Large impact of tiny model domain shifts for the Pentecost 2014 MCS over Germany

Christian Barthlott and Andrew I. Barrett

Institute of Meteorology and Climate Research (IMK-TRO), Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany

Correspondence: Christian Barthlott (christian.barthlott@kit.edu)

Abstract. The mesoscale convective system (MCS) that affected Germany at Pentecost 2014 (9 June 2014) was one of the most severe for decades. However, the predictability of this system was very low as the operational deterministic and ensemble prediction systems failed to predict the event with sufficiently long lead times. We present hindcasts of the event using the COnsortium for Small-scale MOdeling (COSMO) model at convection-permitting (2.8 km) resolution on a large (1668×1807 km) grid, which allowed us to simulate the whole life cycle of the system originating from the French Atlantic coast. Results show that this model configuration successfully reproduces the convective events of that day. However, the low predictability of the event was evident by the surprisingly large impact of tiny changes to the model domain. We systematically shifted the model domain by one grid point in eight different directions, from which three did not simulate any convection over Germany. The analyses show that no important differences in domain-averaged initial conditions nor in the preconvective environment ahead of the convective system exist. That one-third of these seemingly identical initial conditions fails to produce any convection over Germany is intriguing. The main reason for the different model results seems to be the proximity of the track of the initial convective system to the coast and colder sea surface. The COSMO model simulates small horizontal displacements of the precursors of the MCS which then determine if the cells dissipate close to the sea or reach a favourable area for convective development over land and further evolve into an MCS. This study demonstrates the potentially huge impact of tiny model domain shifts on forecasting convective processes in this case, which suggests that the inclusion of this simple method in convective-scale ensemble forecasting systems should be evaluated for different cases, models and weather regimes.

1 Introduction

An accurate forecast of deep moist convection is of great societal and economic relevance due to multiple risks from heavy precipitation, strong winds, lightning, or hail. Convection-permitting models have provided a step-change in rainfall forecasting and are used operationally in many parts of the world (Clark et al., 2016). Although progress has been made through higher grid spacing of numerical weather prediction models and better parameterizations of physical processes, quantitative forecasting of

convective storms remains a challenge. All forecast centers still suffer from so-called forecast busts (Rodwell et al., 2013), in which a strong drop in performance occurs and the forecast skill becomes very low.

The 2014 Pentecost storms over Germany were also partly characterized by a low forecast skill. Following a period of hot weather, a series of convective systems occurred over northwestern Germany leading to significant damages with even six fatalities. The major event took place on Pentecost Monday (9 June 2014) where a mesoscale convective system originating over France traveled across Belgium and hit northwestern Germany in the evening (Mathias et al., 2017). At the German Weather Service, both the deterministic run and all 20 members of the ensemble prediction system failed to predict any severe storms over northern Germany. These events and their poor prediction motivated the study of Barthlott et al. (2017), in which several methods of improving COnsortium for Small-scale MOdeling (COSMO) model simulations were evaluated, including: a larger model domain, higher grid spacing, a more sophisticated microphysics scheme and different initialization times. A series of different numerical simulations for the convective events of 8 and 9 June 2014 were performed, the main findings were:

- The operational model set-up initialized at 00:00 UTC reproduced the events on 8 June only, but not the mesoscale convective system (MCS) on 9 June.

- The enlargement of the model domain towards the West had the largest effect due to better resolving the initiation and development of deep convection over western France and, later, secondary initiation over northern France.

- Changes to both vertical and horizontal grid spacing (highest resolution 1 km) had only minor effects on the simulation results. Use of even higher resolutions up to large-eddy scale as in Barthlott and Hoose (2015) may have helped, but was left for future work.

- The use of a double-moment microphysical scheme improved the rainfall amounts on 8 June only.

- An increased or reduced initial soil moisture had significant effects on the energy balance of the surface (see e.g., Barthlott et al., 2011), but still no MCS-like system was simulated over Germany.

- Although weaker than observed, later initialization times (03:00 UTC, 06:00 UTC) produced deep convection over Germany due to outflow triggering and secondary cell initiation.

Specific reasons for the model failure of the 00:00 UTC run remained unclear, but the analysis of convection-related variables indicated too high values of convective inhibition (CIN) in northern Germany. As was pointed out by Groenemeijer (2014), extending the COSMO-DE domain to the west and south would allow storms to be captured earlier by the model. By enlarging the domain 300 km to the west, the direction from which most severe thunderstorms arrive, the lead time can be increased by 3 h (assuming a system moving with $90\,\mathrm{km\,h^{-1}}$).

Many operational forecast centers produce both a high-resolution forecast and an ensemble of lower resolution to provide a measure of uncertainty (Rodwell et al., 2013). In recent years, the benefits of ensemble techniques over deterministic numerical weather prediction are widely recognized (e.g., Hohenegger and Schär, 2007). The recent advance to convective-scale

55 ensembles can help address the uncertainty associated with convective-scale processes (Barrett et al., 2016). There a various ways of generating an ensemble, such as perturbations to the initial conditions and/or boundary conditions (e.g., Montani et al., 2011; Kühnlein et al., 2014), stochastic physical parameterizations (e.g., Buizza et al., 1999; Berner et al., 2017), or ensemble data assimilation such as ensemble Kalman filter (e.g., Dowell et al., 2004; Zhang et al., 2004; Reich et al., 2011). Because of the fundamental uncertainties of the simulations due to nonlinearities of the model equations, several studies have noted the

60 significant impact of initial and lateral boundary conditions on the simulation of convective precipitation for some situations (e.g., Hohenegger et al., 2006; Trentmann et al., 2009; Richard et al., 2011; Bouttier and Raynaud, 2018) and that ensemble members with the most accurate initial and boundary conditions are most skilful at predicting the location of convective initiation (Barrett et al., 2015).

While trying to get a reasonable model representation of the MCS on 9 June 2014, we conducted several numerical ex-
65 periments with different domain sizes and domain locations and found remarkably large differences in the simulations. For regional climate simulations, the sensitivity to the size and position of the domain chosen is well known (Miguez-Macho et al., 2004). In their study, the center of the grid was successively moved 17° to the west, 10° to the east, 7° to the north, and 10° to the south. These large changes led to a distortion of the large-scale circulation by interaction of the modeled flow with the lateral boundaries of the nested domain which sometimes had a large effect on the precipitation results. Seth and Giorgi (1998)
70 demonstrated that the domain of a regional climate model must be carefully selected for its specific application. In particular, domains much larger than the area of interest appear to be needed for studies of sensitivity to internal forcings, as the inter-actions between boundary conditions and internal model forcings played an important role. Similar results were obtained by Landman et al. (2005); in their regional climate simulations, the positioning of the eastern boundary of the regional model domain is of major importance in the life cycle of simulated tropical cyclone-like vortices.

75 Beside the influence of different domain sizes, the approach of shifting the model domain boundaries (and keeping the number of grid points constant) has been rarely used for short-range convection-resolving numerical weather prediction. The only study, to the authors' knowledge, was conducted by Henneberg et al. (2018) for examining soil moisture influences on convective precipitation over northern Germany. Perturbations were introduced by shifting the domain boundaries by ten to 30 grid points north and eastwards. Their results have shown that by shifting the model domain, an estimate on the uncertainty
80 of the model results can be calculated and a sufficient large model spread can be achieved. A somehow similar technique was used by Schlüter and Schädler (2010) to study the impact of small changes in the synoptic situations on extreme precipitation events. They shifted the large-scale atmospheric fields to north, south, east, and west with respect to the orography by about 28 and 56 km and found that the modeled precipitation can be quite sensitive to small changes of the synoptic situation with changes in the order of 20% for the maximum daily precipitation.

