Responses to the reviewers

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

by Christian Barthlott and Andrew I. Barrett November 26, 2019

Dear Editor,

This letter accompanies our revised manuscript. We are grateful for the reviewer's helpful comments, and hope our revision addresses them all. Below we detail the changes made in our revision. We include the text of the reviews in black, our responses are in blue.

Reviewer 1

This study examines simulations of a rather impactful MCS over Germany in 2014. The COSMO model at convection-allowing resolutions is used to simulate the MCS in a control run, and additional simulations move the model domain one grid point in eight cardinal directions. The predictability and forecast errors of the MCS are largely dependent on convection initiation in western France and subsequent propagation of the system over land, as well as the environment the system encounters during the day before impacting Germany. Substantial variability exists amongst the simulations, whereby some instances of the MCS-induced rainfall is forecast reasonably over Germany and other instances there is no precipitation in this region at all. It doesn't appear that systematic movement of the domain resulted in clustering of forecast errors either.

Major Comments

1. My first and foremost major concern is the contribution of this work to the atmospheric science literature on MCSs, predictability, and forecast generation. I believe what the authors have described is merely a technique to perturb lateral boundary conditions, thereby producing spread in the initial states of the model simulations which filters into the forecasts of the MCS. If we assume the environment at the model boundaries is relatively homogeneous, at least within a few grid points which only amounts to < 10km, then what the authors have described here is essentially a 10-member ensemble forecast system with perturbed boundary conditions. This methodology is not in itself flawed by any means, but I do not believe it is innovative or new. See Torn et al. (2006), Gebhardt et al. (2011), and Romine et al. (2014) for other examples of boundary condition perturbation studies. Given this statement, however, I think the authors could easily address my concern by a number of avenues:

    a. If the authors believe this truly is an innovative technique to generate CAM ensembles, they should either more succinctly clarify this in the introduction with references supporting this claim or demonstrate the methodology alongside some of the more traditional techniques (e.g., covariance perturbations) for this case study.

    We do not believe that our technique is a new method to generate ensembles with perturbed initial/boundary conditions in operational convective-scale ensemble forecasting. However, we were surprised to see such a large influence of these tiny changes on the simulation results and strongly believe that this method should be tested for more cases (also with different extents of domain shifting) and other models. It may also be that the high sensitivity is a feature of days with low predictability only, which would be a useful information to have. Therefore, a more systematic evaluation is left for future work. We adapted the text to make that clearer.

Changes to paper

Abstract:

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~~ *the sensitivity to similarly small initial condition perturbations* should be evaluated ~~for different cases, models~~ *across other cases, model* and weather regimes.

Summary:

The results of this work suggests that ~~the method of~~ model domain shifting could be used to ~~account for~~ *quantify how* uncertainties in the initial and boundary conditions ~~by introducing a small disturbance at model initialization~~ *contribute to the predictability of an event*. 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 example in weather regimes with strong synoptic forcing and more stratiform precipitation and in other models such as ICON...

b. If the authors would still like to use the domain-shifting methodology to investigate the predictability of the MCS, I would caution attributing the methodology to why the MCS is inherently unpredictable. In order to scientifically attribute the poor forecast predictability to the domain-shifting methodology, substantially more analysis and simulations would need to be conducted. For instance, do you see the same poor predictability if the domain is moved 5, 10, or 20 grid points? What about if another perturbation technique is used? Can you reproduce the poor forecasts?

The goal of this paper was not to assess the impact of other perturbation techniques, as we already mentioned the poor forecast quality of the operational COSMO-DE-EPS of the German Weather Service in the introduction. While trying to find a model setup which could reproduce the MCS, we made a lot of tests, also with respect to domain size and domain location. When we changed the location of the domain by 2, 10, and 20 grid points, we already had successful and unsuccessful results. This is why we went to the minimal domain shifting possible, namely 1 grid point in eight cardinal directions. We believe that this is a good first step and this method should be evaluated as mentioned in the reply to the first comment. It is of special interest to see, if other cases with low predictability (i.e. forecast busts) show the same sensitivity. However, we think that such an analysis would not fit into the present paper and is therefore left for future work.

Changes to paper:

none

c. If the authors would rather focus on the predictability aspect of this event, I believe the authors could implement some other analysis techniques to derive some of the dynamic aspects for this case to complement what has been presented. Sensitivity approaches such as those demonstrated by Schumacher and Davis (2010) and Ancell and Hakim (2007) could be valuable additions to the analysis. I invite the authors to consult a number of papers that apply sensitivity analyses to convection-resolving forecasts as well: Bednarczyk and Ancell (2015), Hill et al. (2016), Limpert and Houston (2018), and Torn et al. (2016). Additionally, other aspects of predictability could be garnered through initializing ensemble forecasts at later times, which may answer the particular question of whether CI is the limiting factor of predictability.

