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Modelling strategies for performing convection-permitting climate simulations

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Abstract

The computational cost still remains a limiting factor for performing convection-permitting climate simulations. Choosing a model set-up with the lowest computational cost without deteriorating the model performances is, therefore, of relevance before starting any decadal simulations at convection-permitting scale (CPS). In this study three different strategies that aim at reducing this computational cost are evaluated. These strategies are (1) excluding graupel in the microphysical scheme, (2) reducing the nesting steps to downscale from ERA-Interim scale to CPS and (3) reducing the domain size. To test these strategies, the COSMO-CLM regional model was integrated over a four-month summer period for Belgium and evaluated using both radar and rain-gauges precipitation data. It was found that excluding the graupel parametrization at CPS induces a dry bias, but that excluding the graupel parametrization in the parent nest of the CPS simulation does not impact daily accumulated precipitation. In addition, it was also found that the best downscaling strategy is to use two nesting steps, in our case 25 km and 2.8 km. The 7 km nest was found to be redundant. Finally, it was found that a minimum distance of ~ 150 km between the evaluation domain and the lateral boundary is needed for daily precipitation to converge towards observed values. This indicates that the domain size must be large enough for the model to spin-up convective precipitation and in our case a domain size of 180 × 180 grid-points was found to be necessary. Our recommendations for CPS simulations at lowest computational cost are therefore (1) to include graupel parametrization at CPS but not in the parent nest, (2) to use two nesting steps to downscale from ERA-Interim to CPS and (3) to use a domain size large enough to allow for 150 km spatial spin-up.

Keywords: Convective permitting simulation, Domain size, Graupel parametrization, Nesting strategy, Microphysics, COSMO-CLM

1 Introduction

Global circulation models (GCMs) are essential tools for climate studies, however their resolution remain too coarse to reproduce the local climate variability. In the 1980's, solely statistical downscaling techniques were used to compensate for the lack of local information in GCMs. Then, efforts were made towards more physically-based downscaling solutions. The goal was not only to account more accurately for local geophysical features but also to develop further the crude GCM physics. Dickinson et al. (1989) and Giorgi and Bates (1989) describe the first developments of limited area model nested in GCM, later called regional climate models (RCMs).

Due to this focus on limited areas, at equal computational resources, RCMs can use more complex physical schemes accompanied by finer grid meshes. Since the first developments of RCMs, the continuous increase of computational resources stimulated their developments and applications resulting in improved physical descriptions of processes such as the representation of dynamic forcing at the lower boundary (e.g. soil and ocean models). In addition, grid mesh size has kept on increasing, reaching recently the kilometer-scale, allowing the convection to be partially resolved.

Nevertheless, the available literature pool in the field of convection-permitting climate simulation (CPCS) is relatively low (Suklitsch et al., 2011). Indeed, most of the studies related to convection-permitting scales (CPS) were developed in the framework of numerical weather prediction (NWP). Because of the similarities between NWP models and RCMs, most of these contributions can be directly implemented in RCMs. However, some adjustments specific to climate applications are still needed before performing climate predictions at CPS. Indeed, significant differences also exist between the NWP and climate communities.

The most obvious difference is the integration period, that directly influences the required computational resources. These integration periods can vary from a few days for the NWP community to centuries for the climate one. Due to adapted computational resources, the NWP community started using convection-permitting simulations earlier than the climate community. Although the current development of high performance computing (HPC) platforms starts allowing 30-year

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model integrations at CPS, the computational cost of the model remains a major issue to perform CPCS and need to be lowered for deriving climate projections at CPS.

The relevance of modelling correctly the spatio-temporal characteristics of single meteorological events is another difference between the NWP and climate communities. Indeed, while such characteristics are crucial for the forecaster (e.g. to warn the population against potential meteorological related risks), these characteristics are not crucial to climatologists as long as errors are not systematic and do not impact the statistical analysis. To correctly reproduce an event at the right time and location the NWP community has developed different techniques, such as data assimilation. This technique consists in adjusting the initialisation of NWP models through combination of observations and models' predictions. As opposed to weather forecasts, climate predictions do not heavily rely on the initial state of the earth system, but on a realistic evolution of this state.

Since these differences may also have an impact on the models configuration, it is important to test whether the setups established by the NWP communities are adequate for performing climate integrations. These sensitivity tests focus on modelling strategies which are foreseen to influence the development of convection and have potential for lowering computational cost while keeping performance high:

(1) Graupel representation: Computational cost can be reduced by simplifying the parametrization schemes to the representation of the most important processes. Microphysics parametrizations are among the most computationally expensive parametrizations in RCMs. Indeed, although low resolution models derive precipitation diagnostically, higher resolution models use prognostic schemes with multiple-phase dependencies. These improvements are reflected in the precipitation development but also in the dynamics of the atmosphere (Khain et al., 2000). It is therefore expected that microphysical parametrizations will have an impact on the development of convection. Some studies show no or minor impact on surface precipitation by improving the representation of microphysics in RCM (Cohen and McCaul, 2006; Serafin and Ferretti, 2007a) while Woods et al. (2007), found significant sensitivities of such improvements to precipitation related processes. More specifically, Van Weverberg et al. (2013); Serafin and Ferretti (2007b); Van Weverberg et al. (2010) found that representing graupel in the model results in higher surface precipitation.

(2) Nesting strategy: It is widely accepted that nesting techniques are responsible for an important part of RCM bias (CAS/JSC Working Group, 1999; CAS/JSC Working Group, 2000). It is therefore expected that model performance will deteriorate when dealing with multiple nesting strategies. Nevertheless, because the integration scale of global models (e.g. GCMs, reanalysis) largely differ from CPS, a multiple nesting strategy is required to carry out such simulations. Not only do additional nesting steps tend to increase model biases occurring at CPS but they also have a computational cost. It is therefore of interest to investigate the impact of difference multiple nesting strategies on model performance.

(3) Domain size: Although domain size has been frequently studied at typical RCM resolutions (10 to 50 km), to our knowledge such studies have not yet been performed at CPS. Chomé et al. (2002) have shown the complex role played by the domain size in the framework of one-way nesting and Seth and Giorgi (1998) have found that it has an important impact on regional climate variability. Although a reduction of the domain size results in a lowering of computational cost, the domain must be large enough to enable the development of small-scale processes over the area of interest (Jones et al., 1995; Leduc and Laprise, 2008). Moreover Rojas and Seth (2003) show that a large domain can partially compensate for the deficiencies of lateral boundary conditions, a feature particularly interesting at CPS. Indeed the development of deep convection is not explicitly resolved by the parent model. Using a large domain could therefore limit the impact of physical discontinuities, occurring at the lateral model boundaries.

In this study we investigate whether the options above to reduce computational costs results in substantial reduction of model performance. This will help to optimize CPCS configurations. To do so the domain size, the nesting strategy and the necessity of representing graupel in the microphysical parametrization, are tested.

Like in most sensitivity studies focusing on the representation of convective processes, surface precipitation is used as only observation dataset. This is mainly due to high sensitivity of precipitation to different RCMs (Suklitsch et al., 2011), parametrization schemes (Colle and Mass, 2000; Warner and Hsu, 2000) or even model parameters (Vannitsem and Chomé, 2005; Van Weverberg et al., 2010). The reason for this high sensitivity is the large number of processes involved in the development of precipitation (e.g. microphysics processes, radiation, soil/atmosphere exchange or moist convection).