85 Limited area ensemble predictions are known to be sensitive to the specification of lateral boundary conditions (Bouttier and Raynaud, 2018) and the variability of boundary conditions is essential for representing large-scale uncertainties in limited-area predictions beyond a few hours (e.g. Gebhardt et al., 2011; Vié et al., 2011). Whereas in regional climate simulations, where it is desired to eliminate the dependance of the results on the position of the domain e.g., by spectral nudging (Miguez-Macho et al., 2004), the simple approach of domain shifting could be used to account for errors in the initial and boundary conditions
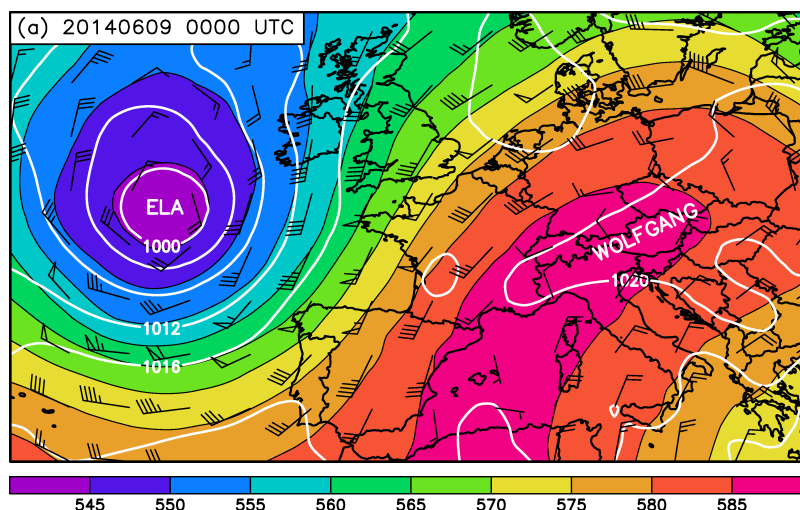
Figure 1. Global Forecast System analyses at 9 June 00:00 UTC showing 500 hPa geopotential height (gpdm, shading), sea-level pressure (hPa, white contours), and 500 hPa wind barbs.

90 and produce an ensemble with sufficient spread. Thus, it is of interest to further evaluate this simple approach of domain shifting to account for uncertainties in the initial and boundary conditions.

This paper reports on the surprisingly large sensitivity of moving the model domain by only 1 grid point. We evaluate what the differences between the simulations were, and what the origin of these differences was. This gives us further insight into the important physical processes for this event, and helps understand why it was so difficult to predict in the operational forecast

95 models. Furthermore, we explore the potential of model-domain shifting to help determine the predictability of convective events within an ensemble modelling framework.

2 Synoptic situation and observed precipitation

To describe the synoptic situation of the event, we briefly summarize the analysis from Barthlott et al. (2017). For more details, we refer to that paper and to the synoptic analysis performed by Mathias et al. (2017). The synoptic situation on 9 June 2014

100 was characterized by a trough stretching across the northern Atlantic Ocean southwards almost to the Canary Islands and an extensive ridge covering central northern Africa, the western Mediterranean Sea, and central Europe (Fig. 1). At the surface, there was a low pressure system named "Ela" corresponding to the upper-level trough. The high pressure system over the continent ("Wolfgang") dominated the region between the Alps, Poland, and the Black Sea. This configuration was already present on the day before and had progressed only slowly eastward. During the period of 8–10 June 2014, the temperature

105 contrast over Western Europe intensified. Cool Atlantic air masses were present at the eastern edge of the low pressure system, while moist and very warm air of subtropical origin was carried north-eastwards by the strong upper-level south-westerly flow.
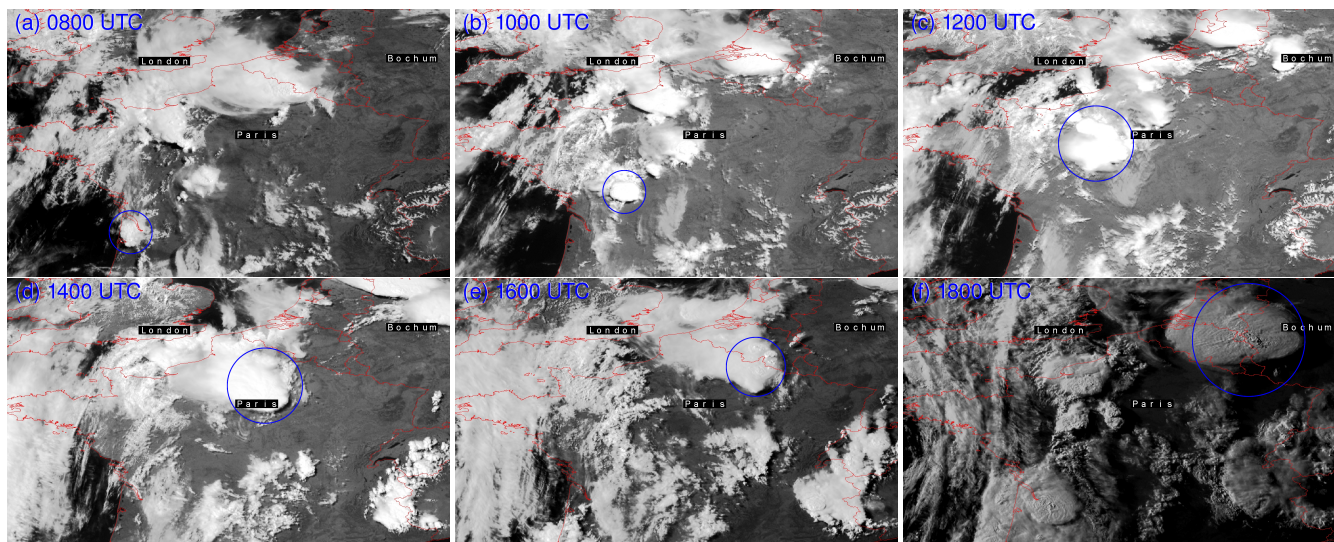
Figure 2. Meteosat visible satellite pictures of northern France and western Germany from 08:00–18:00 UTC (raw data courtesy of EU-METSAT). The convective system investigated here is marked by the blue circles.

Intense thunderstorms developed in northwestern France and the Benelux countries during the night and in the morning hours of 9 June 2014 and also later in the day due to diurnal surface heating. In the evening, an elongated area of convective storms extended from eastern Spain across western and northern France all the way to Benelux (i.e. Belgium, the Netherlands, and Luxembourg) and northwestern Germany. An intense MCS reached its mature phase in the evening over Benelux and western Germany, which is in the focus of this study. The analysis of satellite pictures in Fig. 2 reveals that the system originated over the Bay of Biscay in the morning of 9 June. The temporal evolution was characterized by several cycles of intensification and decay. For example at 16:00 UTC (Fig. 2e), an intensification at the northeastern edge of the system took place which lead to the large MCS over Germany in the evening with overshooting tops and signs of gravity waves (Fig. 2f).