We thank the reviewer for this useful hint and performed an ensemble sensitivity analysis

for our model runs. We present the results in the new section 4.5.

Changes to paper:
We include the sensitivity analysis in a new section 4.5, this includes explanation of the method and interpretation of the results and includes discussion of the newly added Figure 9.

2. A second concern I have is in the presentation of the forecast itself. There is no mention of the upper-level dynamics that could be supporting MCS development, particularly since the orientation of development and distribution of environmental parameters conducive to MCS propagation are misaligned from traditional understanding. For instance, the MCS propagation within a region of predominantly northwesterly or westerly surface winds, which would not advect the CAPE-rich air from the southeast. Typically, we would expect a convergence of moisture and higher theta-e air just ahead of the MCS, but this is not the case. Also, there is no mention as to what causes the MCS to initiate so early in the day. My inclination from reading the forecast description is that the orientation of the longwave mid-tropospheric trough is supporting the traversal of short-wave troughs through western Europe. I suggest the authors add supporting evidence for how the MCS initiates, which could elucidate some other predictability elements that have not been considered, e.g. the position and placement of upper-level vorticity maxima.

   The MCS propagation has not been the subject of the paper so far, as we focused more on the fact why the precursors of the MCS dissipate or not. This is why Figure 9 only presents the period between 1000 and 1400 UTC. The system later evolves into an MCS as can be seen in Fig. R.1, which shows that the distribution of environmental parameters are not misaligned from traditional understanding. We observe exactly what the reviewer has anticipated, but was

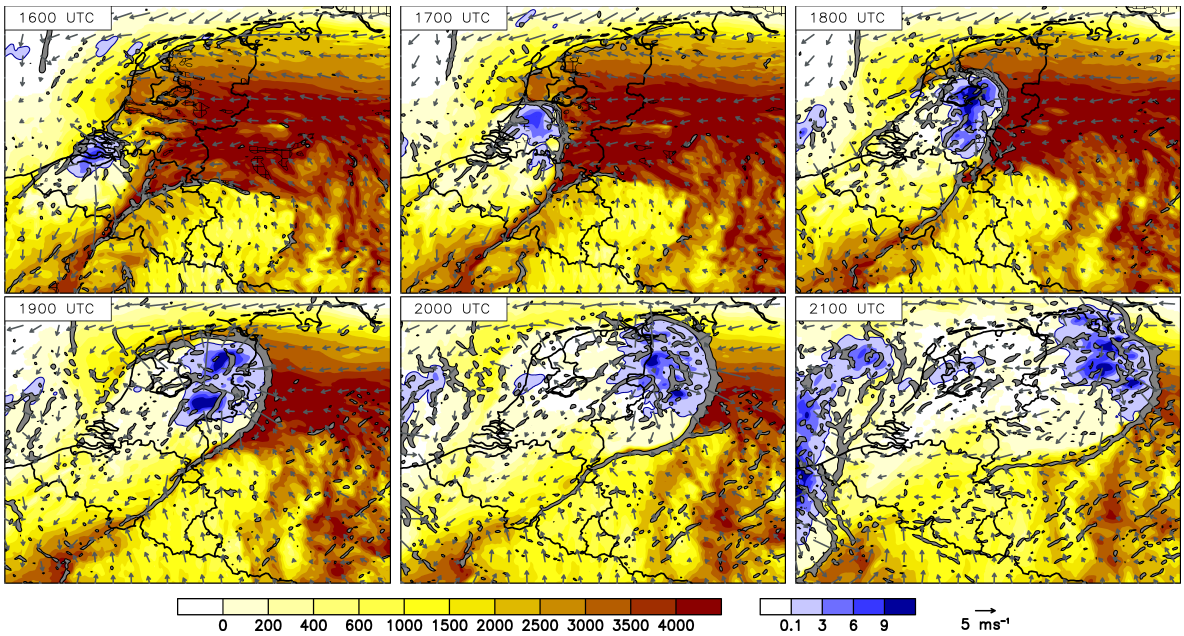

Figure R.1: Convective available potential energy (colour shading, in $\mathrm{J\,kg^{-1}}$, 30-min precipitation rate (blue colour shading, in $\mathrm{mm\,(30\ min)^{-1}}$, and 10-m wind field (arrows) between 1600–2100 UTC on 9 June. Gray areas indicate low-level wind convergence larger than $0.35{\cdot}10^{-3}\ \mathrm{m\,s^{-1}}$ and hatched areas represent regions where convective inhibition is smaller than $5\,\mathrm{J\,kg^{-1}}$.

not able to see in the Figure 9: an advection of CAPE-rich air from the East, with well-defined region of low-level wind convergence at the outflow boundary. The MCS cleary moves into the region with high CAPE which corresponds to high values of equivalent potential temperature.