2 Data and methods

2.1 Observation and reference dataset

Due to its large spatial variability, the evaluation of surface precipitation requires an observational dataset characterized by a high spatial density. For this purpose a spatially continuous product with a daily resolution was acquired from the Belgium Royal Meteorological Institute (RMI). This dataset was produced by merging three ground-based radars together with telemetric rain gauges using the mean field bias technique as described in Goudenhoofdt and Delobbe (2009). These radars

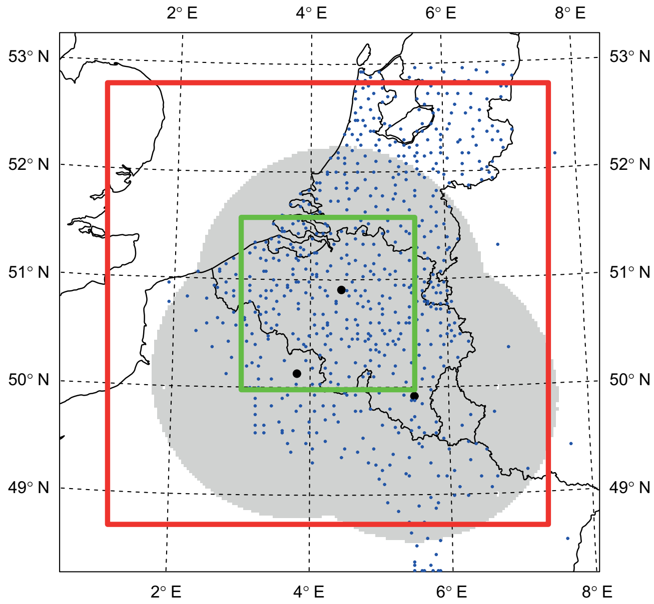


Figure 1: Maps of the different observational datasets used in the evaluation. Shaded zones indicate areas where radars data is available. The black points show the locations of the radar and the blue points those of the tipping buckets systems. The red rectangle shows the large evaluation domain while the green rectangle indicates the small evaluation domain as described in Section 2.5.

are located in Wideumont (49 ° 55 ′ N, 5 ° 30 ′ E), Zaventem (50 ° 54 ′ N, 4 ° 27 ′ E) and Avesnois (50 ° 08 ′ N, 3 ° 49 ′ E) as shown in Figure 1 (black dots). Only the data within a 150 km radius of the radars is used resulting in the spatial coverage shown in Figure 1 (grey shade). In addition only days with at least 280 scans and enough valid pairs of telemetric rain gauges were selected for the evaluation resulting in 90 valid days of radar observations with respectively 78, 15 and 55 days for Wideumont, Zaventem and Avesnois. This dataset is re-gridded to the finest model grid used in this study (2.8 km) through a bilinear interpolation to ease comparisons with the model output.

In addition to the spatially continuous product, a distinct network of 643 tipping bucket systems operating at a daily time-scale was derived based on the RMI and the Global Historical Climatology Network-Daily (GHCN-D) datasets (Menne et al., 2012). Figure 1 shows the station locations of this network (blue points) with the highest density lying in Belgium, Netherlands and north of France. Although the rain gauges network hardly provides any information on the structure of precipitation, its temporal coverage and its accuracy are important added values to the evaluation dataset.

2.2 The COSMO-CLM model

The Consortium for Small-scale Modeling in climate mode (COSMO-CLM) model is a non-hydrostatic climate limited area model. It is based on the COSMO model that was designed by the Deutsche Wetterdienst (DWD) for operational weather prediction on the meso-β and meso-γ scales (Steppeler et al., 2003). Later, it has been adapted by the Climate Limited-area Modelling (CLM) community to perform climate integrations on similar scales (Böhm et al., 2006; Rockel et al., 2008). Based on the basic thermodynamical equations, the model also includes a large number of physical parametrizations that represent physical processes not resolved explicitly at the model's resolution. In this study a particular interest has been given to the parametrization of:

- The cloud microphysics: The interaction of particles are of crucial importance for the formation of clouds, precipitation as well as for the thermodynamics and dynamics of the atmosphere. Because these processes occur on a scale much smaller than the model's resolution, they are represented by means of parametrizations. The complexity of the interactions of hydrometeors and the high computational cost inherent to their representation in climate models has often led to simplified solutions in which not all hydrometeors are included. In the COSMO-CLM a single-moment, two-category ice scheme is implemented that includes water vapour, cloud water, rain, cloud ice and snow (Doms et al., 2011). The latter scheme has been extended to a three-category ice scheme by adding a representation of graupel (Reinhardt and Seifert, 2006). This work was motivated by the added value of a graupel representation for the development of convective cells (Gilmore et al., 2004).
- The moist convection: Convection also has a large impact on cloud and precipitation development. Many parametrizations are available to represent these processes in RCM. The mass flux scheme developed by Tiedtke (1989) is implemented in the COSMO-CLM model. This scheme discriminates three types of convection, namely penetrative, midlevel and shallow convection. While the two first convection types are dynamically resolved at a model resolution finer than ~ 4 km (Weisman et al., 1997), the latter is only resolved at a resolution finer than a few hundred meters. Therefore, in the COSMO-CLM two types of parametrization are implemented, the classic Tiedtke schemes for resolutions coarser than ~ 4 km and a Tiedtke-based parametrization that only considers shallow convection for model grids finer than ~ 4 km and coarser than a few hundred meters.

2.3 Evaluation techniques: SAL and time-averaged precipitation

Point-to-point evaluation has traditionally been used for model evaluation in both the NWP and the climate communities. The recent increase in grid-mesh resolution has led the NWP community to adapt their evaluation techniques due to the so-called "double-penalty" (Anthes, 1983), an overestimation of model deficiencies

Table 1: Summary of relevant setup parameters for each experiments

	25 km		7 km		2.8 km	
Exp	graupel	domain size	graupel	domain size	graupel	domain size
REF	no	100 × 100	no	150 × 150	yes	200 × 200
NO.GRA	no	100 × 100	no	150 × 150	no	200 × 200
GRA7&3	no	100 × 100	yes	150 × 150	yes	200 × 200
SPA180	no	100 × 100	no	150 × 150	yes	180 × 180
SPA160	no	100 × 100	no	150 × 150	yes	160 × 160
SPA140	no	100 × 100	no	150 × 150	yes	140 × 140
SPA120	no	100 × 100	no	150 × 150	yes	120 × 120
SPA100	no	100 × 100	no	150 × 150	yes	100 × 100
NO25	–		no	150 × 150	yes	200 × 200
NO7	no	100 × 100	–		yes	200 × 200
NO25&7	–		–		yes	200 × 200

due to mislocations of precipitation events. Accounting for the double penalty is especially important when comparing two simulations with different resolutions. Indeed a slight mislocation of an event may not be in the same grid box in the finer simulations resulting in a "miss" and a "false alarm". However, in the coarser simulation a similar mislocation may still be encompassed in the correct grid box resulting in a "hit". Due to the random character of these mislocations, the inherent errors are usually averaged out when performing evaluation on long time-scales such as the one used in typical climate simulations. In this study, the evaluation period (four months, described in Section 2.5) is too short not to consider the double penalty. Therefore, verification techniques that are not affected by the double-penalty effect were chosen for this study.

In this paper, the evaluation of the domain-averaged precipitation amounts is performed using the rain gauge network. The normalized bias is derived based on spatially averaged values at rain gauge locations. The structure of precipitation events is evaluated using the S-component of the SAL approach (Wernli et al., 2008). In this approach the S-component is derived by identifying coherent precipitation objects from the observations (here the radar product) and the model's output. The objects are evaluated based on their size and their shape. Values are bounded within $[-2; 2]$, with a perfect fit resulting in a zero value. Positive (negative) values denotes objects that are too big or flat (small or picked). On daily time-scale, precipitation objects have the form of stripes due to the advection of convective cells (Figure 3(a)). When two cells occur at a close location and on the same day, the resulting stripes may cross each other. If such situation occur too frequently, these crossed stripes could bias the estimation of the S-component which would then not only describe the structure of cells but also its lifetime, its advection speed and direction. In both the simulations performed in this study and the radar product, such objects are observed in only five days out of 90. For those five days less than 10 % of the objects contain crossed precipitation stripes. Therefore, the influence of these objects on the results of this study are very small.

