resolution. Since we use a multiple nesting procedure for the higher resolution runs (1km, 500m, and 100m), domain size should not be the limiting factor. Several parameter values are not passed on from the outer domain to the inner domain. By forcing the model to do so, the high resolutions runs show a precipitation area much more comparable to the default runs, with corresponding higher maximum values of accumulated precipitation. Based on these runs, it can be concluded that precipitation intensity increases with increasing resolution. The cloud ice/cloud water distribution is not dependent on horizontal resolution alone. Comparisons with CloudNet data from the Cabauw meteorological site, show that cloud ice concentrations substantially improve by activating the OCND2 option (Ivarsson, 2014), which is default in *cy38h1.2*. The direct impact of changing the water evaporation rate is the most important process for the 100 m runs and its impact is felt instantly (already after 10 minutes). The 24-hr accumulated precipitation increases with decreasing evaporation rate. The triggering of new convection is not visible in the 100 m runs due to the small domain size, but there is larger impact in the 2.5 km run (larger domain, longer forecast). In the default runs, increased evaporation leads to decreased as well as increased precipitation. The increased precipitation occurs later in the forecast, after the triggering of new convection is able to occur.

4.2 Minor conclusions

Striking is the fact that domain size is also an important issue for the HARMONIE to HARMONIE nesting. However, a small domain is possible to work with, but only when the outer domain passes on information very frequently, for example by increased analysis frequency. When going to higher resolutions of under 1 km, the model has to deal with instability issues. Too high wind speeds at the highest model levels, cause the model runs to crash. The use of an LPC scheme is needed in order to complete the forecasts. HARMONIE is capable of doing 100 m resolution runs. However, the several settings to go to 100m resolution, result in time consuming runs. Mainly the time step that is needed for these high resolution 800x800 grid point runs, increases the computation time. The 12-hr forecast that is performed in this study takes approximately 6 hours to complete, which makes these specific runs used in this study not suitable for short-term operational weather forecasting purposes (e.g. Schiphol airport is interested in very high resolution runs, mainly for wind forecasts). However, they can be used for research purposes.

5. Recommendations

This chapter contains a reflection on the research itself and recommendations for further research on these kind of topics.

This study is just a first step in going to 100 m resolution modelling. Many components of the HARMONIE model are not (yet) advanced enough for these kinds of resolutions. It is therefore very important to do further research and try to implement better representations of several model components (e.g. a 3D turbulence scheme, high resolution soil data and more advanced microphysical processes) into HARMONIE.

As stated in other studies and supported by this study, only increasing the horizontal resolution does not necessarily improve the forecast. That is why it is better to go from a deterministic to a more probabilistic approach, especially for these cases of summer convection. The sensitivity analysis performed in this study can give valuable information for this kind of approach. However, further research is needed on whether 0.5 or 1.5 are realistic factors to use for changing the rain evaporation or if these need to be lower/higher.

To use 100m runs for operational weather forecasting (e.g. nowcasting at Schiphol) it is required to decrease the computing time substantially. Decreasing the domain size can decrease the computing time significantly. However, a very frequent analysis or starting from a forecast is then necessary.

In order to see if HARMONIE is working properly under very high resolution, a comparison with results from Large-Eddy Simulations (LES) would allow for a more well-founded conclusion.

Furthermore, this study is based on just one case of summertime convection, which makes the results from Chapter 3 not conclusive. However, they can give insight for further studies in this field of expertise.

Acknowledgements

Special thanks to my supervisors from KNMI and Wageningen University for giving their constructive feedback during this MSc Thesis research. I also want to thank Ulf Andrae from the SMHI for helping out with the nesting problem and the bug in the nesting procedure itself. Also thanks to Sami Niemelä (FMI) for helping out with the instability issues for the runs below 1 km resolution and I would like to thank Henk Klein Baltink (KNMI) for making the CloudNet products available to me.

Appendices

This specific section contains some background information on various subjects that were touched upon in this report. Including a description of the bug in the nesting procedure, model instability and more background on the setting of the model runs.