3   Method

3.1   COSMO model

All simulations were performed with version 5.3 of the numerical weather prediction model COSMO (COnsortium for Small-scale MOdeling, Schättler et al., 2016). The COSMO model is a nonhydrostatic limited-area atmospheric prediction model initially developed by the Deutscher Wetterdienst (DWD, German Weather Service) which is operationally used by several weather services in Europe. It is based on the fully compressible primitive equations integrated with a two-time level Runge-Kutta method (Wicker and Skamarock, 2002). As previous simulations of Barthlott et al. (2017) showed little sensitivity of the results to model grid spacing, we performed all simulations with 2.8 km horizontal grid spacing and 50 terrain-following vertical levels. This corresponds to the operational used setup at the DWD at the time of the event. For consistency with
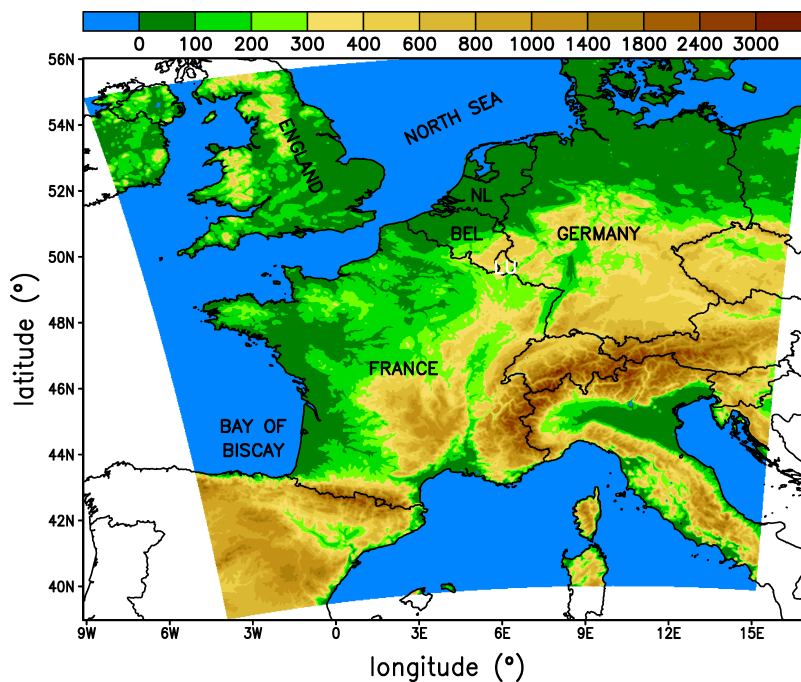
Figure 3. COSMO simulation domain and model orography (in m asl) of the reference run.

previous simulations of this case, the changes suggested by Barrett et al. (2019) to minimise timestep-dependent results from
125 the microphysics parameterization were not included. The model uses an Arakawa C-grid for horizontal differencing on a
rotated latitude/longitude grid. Initial and boundary conditions come from the ECMWF's Integrated Forecasting System (IFS)
analyses with a resolution of 0.125 °. All simulations are initialized at 00:00 UTC with an integration time of 36 h. The
time step is set to 25 s. Deep convection is resolved explicitly and a modified Tiedtke-scheme (Tiedtke, 1989) is used to
parameterize shallow convection. A 1D turbulence parameterization based on the prognostic equation for the turbulent kinetic
130 energy after Mellor and Yamada (1974) is applied. No latent heat nudging or other data assimilation technique is used. Instead
of the operationally used single-moment microphysics scheme, we use the double-moment scheme of Seifert and Beheng
(2006) assuming continental concentrations of cloud condensation nuclei ($N_{CN} = 1700\,cm^{-3}$). In our configuration, the CCN
concentration remains constant and is not varied as, for example, in the study of Barthlott and Hoose (2018) investigating
aerosol effects on clouds and precipitation in central Europe.

135 ## 3.2 Model domain choices

The model domain contains $600{\times}650$ grid points, which corresponds to an area of about $1668\,km{\times}1807\,km$. To be able to
simulate the entire life cycle of the convective system, the domain covers France, Benelux, Germany, and the Alps with parts of
the neighboring countries (Fig. 3). The sensitivity of the model results to domain shifting is assessed by conducting simulations

Table 1. Domain shifting.

name	domain shifting
N	1 grid point towards the North
NE	1 grid point towards the North-East
E	1 grid point towards the East
SE	1 grid point towards the South-East
S	1 grid point towards the South
SW	1 grid point towards the South-West
W	1 grid point towards the West
NW	1 grid point towards the North-West

where the model domain is shifted by one grid point in eight different directions (Table 1). All other model settings remained
140 unchanged.

4 Results

4.1 Reference run

In the reference run, simulated precipitation on the evening of 9 June occurs over Benelux and northern Germany (Fig. 4b).
The area covered by precipitation generally agrees well with that from radar observations (Fig. 4b). However, the simulated
145 precipitation is slightly too far north and areas near Cologne, Frankfurt, and south of Karlsruhe, the model produces less
precipitation and some single convective cells are not simulated. In contrast, precipitation covers more of the English Channel
northern Netherlands and Belgium than observed. As far as the total precipitation amounts are concerned, the COSMO model
produces similar values to those observed with slightly lower maximum values. However, radar is not an instrument measuring
precipitation in a quantitative sense (see e.g., Rossa et al., 2005) and differences in the amount do not necessarily indicate a
150 poor performance of the model. Unfortunately, this radar composite also suffers from missing data at some locations (e.g. over
Belgium south-west from Cologne) and also different calibrations or Z-R-relationships (obvious from the strong precipitation
gradient about 100 km north of Cologne).

The temporal evolution of of the convective system from both radar-derived and simulated 30-min precipitation rates is
presented in Fig. 5. Both systems follow a very similar track. We observe the following two main differences: (i) the model
155 simulates the convective system too far to the North and (ii) the simulated MCS moves faster towards the East. These differences
are similar to the simulations of Mathias et al. (2017). Moreover, the observed area covered with rain is larger than simulated.
However, the model succeeds in producing the bow-like structure of precipitation, typical of storms with an intense rear-inflow
jet. Given the overall good agreement in precipitation location and timing with reasonable accumulations, we conclude that the
reference run serves as a good basis for our sensitivity studies.
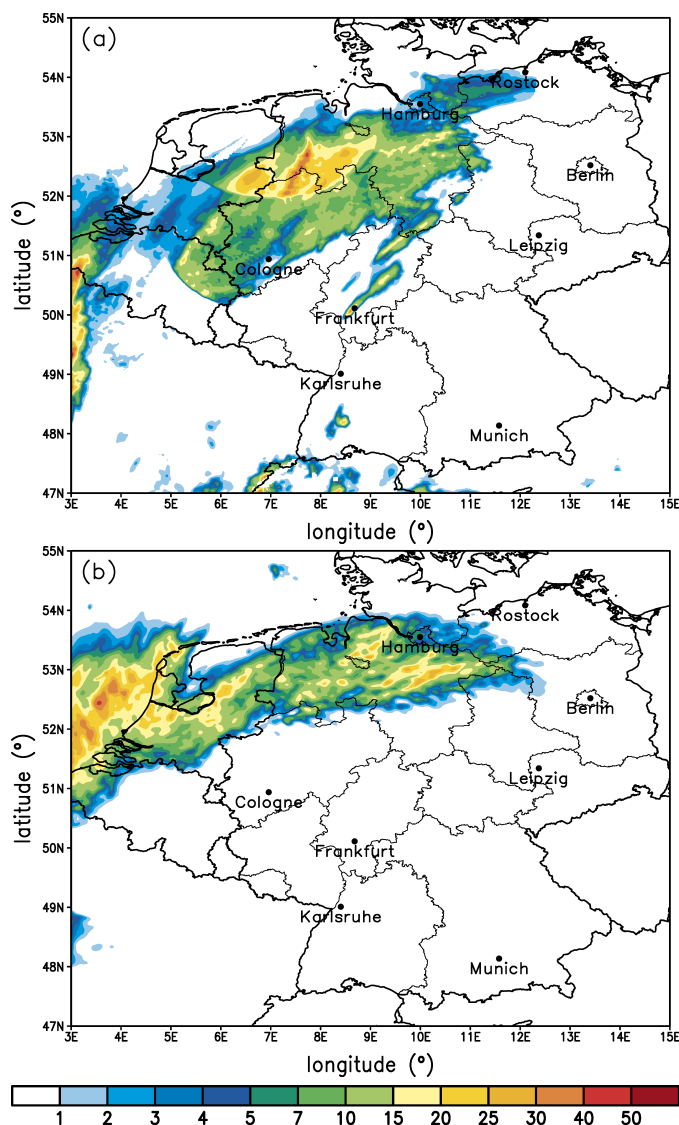
Figure 4. Radar-derived (a) and simulated (b) accumulated precipitation in mm on 9 June 2014 (17:00–24:00 UTC).