The SAL approach includes two more components, namely the A-component (amplitude) and the L-component (location) which are not used in this study. Indeed, by construction the A-component is constrained to the use of spatially continuous datasets over a given area. However, the radar product does not cover the same area for each observational timestep (e.g. Section 2.1) which is an issue when deriving temporal statistics (e.g. mean, standard deviation, etc.). Therefore, the normalized bias calculated from the rain gauges network is used for describing precipitation intensity biases. In addition, due to the low interest in identifying mislocations of individual events for climate purposes, the L component was not used in this study. Both the S-component and the normalized bias are derived based on daily values.

2.4 Experimental design

In addition to the reference simulations (described in Section 2.4.1) three experiments have been performed. They address the necessity of using a graupel parametrization, the sensitivity of the model integrations to domain size and the most efficient nesting strategy to represent accurately precipitation. All of these experiments are described below and summarised in Table 1.

2.4.1 Control run (ERAInt, NEST22, NEST0625 and REF)

The reference setup consists of a one way nesting with three successive domains. The EraInterim reanalysis (Simmons et al. (2007) – 0.75° resolution and 6 h interval) from the European Center for Medium-Range Weather Forecast (ECMWF), refered to as ERAInt, was used as initial conditions and as lateral boundary conditions for the 0.22° (∼ 25 km) nest (NEST22). The latter simulation produces output every three hours at 100 × 100 grid points. This data is used as input for the 0.0625° (∼ 7 km) nest (NEST0625). During this nesting step, hourly output are produced on 150 × 150 grid points. Finally the 0.025 ° (∼ 2.8 km) simulation (REF) is integrated using the NEST0625 output. REF has a domain of 200 × 200 grid points. The default nesting strategy and model settings are based on settings used in DWD for their operational simulations except for the assimilation processes which is switched off. The graupel parametrization is, therefore, used in REF.

2.4.2 Graupel parameterisation (NO.GRA and GRA7&3)

The graupel parameterisation experiments consist of simulations with or without graupel parametrization. Two experiments, namely NO.GRA and GRA7&3, have been performed to evaluate the impact of the representation of the graupel phase on the ground precipitation. NO.GRA does not use any graupel parametrization in any of the nesting step while in GRA7&3, it is used for both the 0.0625 ° and the 0.025 ° resolution nests, but not for the 0.22 ° nest.

2.4.3 Domain size (SPA180, SPA160, SPA140, SPA120 and SPA100)

Different horizontal domain size were tested while keeping the center of the domain unchanged. The reference simulation contains 200×200 gridpoints while 180×180, 160×160, 140×140, 120×120 and 100×100 gridpoints were used in respectively SPA180, SPA160, SPA140, SPA120 and SPA100.

2.4.4 Nesting strategy (NO25, NO7 and NO25&7)

The reference simulation is composed of three nesting steps. The method followed to prepare the nesting strategy experiments is to remove one or two nesting steps. In N07 and NO25 the 0.0625 ° and 0.22 ° resolution nests are respectively absent. In NO25&7 none of the 0.22 ° and the 0.0625 ° nesting steps are performed. In NO25&7, the 0.025 ° lateral boundaries are updated only every six hours due to the lower temporal resolution of ERA-Interim output.

2.5 Evaluation period and domain

Four-month integrations are performed and evaluated for each experiment from the early summer to the early autumn 2007 (01/06/2007 to 30/09/2007). This period is characterized by abnormal intense convective activity resulting in large precipitation events. A 2-year spin-up was performed on the 0.22 ° nest for the soil model to reach a steady state. The soil moisture and soil temperature derived from this 0.22 ° simulation are fed to the next nesting step. Only a shorter spin-up period, namely from the 17/05/2007 to 31/05/2007, that corresponds to the spin-up time of the atmospheric model, is used for the 0.0625 ° and the 0.025 ° nests.

The evaluation domain for the graupel and nesting strategy experiments is limited to 164 × 164 gridpoints (red rectangle in Figure 1) so that the area sensitive

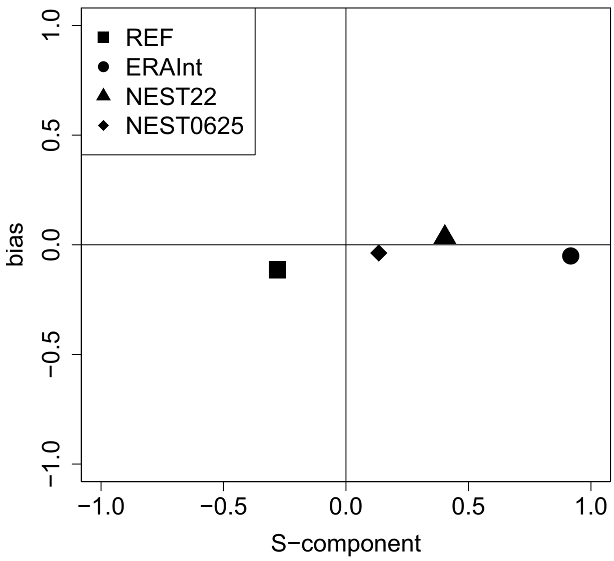


Figure 2: Skill scores of different experiments (e.g. REF, ERAInt, NEST0625 and NEST022) for the four-month evaluation period. The mean S-component of the SAL approach is displayed on the *x*-axis, the mean bias on the *y*-axis.

to lateral boundary conditions is left out. Due to the variation in the domain size only output on a smaller domain (green rectangle in Figure 1) was evaluated for the domain size experiments. The size of this domain is 64 × 64 which consists of the smallest domain (SPA100) without the area sensitive to lateral boundary conditions.

3 Results

3.1 Control run (REF)

Normalized bias values obtained from the rain gauges network range from −0.11 (REF) to 0.03 (NEST0625) (Figure 2). None of these under/over-estimations were found to be significant. Due to their coarser resolutions ERAInt, NEST022 and NEST0625 usually produce too flat/big precipitation objects (Figure 2) which, in the end, result in an underestimation of the precipitation variability. Indeed the temporal standard deviation (derived from spatially averaged daily values) significantly (1 % level) differs from the rain gauges network for these three nests and can be underestimated at up to 33 %. On the contrary REF produces too small/peaked objects but the temporal standard deviation is not significantly differing from observations.

Figure 3 shows the precipitation of the 16th of June 2007, illustrating the model deficiencies. ERAInt, NEST022 and NEST0625 produce flatter precipitation (Figure 3(c), 3(d) and 3(e)) and do not reproduce the structure of convective events (e.g. stripes in