Appendix A – Detailed run settings

This appendix contains a more detailed description of the specific run settings. These include only a few changes in the HARMONIE code itself. Table A1 shows a short description of the model runs, including the domain size and resolution and corresponding mother domain (when appropriate). Table A2 shows how the nesting is set up. It shows the combination of HARMONIE domain and mother domain (ECMWF or HARMONIE) for all the model runs.

Table A1. Model run descriptions.

Run	Description	Domain/resolution	Notes
ZL1.1	Default 38h1.1 run	800*800/2.5 km	
ZL1.2	Default 38h1.2 run	800*800/2.5 km	
ZL1.2f	38h1.2 run LOCND2=FALSE	800*800/2.5 km	
SanityCheck	“sanity check”	400*400/2.5 km	Nested in ZL1.2
ZL1000	1 km run	800*800/1.0 km	
ZL1000n	Nested 1 km run	800*800/1.0 km	Nested in ZL1.2
ZL500n	Nested 500 m run	800*800/500 m	Nested in ZL1.2
ZL100n	Nested 100 m run	800*800/100 m	Nested in ZL500n
HaRatu	100m/2.5km with RACMO TS	800*800/100 m/2.5 km	
EVAPx1.5	100m/2.5km with increased evaporation	800*800/100 m/2.5 km	
EVAPx0.5	100m/2.5km with decreased evaporation	800*800/100 m/2.5 km	

Table A2. Overview of the nesting set up. It shows which HARMONIE domain is linked to which mother domain. Example: ZL1000n is a HARMONIE domain with 1000 m resolution nested into a HARMONIE domain with 2500 m resolution.

Harmonie domain	Mother domains			
	ECMWF	***2500 m***	***1000 m***	***500 m***
2500 m	ZL1.1; ZL1.2; ZL1.2f; HaRatu; EVAPx1.5; EVAPx0.5	SanityCheck	-	-
1000 m	ZL1000	ZL1000n	-	-
500 m	-	ZL500n	-	-
100 m	-	-	-	ZL100n; HaRatu; EVAPx1.5; EVAPx0.5

ZL1.1/ZL1.2

These two runs are the default runs with HARMONIE versions *cy38h1.1* and *cy38h1.2*, where no large changes have been made in run settings. In the *config_exp.h* script (which defines the experiment settings) only few changes have been made: *ANAATMO = NONE* and *ANASURF = NONE*. Since the 3DVAR data assimilation technique is not used in this study, these options are not needed. The domain is set at *NETHERLANDS* (centered at De Bilt) and the *WRITEUPTIME* is set at 1 hour for hourly output during the 24h forecasting time.

ZL1.2f

This run is a default *cy38h1.2* run, where the *OCND2* option is set at *FALSE* instead of the default *TRUE*. This is done by putting *LOCND2* at *FALSE* in the namelist *NAMPARAR* in the script *harmonie_namelists.pm.*

SanityCheck

This experiment is the first experiment in this study that uses the multiple nesting (nesting into *HARMONIE* instead of into the *ECMWF* environment). The *HARMONIE* environment (in this study *ZL1.2*) is set as the new boundary experiment. In *config_exp.h* some alterations are needed: *HOST_MODEL = aro, BDLIB = ZL1.2, HOST_SURFEX = yes* (*HARMONIE* uses *SURFEX*), *BDINT = 1* (1-hourly *HARMONIE* input instead of 3-hourly ECMWF input), *SURFEX_INPUT_FORMAT = fa* and *SURFEX_PREP = yes*. The domain *NETHERLANDS* is changed to 400x400 gridpoints in harmonie_domains.pm. LFPQ is set at TRUE in *nam/harmonie_namelists.pm* to get rid of the drying upper air (with this option, Q is preserved in the interpolation and it allows for supersaturation).