4.2 Sensitivity to domain choice

The 24 h accumulated precipitation for the REF run and all shifted model runs is displayed on the full model domain in Fig. 6. All model realizations show convective systems initiated near the Bay of Biscay in southwestern France which later move in a northeasterly direction. However, these systems are not related to the life cycle of the MCS that forms later over Germany and are not important for this study. The system that later became the MCS started as several smaller convective showers near the city of Nantes in the morning hours (starting around 0600 UTC). The track of the system in the REF run is marked by the red
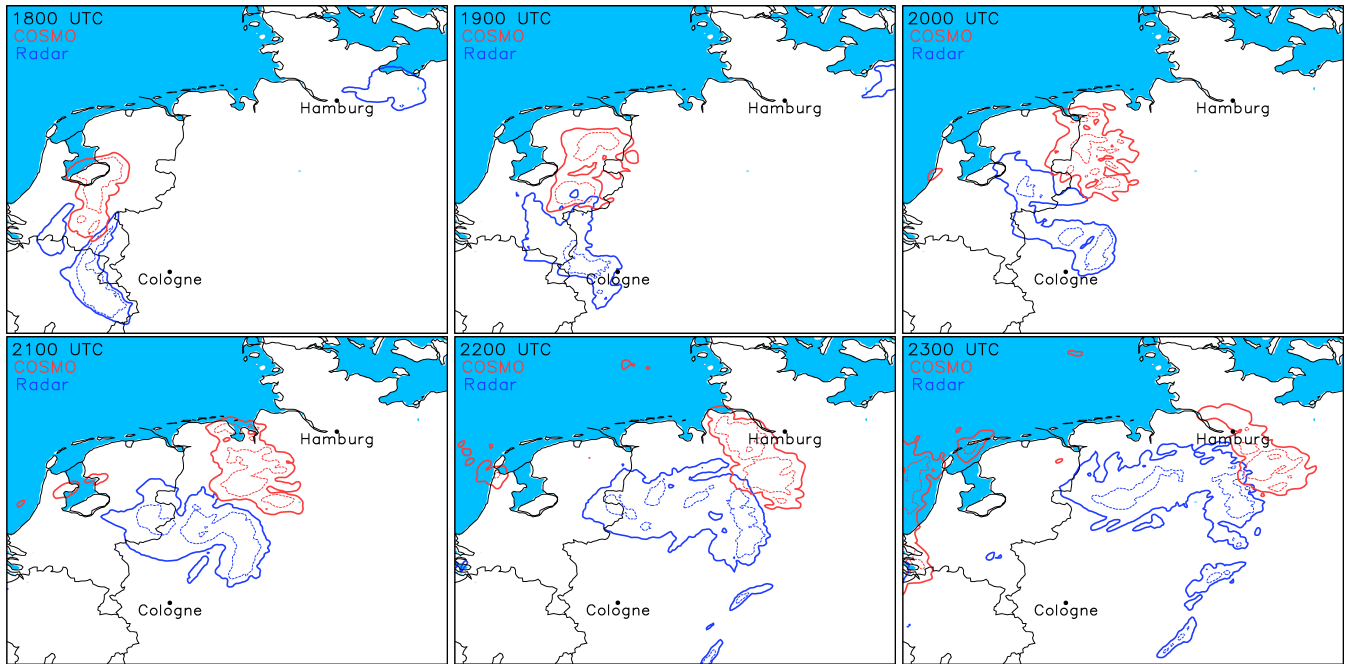
Figure 5. Radar-derived (blue contours) and simulated (red contours) 30-min precipitation of 1 mm (solid) and 5 mm (dashed) on 9 June 2014.

lines in all model runs. This first convection initiation is displaced to the North compared to the satellite observations (Fig. 2), which was nearer Bordeaux, and explains the northward displacement of the MCS track over Germany later in the evening. In addition to the REF run (Fig. 6e), the runs NW, N, SW S, and, to a lesser extent also run E, successfully simulate convective precipitation over northern Germany. In run E (Fig. 6f), the area with precipitation is too far in the North and the system

170 decays too early, west of Hamburg. The other successful model runs differ slightly from REF in the maximum rain amounts and horizontal extent of precipitation on the ground. Nevertheless, the results of those runs is rather similar with respect to 24-h accumulated precipitation. From these accumulations alone, the runs N, NW, or SW seem to be better suited as reference simulation due to the larger precipitation amounts. However, the analysis of the temporal evolution (not shown) reveals that reference run is closest to observations when both rain distribution and temporal development are considered.

175 The runs without any deep convection over northern Germany are the runs NE, W, and SE. Except for some weak and isolated showers north of Cologne in the W run, there is no precipitation simulated in the region of interest. Given that the model domain was shifted by only one grid point, this pronounced difference in the simulation results is surprising. All of these unsuccessful runs simulate more precipitation over the English Channel and the coastal regions of the Netherlands than the REF run. Additionally, there is no systematic response of the model to domain shifting in any direction, e.g. there is no