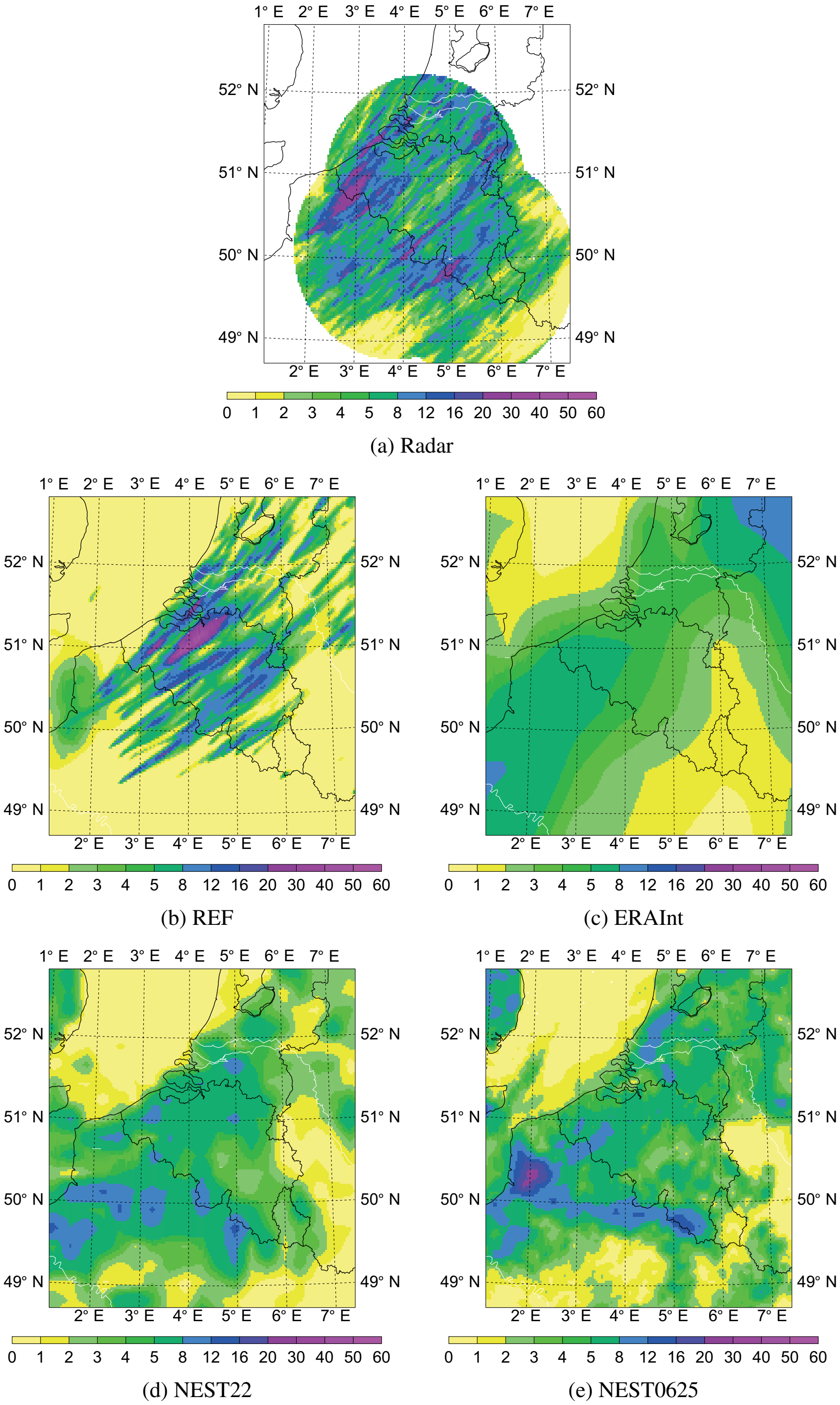


Figure 3: Precipitation accumulation (mm/day) for the 16th of June 2007 for the radar dataset and for different experiments (e.g. REF, ERAInt, NEST22 and NEST0625)

Figure 3(a)). Although REF was able to simulate the convective events, it produces less precipitation than the NEST022 and NEST0625. It can be concluded that even though the precipitation spatial average was already well estimated by the parent nests of REF, a downscaling at 0.025 ° improves the variability which is an important added values for the representation of extreme events.

3.2 Graupel representation (GRA)

A significant (1 % level) dry bias was introduced in NO.GRA compared to REF (Figure 4). A case-to-case analysis indicates that for almost all convective days, NO.GRA produces lower precipitation intensity and less convective cells. Figure 5 shows the average precipita-

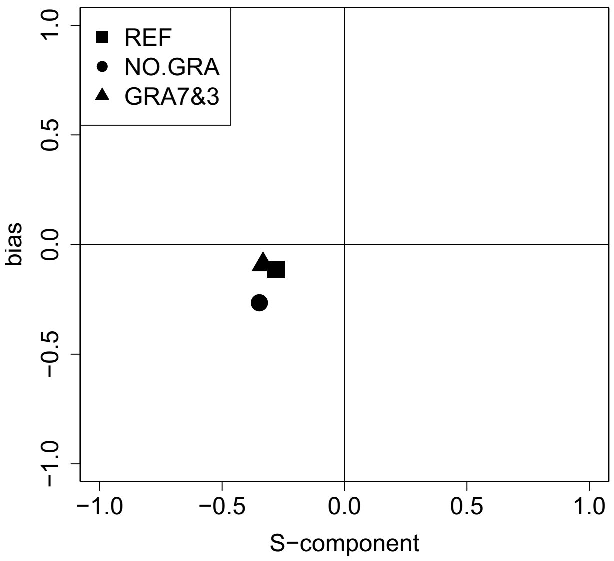


Figure 4: Skill scores of different experiments (e.g. REF, NO.GRA, GRA7&3) for the four-month evaluation period. The mean S-component of the SAL approach is displayed on the *x*-axis, the mean bias on the *y*-axis.

tion for the Southern, South-western and Western advection flow (e.g. 54 days in total). These flows directions were selected due to their high potential for convective activity. Indeed more than half (55.4 %) of the precipitation coming from these directions is found to be convective in the 7 km nest. This analysis shows that most of the precipitation is located at the end of the air mass course in the domain (top-right corner of Figure 5) suggesting that precipitation is occurring too late in NO.GRA. This is mainly due to the lack of graupel particles characterized by a high fallspeed. Indeed by comparing the hydrometeors evolution in the different simulations, it was found that the riming processes are mainly occurring on snow in NO.GRA instead of graupel (REF). Because the falling velocity of the graupel is much higher than the one of snow, the water is advected faster to the lowest levels in REF compared to NO.GRA. At these low levels snow/graupel melts to rain water.

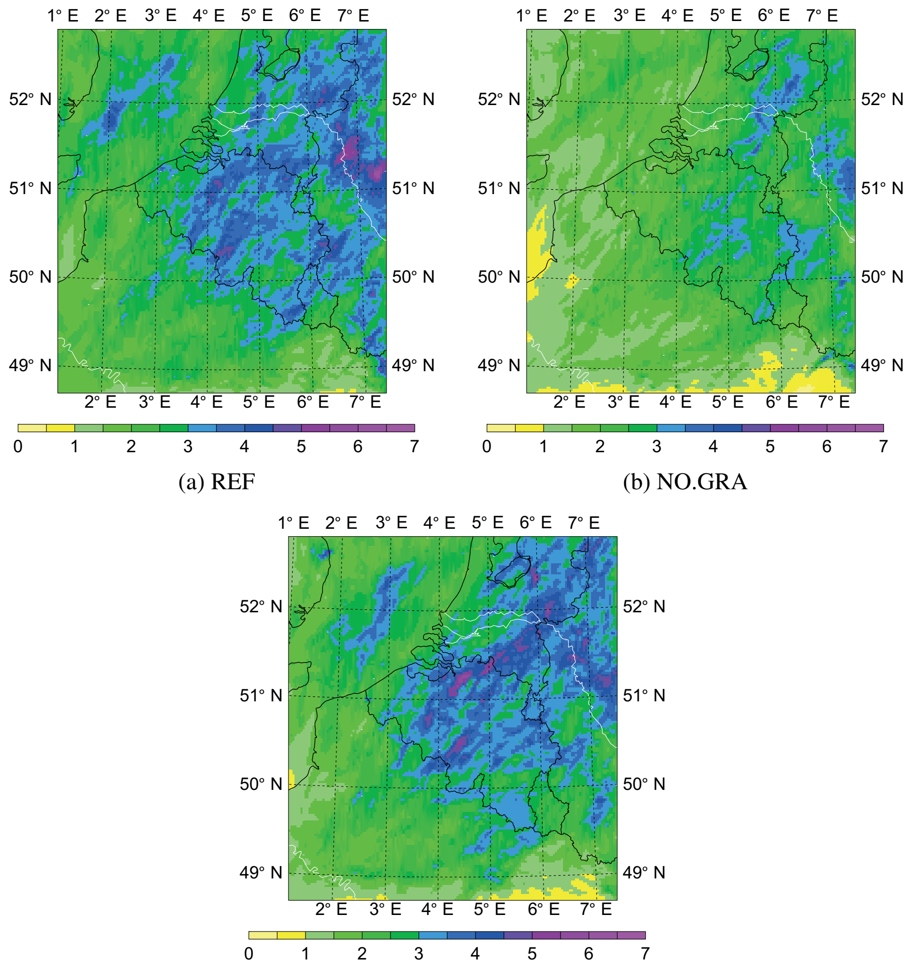
Higher rain water mixing ratios in REF compared to NO.GRA result in an increase of both precipitation occurrence and precipitation intensity for two different reasons. First, a large amount of rain water is parametrised using an increased number of large water drops because in the one moment micro-physical scheme the number concentration is constant. As large droplets have a higher falling velocity in the model than small droplets, the sedimentation processes may occur earlier in REF than in NO.GRA. Second, the presence of vertical levels with high humidity along the path of the falling water can also explain the higher precipitation depth and the higher occurrence of wet days observed in REF compared to NO.GRA. Indeed, in these levels water will evaporate until saturation. Large amounts of falling water have therefore higher chances to reach the ground than small amounts. Thus, more precipitative events occur in REF compared to NO.GRA. Both an increase in precipitation occurrence and in lowest levels evaporation are observed in REF compared to NO.GRA.