ZL1000

This experiment uses the same settings as the default *ZL1.2*, other than a change in Harmonie_domains.pm: *TSTEP = 30* and *GRIDSIZE = 1000.*

ZL1000n

This experiment uses the same settings as the *SanityCheck* experiment described above combined with the *ZL1000* experiment. The changes in *Harmonie_domains.pm* for the *NETHERLANDS* domain compared to *SanityCheck*: *TSTEP = 30, GRIDSIZE = 1000* and 800x800 gridpoints.

ZL500n

For this experiment, the changes in *Harmonie_domains.pm* are: *TSTEP = 20* and *GRIDSIZE = 500*. Due to instability issues (too high wind speeds on high model levels) an LPC (predictor-corrector) scheme with one iteration is needed in order to complete the forecasts. The settings for this are taken from Niemelä et al (2013) and are mainly changes in *nam/harmonie_namelists.pm*:

```
&NAMCT0
LPC_FULL=.TRUE.,
LPC_NESC=.TRUE.,
LPC_NESCT=.FALSE.,
LPC_CHEAP=.TRUE.,
/
&NAMDYN
LSETTLS=.FALSE.,
LSETTLST=.TRUE.,
NSITER=1,
LRHDI_LASTITERPC=.TRUE.,
/
```

Some additional changes have been done in the *sms/config_exp.h* file: the *LSPBDC*, *LGRADSP* and *LUNBC* options are set at *NO*. They do not seem to work in combination with the predictor-corrector schemes.

ZL100n

This experiment uses approximately the same settings as *ZL500n*. Changes in *sms/config_exp.h* include: *TSTEP = 5* and *BDLIB = ZL500n*, because the 100m run is nested into the 500m run (see Table A1 and A2).

HaRatu

HaRatu uses the settings of the *ZL100n* experiment and the *ZL1.2* experiment, other than the addition of the *RACMO* turbulence scheme.

EVAPx1.5/EVAPx0.5

These experiments use the settings of the *ZL100n* experiment and the *ZL1.2* experiment. The only difference is in the routine *src/mpa/micro/internals/rain_ice.f90,* where the rain evaporation rate is multiplied by 0.5 (low evaporation) and 1.5 (high evaporation).

Appendix B – Bug in the Nesting procedure

Multiple nesting, as explained in section 3.2, is needed for performing the simulations with a higher horizontal resolution. From this study, it turned out that this nesting procedure did not result in the right meteorological conditions for the inner domain. A drying occurred in the upper air between model levels 10 and 30 approximately. The upper air moisture problem eventually turned out to be a bug in the HARMONIE nesting procedure, which caused concern, because some meteorological institutes already used the same model settings in operational mode. The bug concerned the allowance of RH supersaturation and was removed from the model (by Ulf Andrae, SMHI). Changes have been made in the model code (also on hirlam.org):

- Add FPRHMAX to NAMFPC to allow supersaturated RH. Final value of FPRHMAX to be settled

This is added in *nam/harmonie_namelists.pm* after line 1203:

```
NAMFPC=>{
  'FPRHMAX'    =>   '1.0,',
},
```

The change in *src/arp/namelist/namfpc.h* at line 13:

```
&L_READ_MODEL_DATE   ,LFPCLSTOGMV, LCRITSNOWTEMP,  LFPBOYD
```

becomes

```
&L_READ_MODEL_DATE   ,LFPCLSTOGMV,  LCRITSNOWTEMP,  LFPBOYD,  FPRHMAX
```

- Correct inconsistency in RH limits in apache.F90

The change in *src/arp/pp_obs/apache.F90* at line 434:

```
ZRH1(JROF, JLEV) = MAX(0.0_JPRB, MIN(ZRELH, 1.0_JPRB))
```

becomes

```
ZRH1(JROF, JLEV) = MAX(PRHBNDS(1) , MIN(ZRELH, PRHBNDS(2) ))
```

The change in *src/arp/pp_obs/apache.F90* at line 754:

```
PRH2(JROF, JLEV) = MAX(0.0_JPRB, MIN(ZRELH, 1.0_JPRB))
```

becomes

```
PRH2(JROF, JLEV) = MAX(PRHBNDS(1) , MIN(ZRELH, PRHBNDS(2) ))
```

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