180 systematic decrease of precipitation when shifting the domain from North to South or East to West and the three unsuccessful simulations are not adjacent to one another.
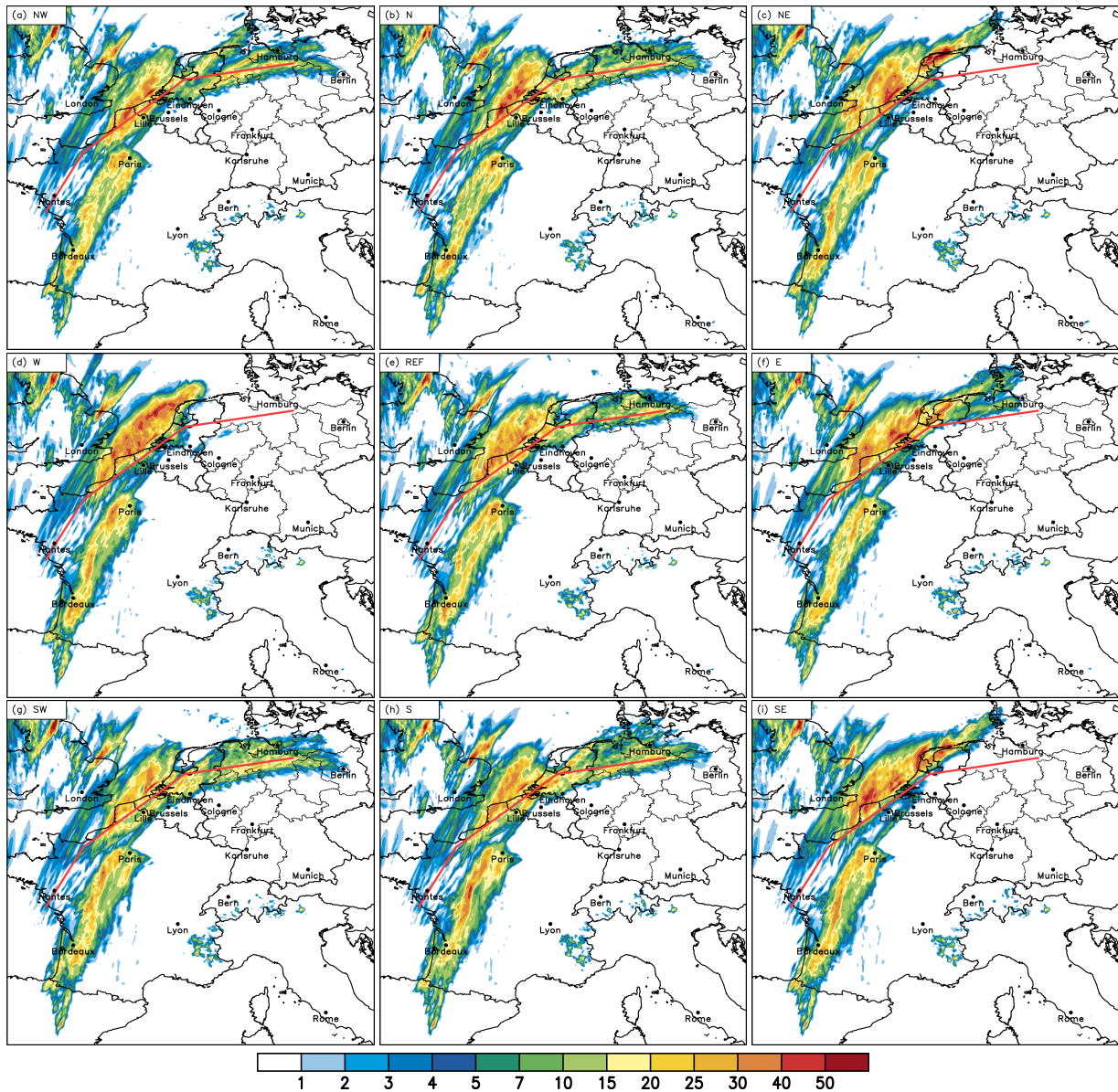
Figure 6. 24-h precipitation (00–24 UTC on 9 June) amount in mm. The red line indicates the approximated storm track of the REF run.
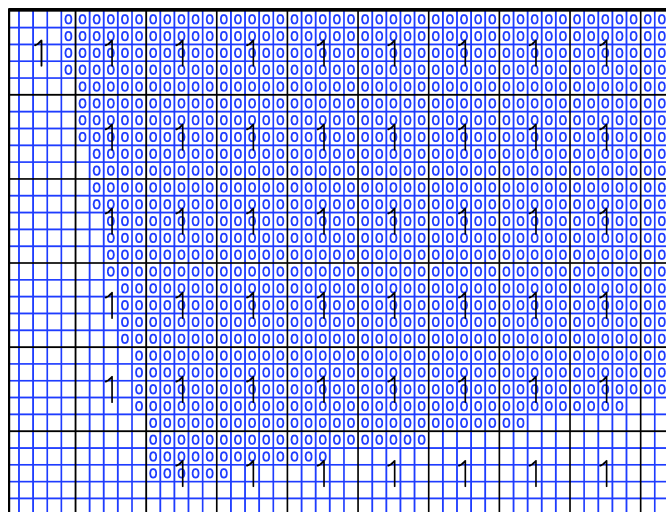
Figure 7. Southwest corner of the simulation domain with illustration of IFS grid (black) and COSMO grid (blue). Numbers of 1 indicate IFS grid points whereas 0 indicates COSMO grid points.

4.3 Differences in initial and boundary conditions

As we shifted the model domain only by one grid point towards the eight possible directions (referred to as Queen's case in spatial statistics), we expect only small differences in the initial and boundary conditions. This is justified by the difference in horizontal resolution of the initial data and the one used for the COSMO simulations. The spatial resolution of the IFS analyses used in this study is approximately 13 km. As the COSMO simulations are run with 2.8 km grid spacing, many of the grid points used in the preprocessor are the same if they are shifted by $\Delta x = 2.8$ km. This circumstance is illustrated in Fig. 7 in which the grid boxes of the input data and the COSMO grid of the southwest corner are displayed. Only for parts of the model boundary does the domain shifting of the high-resolution grid also imply a different grid point used for interpolation in the preprocessor of our model. Moreover, even when analyzing only the IFS input data, we do not see large point-to-point gradients in any meteorological fields near the boundary of the nested COSMO simulations (not shown).

However, small differences are present and assessed quantitatively by domain-averaged meteorological variables at initialization time (Table 2). Neither the surface fields (2 m temperature and specific humidity), nor the vertically-integrated variables (convective available potential energy CAPE, convective inhibition CIN, 2.5–5-km averaged relative humidity RH, liquid water path LWP, ice water path IWP, and deep layer shear DLS) does the model simulate any large differences in our ensemble of simulations. For example, the 2 m temperature differs by a maximum of 0.1°C between individual model runs. It is also of interest to investigate if the lateral boundaries (updated every 6 h) show any differences when the model domain is shifted. We therefore calculated averaged profiles for each of the four model boundaries for temperature, specific humidity and both horizontal wind components. The analysis of probability distributions (not shown) reveals that the range of simulated values is identical for all variables and only minor differences in the frequency of occurrence exist. Furthermore, averaged values of

Table 2. Domain averaged 2 m temperature (T in °C), 2 m specific humidity (QV in $g\,kg^{-1}$), convective available potential energy (CAPE in $J\,kg^{-1}$), convective inhibition (CIN in $J\,kg^{-1}$), 2.5–5 km averaged relative humidity (RH in %), liquid water path (LWP in $g\,m^{-2}$), ice water path (IWP in $g\,m^{-2}$, and deep layer shear (DLS in $m\,s^{-2}$) at initialization time.

run	T	QV	CAPE	CIN	RH	LWP	IWP	DLS
NW	18.5	10.35	215.0	297.7	44.8	0.32	2.72	14.1
N	18.5	10.35	214.7	297.6	44.7	0.32	2.74	14.1
NE	18.5	10.36	214.8	297.5	44.7	0.32	2.76	14.1
W	18.5	10.36	215.0	298.1	44.7	0.32	2.72	14.1
REF	18.5	10.36	214.8	298.0	44.7	0.32	2.74	14.1
E	18.5	10.36	214.9	297.9	44.7	0.32	2.76	14.1
SW	18.5	10.37	215.1	298.6	44.7	0.32	2.72	14.1
S	18.5	10.37	214.9	298.4	44.7	0.32	2.73	14.0
SE	18.6	10.37	214.9	298.3	44.6	0.32	2.76	14.0

those profiles are compared for every lateral boundary condition file (not shown). The maximum difference of the sensitivity runs to the REF runs is 0.02 K for temperature, $0.01\,g\,kg^{-1}$ for specific humidity, and $0.1\,m\,s^{-1}$ for the wind components. We therefore conclude that all differences in the initial and boundary conditions of the domain-shifted model runs are small. But given the chaotic nature of the atmosphere in convective weather events and the nonlinearity of the system with many feedbacks involved, these small deviations can determine whether a large MCS develops or not.

4.4 Convection-related parameters

The general preconditions for the initiation of deep moist convection are (i) conditional instability, (ii) a sufficient amount of humidity in the lower and middle troposphere to form clouds, and (iii) a trigger process to bring air parcels to their level of free convection (e.g., Doswell III, 1987; Bennett et al., 2006). Trigger processes are e.g., the reaching of the convective temperature, lifting by convergence zones (e.g., Crook and Klemp, 2000), or terrain-induced ascent (Kirshbaum et al., 2018). The organization and further life cycle is then affected by the vertical wind shear, CAPE, and relative humidity. To assess the state of the atmosphere in the vicinity of the MCS affecting northern Germany, we calculated several convection-related variables averaged over a rectangular box surrounding the convective system. The box has a size of 3°×2.5° and follows the storm along the path depicted in Fig. 6. The box has been positioned in such a way that the convection is not centered in the domain, but rather on the western edge to better capture the (preconvective) environment into which the storm is moving.