There is no significant difference between GRA7&3 and REF (Figure 4). However, the S-component points toward a representation of more peaked/smaller precipitation objects in GRA7&3 than in REF. This is due to an increase in the precipitation intensity in the convective cell center (more peaked objects). Although this increase is limited to a few mm/day, it was found in almost all convective cells. This increase is due to a ~ 5 % increase in graupel density in GRA7&3 compared to REF. This amount is relatively low and does not entirely overcome the dry bias observed in REF. In addition, the amount of graupel introduced in the lateral boundary in GRA7&3 is five times lower than the amount of graupel found in the middle of the domain. This low graupel mixing ratios in the 0.0625 ° nest compared to REF probably results from a lack of vertical mixing (averaged vertical wind speed are twice lower in the 0.0625 ° nest compared to the REF) inherent to the poor representation of updrafts/downdrafts at this resolution. Indeed, vertical updraft are essential to graupel production as it allows graupel to grow from riming processes before it reaches the melting levels. Parametrizing graupel is, therefore, efficient if and only if updrafts/downdrafts are dynamically resolved.

Finally, on days with low convection neither NO.GRA nor GRA7&3 shows precipitation depth significantly differing from REF. This indicates that although there is an added value in representing graupel to model convective processes, none was found for non-convective precipitation. Consequently, it is advised to use graupel parametrization only at CPS and for the simulations of time-periods characterized by convective activities.

3.3 Domain size (SPA)

When decreasing the domain size all verification indices point toward a deterioration (Figure 6(a)). This deterioration is higher on days with high precipitation depth (not shown). The normalized bias for days with occurrence of Western, South-western and Southern advection (Figure 6(b)) shows similar patterns than those displayed in Figure 6(a) although the observed deficiencies are larger. In addition the representation of precipitation daily accumulation in SPA140, SPA120 and SPA100 significantly (respectively at 10 %, 5 % and 1 %) differ from the observations. Figure 7 shows that when reducing the domain size, the south-west part of the evaluation domain exhibits a drastic (unrealistic) reduction in precipitation. The increase in distance between the south-east corner and the area with realistic precipitation accumulation is of about the same length as the decrease in domain size between different simulations.

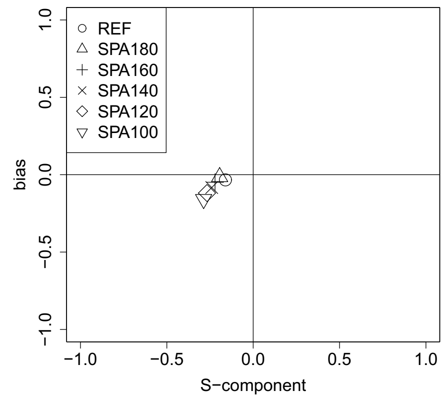


(c) GRA7&3

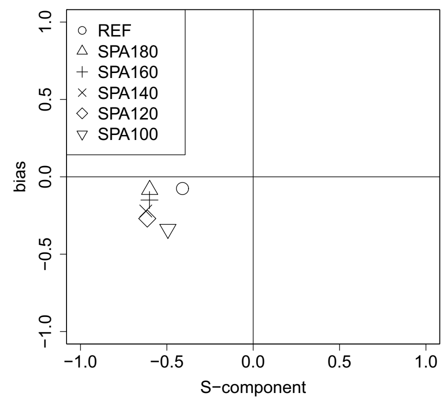
Figure 5: Temporal average of daily precipitation (mm/day) for days with occurrence of Western, South-western and Southern advection during the period between 01/06/2007 and 30/09/2007.

The intensity of precipitation is gradually increasing from the South-western corner of the domain to the North-eastern corner of the domain. This feature coincides with the graduate presence of graupel in the domain illustrated in Figure 8 showing a zonally-averaged vertical profile of graupel during days with Western, North-western and South-western flow occurrence as modelled in REF. Because of this weather type stratification, the advection, and therefore the evolution in time and space of the graupel production, is occurring along the longitudinal axis. It can be observed that the specific graupel water content is low on the western side of the domain ($< 1 \times 10^{-6}$ kg/kg) and is increasing all along the domain reaching a maximum at the end of the air mass course. This behaviour can be explained by the parametrization of graupel in the model. Indeed, in the model, the condition to initiate the presence of graupel is determined by the presence of snow and cloud water in the same grid-box. Because these conditions are only occurring near the 0 °C isotherm, the conversion of snow to graupel is also limited to these grid-boxes. In Figure 8 this conversion is occurring around 3000 m and starts between 1 and 2 ° E. Graupel is then advected to higher levels by means of verticals updrafts. At these levels the riming processes will contribute to the graupel growth, a decisive process for determining the intensity of precipitation depth (as described in Section 3.2). To conclude, all the processes inherent to the development of graupel, namely the conversion of snow to graupel, the vertical advection and the riming processes, are occurring on spatial-scales large enough to cause a spatial shift of surface precipitation in SPA100 compared to the REF. This indicates that there is a "spatial spin-up" needed before convective precipitation can occur in a CPCS and that a large domain is necessary to allow this spin-up.

Finally the decrease in the S-component observed in Figure 6(a) results from a decrease of precipitation objects size as observed on a case-to-case analysis (not shown). In 6(b), the S-component is stable due to changes in both the size of the area covered by precipitation and the shape of precipitation objects. Indeed a case-to-case analysis reveals that objects are both too small and too flat in the smaller domain experiments. The behaviour of the S-component arises from the graduate production of graupel described earlier in this section.



(a) SAL diagram (All days)



(b) SAL diagram (W, SW and S days)

Figure 6: Skill scores of different experiments (e.g. REF, SPA180, SPA160, SPA140, SPA120 and SPA100). The mean S-component of the SAL approach is displayed on the *x*-axis, the mean bias on the *y*-axis. On the upper panel (a) skill scores were derived using the full evaluation period (01/06/2007 to 30/09/2007) while on the lower panel (b) only the days with the occurrence of Western, Southwestern and Southern advection were considered.

The DWD uses a large domain (larger than Germany). Their forecasts are therefore not impacted by such spatial spin-up. For smaller simulation domain such as the one used in this study, it is required to use a domain large enough to model correctly precipitation over the area of interest. In this study, precipitation accumulations are very similar for the simulations SPA180 and SPA200 while they diverge for simulations with smaller domains (e.g. Figure 6(b) and 7). Assuming that the domain size must be at least as large as the one of SPA180 to allow for a proper spin-up of precipitation, a minimum distance from the boundary to the domain of interest of ~ 150 km is required. In further studies, it would be important to test even larger domains to more thoroughly investigate spin-up of different spatial variables.

3.4 Nesting strategy (NES)

Removing the 0.22 ° resolution nest (NO25) results in a significant (at the 1 % level) dry bias (Figure 9), mainly due to the model deficiencies in reproducing convective events. In addition, large-scale precipitation events are underestimated. The low spatial and temporal resolution of the parent nest of the 7 km nest (ERAInt) are likely to be responsible for these deficiencies but further investigations are needed to assess the role played by these two factors. Except from the dry bias, the timing of precipitation events is improved. Indeed, the increase of the temporal correlation (averaged of daily values at stations locations) of observation with NO25 compared to REF and a case-to-case analysis confirm this hypothesis. However, this improvement is of little relevance for climate modelling that deals with statistics rather than timing of single events.

Removing the 7 km resolution nest (NO7) results in very similar precipitation depth compared to REF (Figure 9 and 10). For some days the NO7 produces higher intensity cells, resulting in slightly higher precipitation depth but this increase is not systematic.

Removing both the 25 km and the 7 km resolution nests results in significantly (at the 1 % level) increased model deficiencies (Figure 9). Large-scale precipitation is not well represented and convection hardly occurs resulting in strong underestimation of precipitation.

According to previous results, the 0.22 ° nesting step is essential to correctly model precipitation depth while the 0.0625 ° nesting step does not have a significant impact. For decreasing computational cost, this latter nest could, therefore, be removed. However, further investigations are needed to check whether this low sensitivity for the 0.0625 ° nest is also valid for other meteorological variables and other model configurations.

4 Discussion on the role of explicit convection

An important difference between the CPS simulation (e.g. 0.025 °) and the other nests is that only the latter experiments make use of the Tiedtke parametrization. The Tiedtke parametrization has been developed for larger scale (> 20 km) and is dependent on assumptions that don't hold any more at kilometre-scale resolution. For example it is assumed that the ratio of the area where updraft occurs compared to the area covered by the grid mesh is much lower than 1. Nevertheless the Tiedtke scheme is still use in the operational COSMO-EU (7 km), although it produces too widespread convective precipitation with too flat cells (Kuell and Bott, 2008).

To ensure that most of the conclusions drawn from experiments performed in Section 3 are related to resolved convection processes and not to any other parameters, the Tiedtke parametrization was also implemented for all sensitivity experiments. It is not proposed to use the simulations performed with the Tiedtke

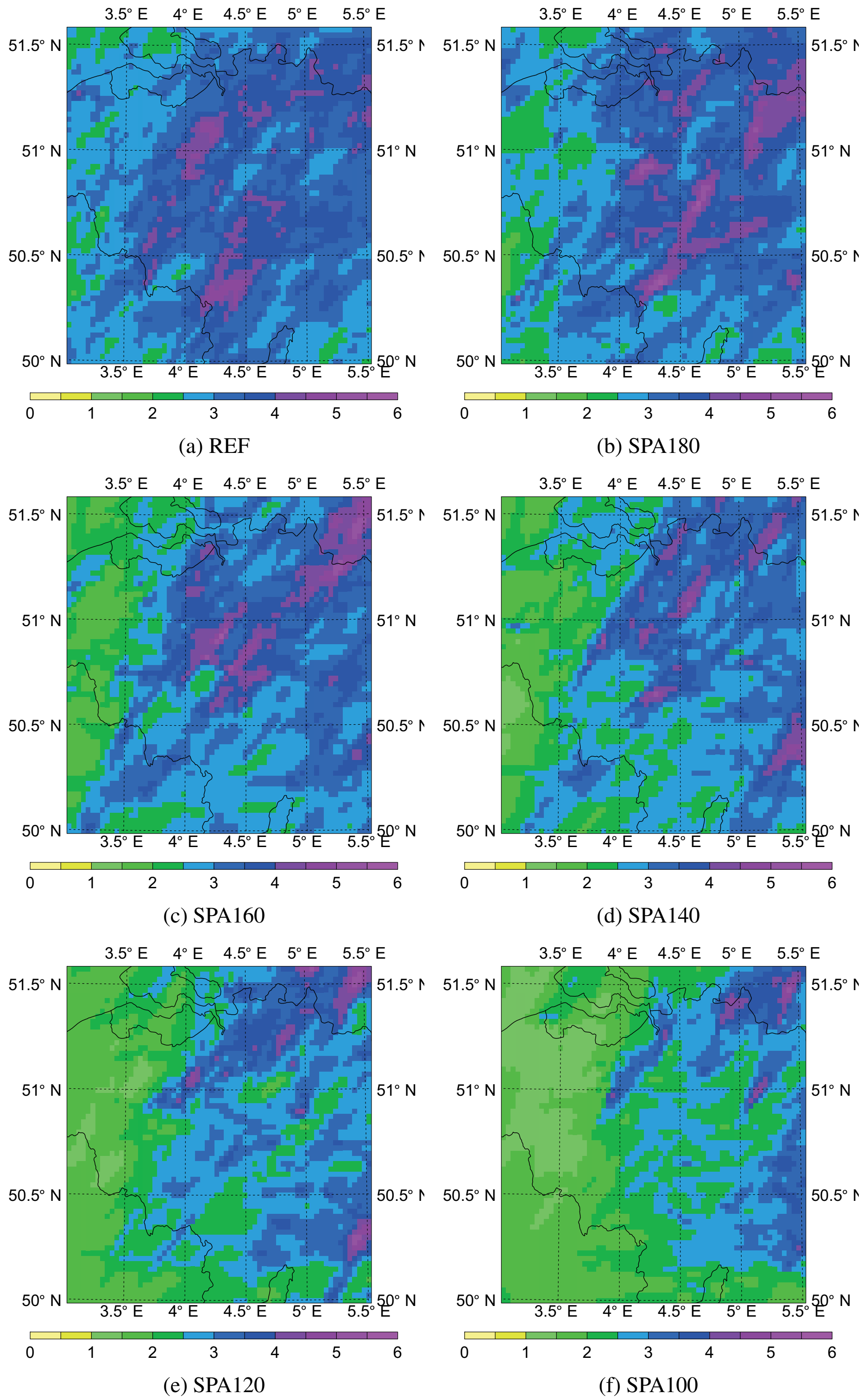


Figure 7: Temporal average of daily precipitation (mm/day) for days with occurrence of Western, South-western and Southern advection during the period between 01/06/2007 and 30/09/2007.

parametrisation as reference but to assess to which extend the previous findings are dependent on explicitly resolved convection and not inherent to other processes or parametrizations. For this purpose the Tiedke scheme is of major relevance. Indeed, the Tiedtke scheme overtakes explicitly resolved convective precipitation and destroys atmospheric stability necessary for the simulation of deep convection. Figure 11 shows that the typical mid-afternoon convective precipitation is modelled through the convective Tiedtke parametrization when this scheme is included. In addition, in the simulation with parametrized convection the peak is modelled earlier than in the simulation with explicitly resolved convection. This result is consistent with the findings of

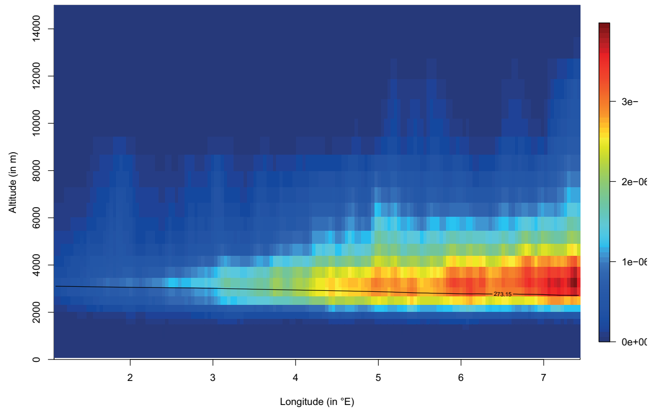


Figure 8: Vertical profile of specific graupel content (kg/kg) zonally and temporally averaged for days with occurrence of North-Western, Western and South-western advection during the period between 01/06/2007 and 30/09/2007 for the REF simulation. The black line represents the 273.15 K isotherm.