Figure 8 presents time series of some of these parameters during the life cycle of the convective storm. The brightly coloured lines represent the successful simulations, black is the reference simulations and gray and blue colored lines represent the unsuccessful simulations. The precipitation rate of the REF run is gradually increasing until 17:00 UTC (Fig. 8a) then there is a slight reduction in intensity before a second maximum is reached at 21:00 UTC. After 22:00 UTC, the precipitation rate
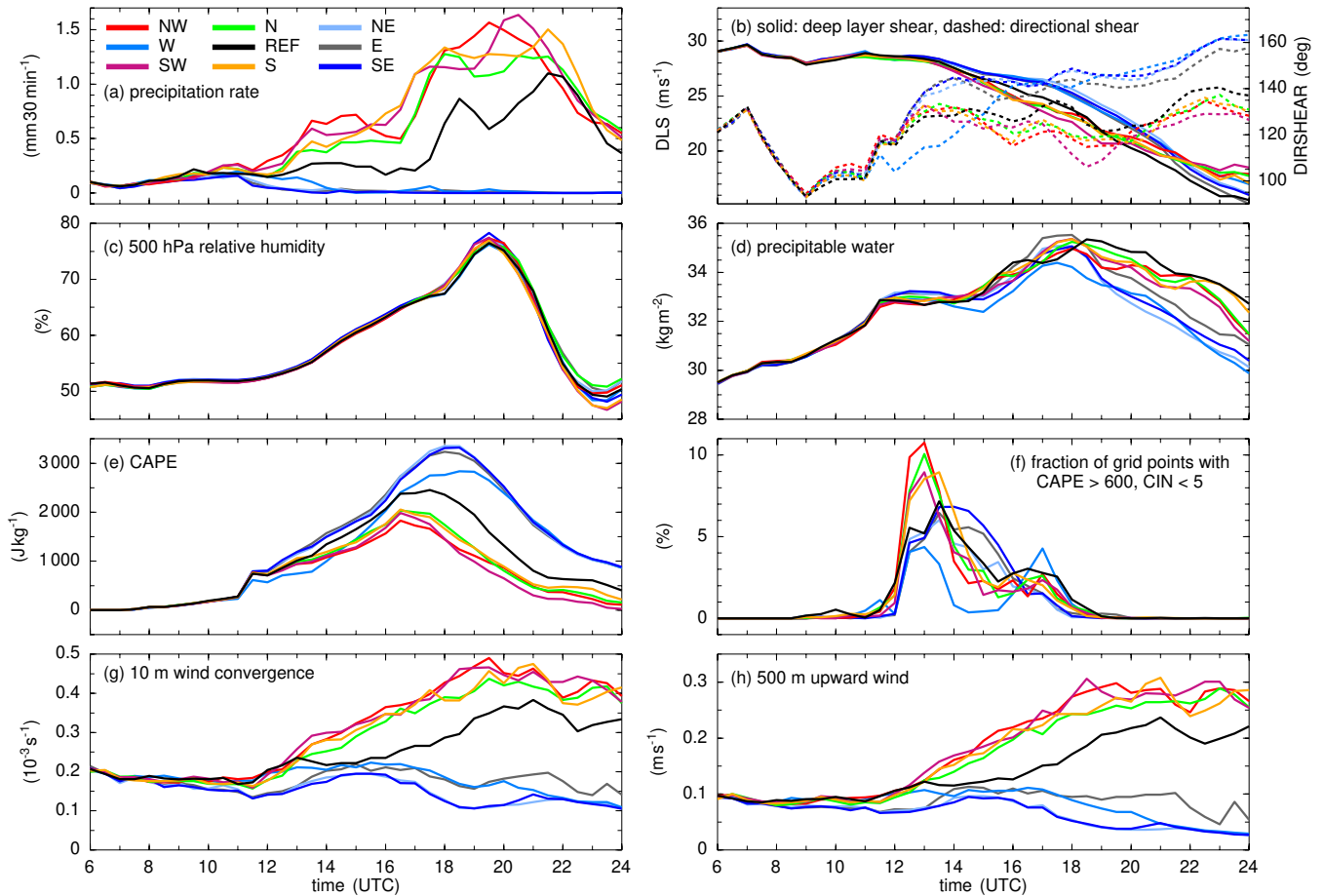
Figure 8. Time series of convection-related parameters averaged over a 3°×2.5° box surrounding and following the convective system. Shear parameters are based on surface and 6-km altitude winds.

decreases and the convective system slowly dissipates. The other successful runs (NW, N, SW, S) show larger precipitation rates and an earlier increase already from 12:00 UTC. As already mentioned earlier, these runs agree less well with observations in terms of precipitation location and timing than the REF run. The runs without an MCS over northern Germany (W, NE, SE) simulate similar precipitation amounts to the other runs until 11:00 UTC, but then rain gradually stops. Only run W simulates longer lasting precipitation until 14:00 UTC and a minor peak from a short-lived cell east of Eindhoven at 17:30 UTC.

The 0-6 km deep layer shear (Fig. 8b) is similar in all model runs with values of 27–30 m s⁻¹. Such high values indicate suitable conditions for highly-organised convection to develop in all runs because the precipitation and outflow become separated from the low-level updraft. Before the storms form there is almost no difference between the speed or direction of the wind shear in any of the simulations.

There is plenty of moisture available for convection, and both the mid-level relative humidity (Fig. 8c) and precipitable water (Fig. 8d) show large values that increase as the storm environment moves further East later in the day. The simulations

are again all very similar. The maxima in relative humidity are reached at 19:30 UTC which corresponds to the period with highest rain intensities. As the differences in relative humidity between the individual model runs are very small (2–4%), we determine that evaporation or entrainment processes are not responsible for the different model results. Moreover, between 14:00–22:00 UTC, the mid-level relative humidity is always higher than 60% which suggests that the role of entrainment of
235 drier environmental air is probably only small. The same applies for the precipitable water for which all model realizations lie close together until 14:00 UTC (Fig. 8d). At later times, the precipitable water is affected by different rain formation and evaporation processes.

Additionally all simulations show substantial conditional instability, especially later in the day. Before 11:00 UTC, all models produce similar amounts of CAPE (Fig. 8e). Later on, in simulations with larger precipitation totals, the more CAPE has
240 been consumed. This leaves the runs without an MCS over Germany with the highest CAPE values in the early evening (2500-3300 J kg^{-1}). For convection initiation or development, CAPE alone is not a suitable parameter. We therefore calculated the fraction of grid points, for which CAPE is larger than 600 J kg^{-1} and CIN is lower than 5 J kg^{-1} (Fig. 8f). Here there is a large contrast in the number of grid-points where convection is expected at 13:00 UTC between the successful (around 10%) and unsuccessful (around 5%) runs. However, the reference run and the unsuccessful runs show rather similar curves. The W
245 run reveals a somewhat lower maximum and a quick decrease afterwards. The secondary maximum occurring at 17:00 UTC corresponds to the aforementioned isolated cell initiated near Eindhoven.