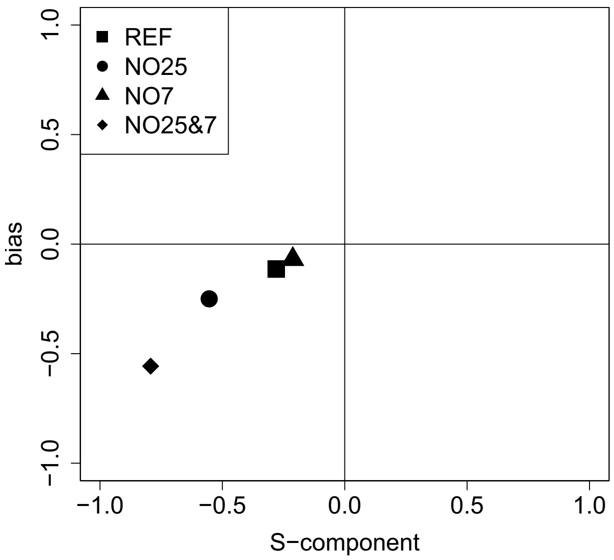


Figure 9: Skill scores of different experiments (e.g. REF, NO25, NO7 and NO25&7) for the four-month evaluation period. The mean S-component of the SAL approach is displayed on the *x*-axis, the mean bias on the *y*-axis.

Dai et al. (1999), Bechtold et al. (2004), Prein et al. (2013), Prein et al. (in press) and Brisson et al. (submitted) which compare CPS to non-CPS simulations at coarser resolution.

The experiments performed with the Tiedtke parametrization (Figure 12(a)) exhibit less variability in skill scores compared to the original experiments (Figure 12(b)). The graupel experiments without the Tiedtke parametrization are characterized by similar verification indices. Parametrizing graupel is, therefore, not influencing the representation of precipitation depth when convection is parametrized. Based on the latter statement and conclusions drawn in Section 3.2, it can be concluded that graupel plays an important role in the development of convection at CPS only.

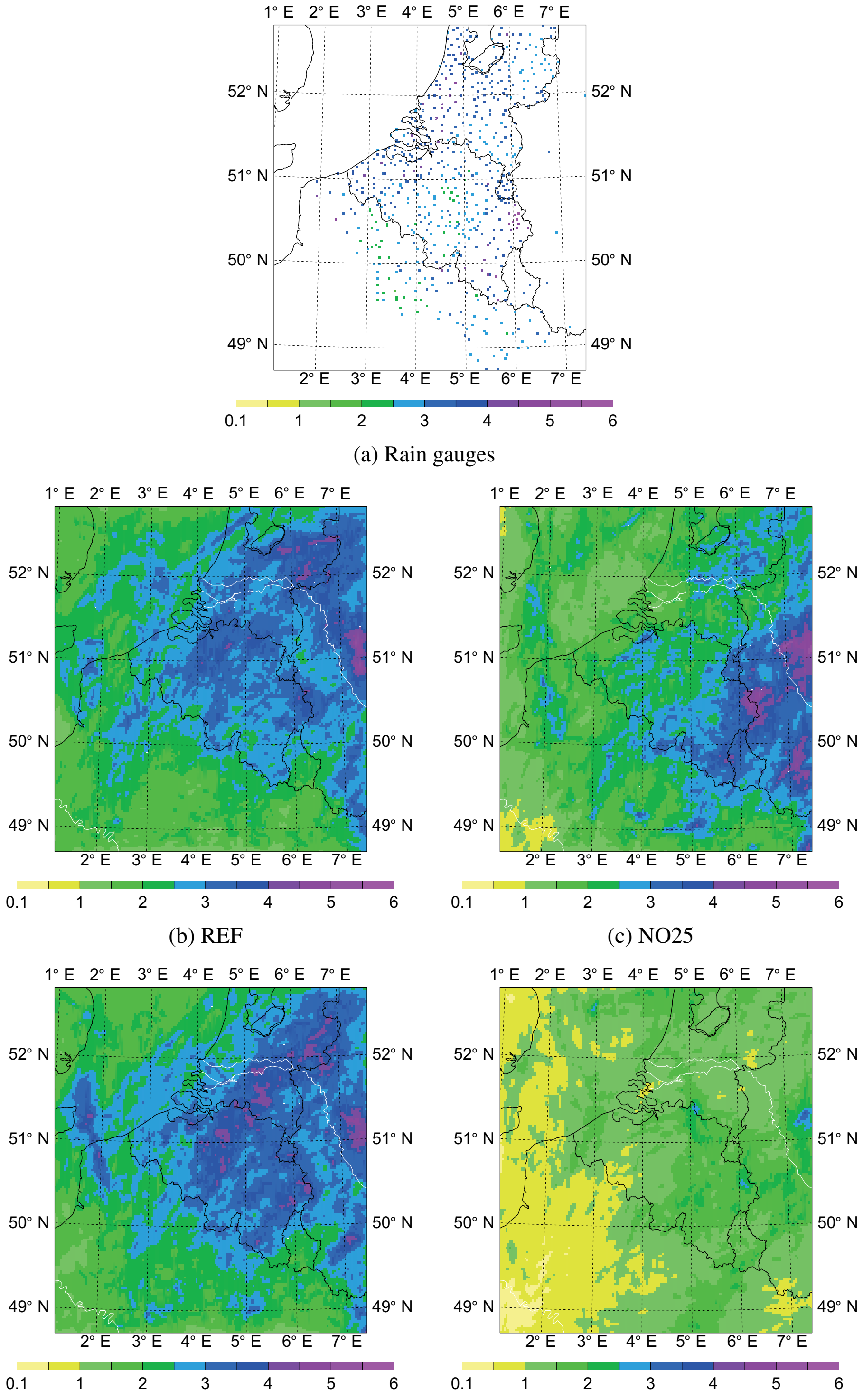
Although the domain size experiments with Tiedtke parametrization at 0.025 ° exhibit a small variability in the S-component (Figure 12(a)), no persistent features were found in the case-to-case analysis. This variability may arise from different forcings at the boundary. However, although the precipitation depth simulated in both SPA100 simulations (e.g. with and without the Tiedtke parametrization) differ significantly, the REF simulations are in general agreement (e.g. Figure 13). It can therefore be concluded that using a large domain is of major relevance for the dynamic development of convection at CPS and of less importance when a parametrization of convection is used.

A significant bias still exists in the nesting strategy experiments when using the Tiedtke parametization at 0.025 °. This suggests that the differences shown in Figure 12 are not related to explicitly resolved convection. It can be noticed that NEST0625 is still producing similar values compared to REF, suggesting that for modelling precipitation removing the 7 km nesting step is still a valid option.

5 Conclusion

This paper evaluates different strategies to keep the CPCS performance high while lowering the computational cost. Three experiments, that focus on the domain size, the nesting strategy and the graupel parametrization, were performed to reach this goal. Both the structure and the amplitude of modelled precipitation were evaluated by using a radar product and a rain gauges network. While a statistical approach on the full simulated period provides quick information on the model deficiencies related to the structure and the amplitude of precipitation events, maps and refined statistics provide more details on convection developments allowing deeper understanding of the model deficiencies.