Low-level wind convergence (Figs. 8g) is one mechanism for producing lift that leads to convection. The time series of convergence values are very similar to the upward vertical motion in the boundary layer (Figs. 8h) which indicates that the lift is primarily produced by convergence, mostly along convective outflow boundaries. Convergence early in the day can not
250 be solely attributed to surface inhomogoneities or terrain features, because small amounts of rain are already simulated in the morning hours leading to wind convergence at outflow boundaries. Between 08:00–11:00 UTC, the convergence of the unsuccessful runs (NE, SE) is slightly weaker despite similar precipitation rates (Fig. 8a). However, after 11:00 UTC there is a clear split between the successful and unsuccessful simulations, with increased convergence and upward wind velocities in the successful simulations. Of the unsuccessful runs, only W exhibits similar convergence strength and lifting in the boundary-layer
255 as the successful model runs and only until 13:00 UTC.

While this analysis does not completely separate the simulations into successful and unsuccessful subsets, there is information that helps explain the chance of producing an MCS. Clearly increased low-level convergence before 12:00 UTC is a good predictor of the later MCS, as is a large increase in the number of grid points with high CAPE but low CIN at 13:00 UTC. The lower CAPE and reduced deep-layer shear in the successful runs after 15:00 UTC are evidence of the storm modifying its own
260 environment rather than a useful predictor of the MCS. To refine the causes of the differences in these simulations we look at the evolution of the convective cells in more detail.

4.5 Simulation result differences

In this section we discuss horizontal cross-sections of convection-related parameters to elucidate the differences (and their possible causes) of the different model results. For the sake of brevity, we only compare the reference run to two unsuccessful

265 runs, namely the ones with the model domain shifted towards the W and the SE. Figure 9 presents a time series of those cross-sections for the region of northwestern France and southern England.

The analysis at 10:00 UTC shows a very similar picture for all simulations at all times, with CAPE increasing to the South and East, wind is westerly over the English Channel, turning to northerly direction over France and there is low CIN over France from 1100 UTC at the latest. The simulations all have weak, disorganised convection over northwestern France and
270 a more isolated cell at the border between France and Belgium. The region with the convective system of interest is marked with a red circle. However, as time develops, only the REF simulation produces a convective system that moves into the high CAPE region to the East and later becomes an MCS over Germany. By 10:30 UTC, CIN is less than $5\,\mathrm{J\,kg^{-1}}$ in the REF and SE run, whereas it is still above that threshold until 11:00 UTC in the W run. The highest rain intensities are also simulated in the REF run. At 11:00 UTC approximately half of the cell of interest in the W run is over the sea, where CAPE is lower and
275 CIN higher than over land. In contrast, the area of convective rain in the REF run is separated from the rain over the sea and precipitation intensity remains high. The precipitating area in the SE run is also separated from the larger rain area over the sea, but the precipitation rate is already weaker than in the REF run. At 11:30 UTC, the cell in the W run is weakening and lies almost at the coastline, whereas the cell in the REF run still remains almost entirely over land while moving towards the North-East. The corresponding system in the SE run is also weakening while travelling towards the North-East; approximately
280 half of the cell is now located over the sea. The systems in the W and REF runs both weaken at 12:00 UTC, but the one from the SE run has already decayed. Only the cell in the REF run intensifies again at 12:30 UTC. In the W run, the cell continues to move along the coastline while weakening, until it is completely dissolved at 14:00 UTC. In the REF run, however, the cell stays almost completely over land and intensifies further while moving towards the Netherlands (13:00–14:00 UTC).

The proximity of the cell to the colder sea surface appears to have a decisive influence on the further life cycle of convection.
285 In the REF run and the other successful runs (not shown), the system stays more or less entirely over land between 11:00–12:00 UTC. In these successful simulations, the systems travels further towards Belgium and Germany (rather than over the sea), where it encounters more favourable convective conditions including higher CAPE, which later allows it to evolve into an MCS.

The isolated cell, to the north west of these plots between 1000-1100 UTC, does not appear to be important to the decay of
290 the cell of interest. It is located approximately $150\,\mathrm{km}$ upstream. The cell is stronger in the W run leading to a slight reduction of CAPE and therefore creating slightly less favorable environmental conditions in the area into which the main cell would later move. However, it appears that the weakening of the main cell occurred independently of the cell upstream and can rather be attributed to the proximity to the colder sea surface.