The use of graupel in the COSMO-CLM at CPS is found to be essential to accurately model precipitation. Without graupel parametrization the model hardly triggers convective events. Indeed, while updrafts favour the occurrence of riming and therefore the growth of hydrometeors in ice phases, these hydrometeors still need to be advected to the ground. Without graupel parametrization, snow is the main hydrometeor on which riming is occurring. However, the falling speed of snow is much slower than the one of graupel which results in strong evaporation during its sedimentation. Graupel is therefore essential to represent realistically convective precipitation in CPS simulations. It was also found that without realistic representation of updrafts, the parametrization of graupel is ineffective. Therefore, the introduction of graupel in non-CPS simulations is not recommended due to the high computational cost of representing graupel in the model.



(a) Rain gauges

(b) REF

(c) NO25

(d) NO7

(e) NO25&7

Figure 10: Temporal average of daily precipitation (mm/day) during the period between 01/06/2007 and 30/09/2007 for the rain gauges network (a) and different model integrations (e.g. REF (b), NO25 (c), NO7 (d) and NO25&7 (e)).

It was found that at 2.8 km and for Belgium, the COSMO-CLM requires a spatial spin-up to develop precipitation events produced by convective processes. As explained in the previous paragraph, the production of large graupel hydrometeors is essential to intense precipitation occurrence. This production is occurring through different processes such as the conversion of snow to graupel, the vertical advection and the riming processes. These processes are occurring on spatial-scales large enough to cause a spatial shift between the location where graupel was produced and of the location of sedimentation. This indicates that there is a “spatial spin-up” needed before precipitation can occur and that a large domain is necessary to allow this spin-up.

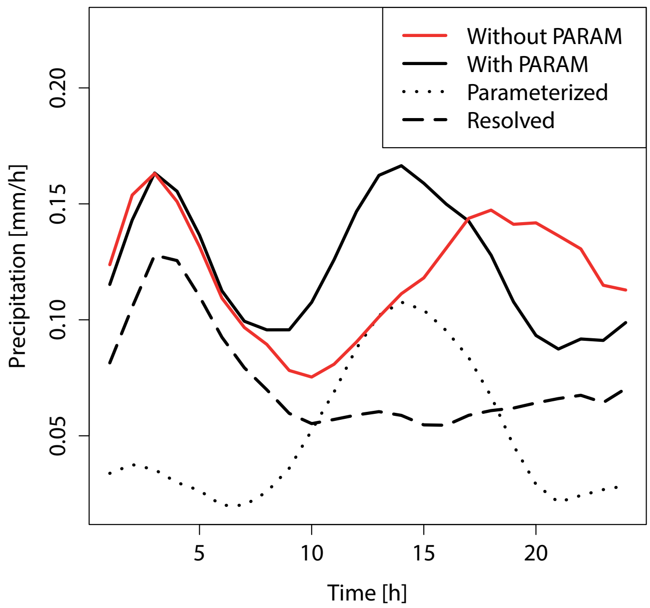
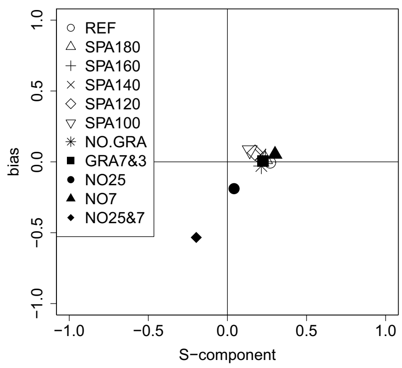
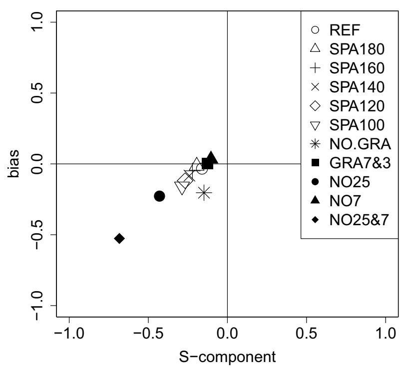


Figure 11: Diurnal cycle of precipitation for simulations with (black) and without (red) the Tiedtke parametrization are shown with solid lines. In addition both contributions of the resolved and the parametrized precipitation are shown with dotted lines.

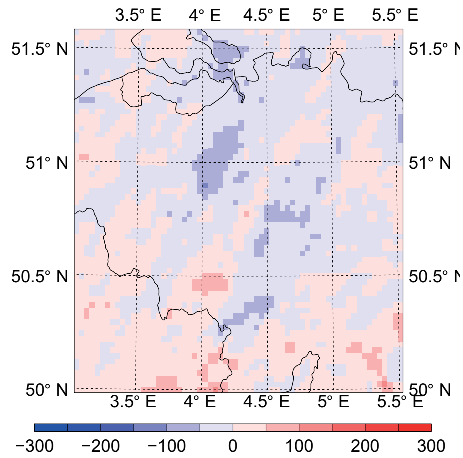


(a) With Tiedtke parametrization

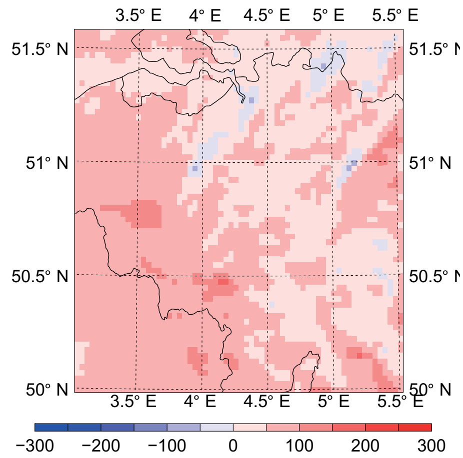


(b) Without Tiedtke parametrization

Figure 12: Skill scores of all experiments performed in this study for the four-month evaluation period. The mean S-component of the SAL approach is displayed on the *x*-axis, the mean bias on the *y*-axis. The left (a) and right (b) panel show experiments respectively performed with and without the Tiedtke parametrization.



(a) REF



(b) SPA100

Figure 13: Difference of temporally-averaged daily precipitation (mm/day) between simulations with and without Tiedtke parametrization for days with occurrence of Western, South-western and Southern advection during the period between 01/06/2007 and 30/09/2007. The left (a) and right (b) panel respectively show the REF and the SPA100 experiments. Positive (negative) values denote a dry (wet) bias of simulations without the Tiedtke parametrization compare to simulations with Tiedtke parametrization.

A first guess for the spatial spin-up of precipitation accumulation is ~ 150 km. In further studies, it would be important to test even larger domains to more thoroughly investigate spin-up of different spatial variables.

Among the different nesting strategies tested, the 0.22 °–0.025 ° was found to be the less computational intensive and have reduced deficiencies due to the multiple boundary forcing steps. Indeed, removing the 0.0625 ° nest does not significantly influence the representation of precipitation at CPS. However removing the 0.22 ° nesting step always results in dry biases.

Most conclusions drawn from the three set of experiment (e.g. graupel representation, domain size, nesting strategy) are related to the explicit modelling of convective processes. To validate these conclusions, similar experiments, except that they include a convective parametrization, are performed. The parametrization aims at destroying the atmospheric stability necessary for the simulation of deep convection so that the explicit modelling of convective processes is unlikely to occur. As expected, the graupel parametrization and the domain size experiments were found to be sensitive to the explicit modelling of convective processes while such a sensitivity was not found in the nesting strategy experiments.

In summary of the different strategies to reduce computational cost only the nesting strategy was found to be effective. Indeed the representation of graupel in the model is crucial to the production of realistic convective precipitation and should, therefore, not be considered as an options for reducing computational cost. Similarly, the domain should be large enough for allowing the growth of graupel particles necessary for the production of realistic convective precipitation.

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