5   Summary and conclusions

295 During Pentecost 2014, following a period of hot weather, a mesoscale convective system formed over France and traveled towards Germany in the afternoon of 9 June. A strong southwesterly flow lead to a favorable environment for deep convection
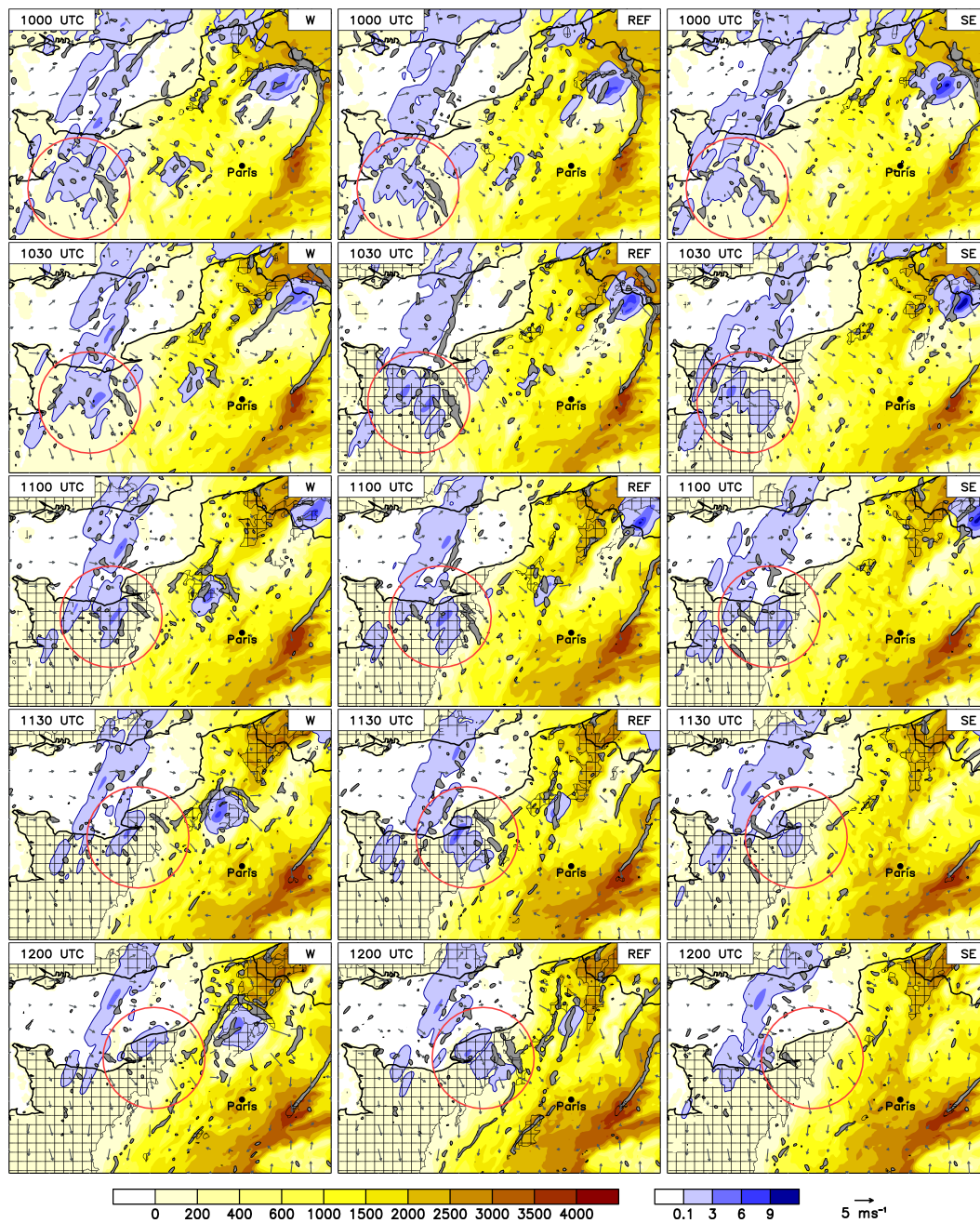
Figure 9. Convective available potential energy (colour shading, in $\mathrm{J\,kg^{-1}}$, 30-min precipitation rate (blue colour shading, in $\mathrm{mm\,(30\,min)^{-1}}$, and 10-m wind field (arrows) between 1400–1800 UTC on 9 June. Gray areas indicate low-level wind convergence larger than $0.35\cdot10^{-3}\,\mathrm{m\,s^{-1}}$ and hatched areas represent regions where convective inhibition is smaller than $5\,\mathrm{J\,kg^{-1}}$. Left: domain shifted to W; Middle: reference run; Right: domain shifted to SE. The red circle indicates the region of the convective cell developing into a MCS.
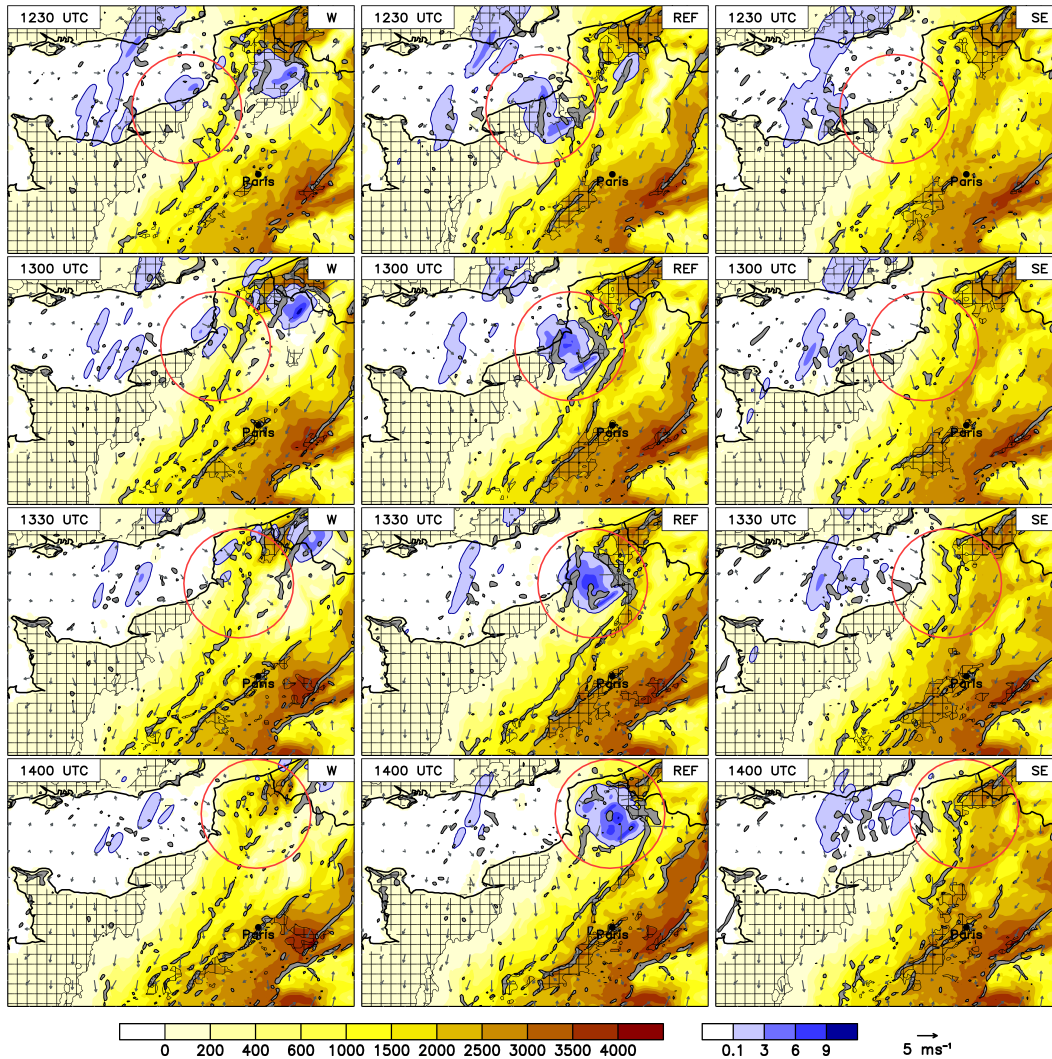
Figure 9. Continued.

due to the advection of warm and moist air. However, the predictability of this event was very low; neither the operational deterministic nor the ensemble prediction system captured the event with more than 12 hours lead time (Barthlott et al., 2017).

Hindcasts of this situation were performed with convection-permitting resolution on a large model domain, enabling the simulation of the whole life cycle of the system originating from the western Atlantic coast. The results show that the MCS was reasonably well represented by the COSMO model in this setup. When compared to radar-derived precipitation rates, the MCS was simulated somewhat shifted to the North and the translation speed was slightly higher than observed.

The low predictability of the event was again evident; moving the model domain by just one grid point changed whether the MCS over Germany is successfully simulated or not. The domain was shifted systematically in eight directions (N, NE, E, SE,

305 S, SW, W, NW) by just one grid point and three of these configurations completely failed to simulate deep convection over Germany on that day, while a fourth had some convection but did not capture the organised MCS. This large impact is even more surprising when considering the comparatively large computational domain of $1668\,\mathrm{km}\times1807\,\mathrm{km}$.

The evaluation of domain-averaged initial conditions, like low-level temperature, moisture, relative humidity, or wind shear showed only negligible differences. The temporal evolution of convection-related parameters in the vicinity of the storm system 310 also revealed similar conditions in its preconvective environment. An explanation of the large differences in the model results lies in the proximity of the track of the convective system to the north coast of France and the colder temperatures over the sea than the land. The convective system in the successful runs stays more or less entirely over land, allowing it to eventually reach a region favorable for convective organisation (with high CAPE, large shear and low CIN), whereas the early convection in the unsuccessful runs moved closer to the coast and had considerable portions located over the sea. This small displacement 315 seems to be the main point deciding if the system decays or is able to live on and intensify into an MCS.

Although perhaps an extreme example, this case is in agreement with many previous studies pointing out the effects of small-scale variability in atmospheric parameters (e.g. Crook, 1996; Weckwerth, 2000). These results emphasize the difficulty of forecasting the location and intensity of convective precipitation due to the chaotic nature of the atmosphere in convective weather events and the nonlinearity of the system with many feedbacks. In this case it is required to capture a chain of events 320 that is dependent on precisely predicting the location of initial convection; only if the outflow of the initial convective system occurs in the right location can the damaging MCS be triggered.

The results of this work suggests that the method of model domain shifting could be used to account for uncertainties in the initial and boundary conditions by introducing a small disturbance at model initialization. However, this single case study needs to be expanded to cover more cases. Thus, it is of interest to further evaluate this simple approach of domain shifting, for 325 example in weather regimes with strong synoptic forcing and more stratiform precipitation and in other models such as ICON (ICOsahedral Non-hydrostatic) (Zängl et al., 2015). Moreover, whether changing the extent of domain shifting (e.g. from 1–10 grid points) is important should be evaluated.

Data availability. COSMO model output is available on request from the authors.

Author contributions. CB and AB both designed the numerical experiments, CB carried them out and performed the data analyses. Both 330 authors contributed equally to the writing of the paper.

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