We included this Figure in a new subsection 4.7 in the manuscript.

Changes to paper:
new Figure 11 and new subsection 4.7:

"Having established a possible explanation for the decay of the precursors of the MCS in the previous section, we now analyze the further evolution of the system into a MCS using the reference simulation (Fig. 11). To the east of the system, the model simulates an east-west oriented region of high low-level equivalent potential temperature in the north-central part of Germany, which corresponds to CAPE values between 3000–4000 $J\,kg^{-1}$. This CAPE-rich air is advected with easterly winds towards the convective system over the Netherlands. Colliding with the cell's outflow, a strong low-level mass and moisture convergence occurs, which fosters the evolution into a MCS. As already discussed in section 4.4, the 0-6 km deep layer shear shows suitable conditions for highly-organised convection (27–30 $m\,s^{-1}$). The maximum rain intensities reach locally up to 22 mm $(30\,min)^{-1}$ with a weakly defined bow-like structure of precipitation, typical of storms with an intense rear-inflow jet. In the wake of the MCS, CAPE is almost entirely consumed. From 23:00 UTC onwards, the MCS is decaying while further travelling towards Poland (not shown)."

3. Why is accumulated rainfall used as the sole metric of forecast evaluation? I would think observed radar reflectivity compared to simulated reflectivity would be a better metric for comparing model runs. Comparing reflectivity would better illuminate the intensity and structure of the MCS between observations and simulations; accumulated rainfall doesn't discriminate these differences well.

   We believe that rainfall at the ground is a suitable metric to assess the sensitivity of the model in simulating an MCS. Even if the model shows some discrepancies with respect to location and propagation speed, an overall good agreement between simulation and observation exists. Moreover, the focus of our paper lies on the sensitivity of the model to domain shifting and in-depth comparison of the MCS of the reference run with radar observations is not necessary for the reader to follow our story. Also, radar reflectivities are not available to the authors and the simulations would have to be done again with a radar-forward operator. Having said that, we think that an evaluation with rainfall is sufficient for our purpose.

Minor Comments:

1. Why was the predictability low for the operational prediction systems? Do those systems parameterize convection or is it explicitly solved?

   The origin of the low predictability of this case was unknown so far. This paper is another contribution to that topic. While in the Barthlott et al. (2017) paper, an enlargement of the model domain, a higher grid spacing and a single/double moment microphysics scheme were addressed, this study has shown show that small displacements of the convective system over France can lead to a decaying system or to a system developing into an MCS later on. The operational prediction systems used the same grid spacing as in our study, so deep convection was resolved and shallow convection parameterized. We added remarks in the model description and in the summary.

   Changes to paper
   Model description:

   Deep convection is resolved explicitly and a modified Tiedtke-scheme (Tiedtke, 1989) is used to parameterize shallow convection *(as did the operational deterministic and ensemble prediction system at that time)*.

Summary:

However, the predictability of this event was very low; neither the operational deterministic nor the ensemble prediction system *(both convection resolving)* captured the event with more than 12 hours lead time.

2. "However, the low predictability of the event was evident by the surprisingly large impact of tiny changes to the model domain": Is the argument there is low predictability because of dynamics or because of the model configuration? There appears to be two separate statements of predictability related to this event, but it is unclear what statements the authors really want to make. I'm assuming the main predictability element comes through the numerical (domain) aspect.

   As outlined in the reply to the previous comment, we do not know the origin of the low predictability. In our study, the low predictability is reflected by the domain effect.

   Changes to paper:
   none

3. Introduction Lines 28-30: Were the German Weather Service operational models convection resolving? Is there any indication as to "why" the deterministic and ensemble systems failed to produce convection over Germany? This piece of discussion would be a good addition to the manuscript to help explain "why" the model forecasts failed and potentially motivate the use of convection-allowing models.

   The operational models were convection-resolving, i.e. with a horizontal grid spacing of 2.8 km. As already mentioned earlier, we do not know why these model runs failed to produce convection over Germany. We added two remarks in the manuscript about this fact and the operational resolution.

   Changes to paper
   Model description:
   Deep convection is resolved explicitly and a modified Tiedtke-scheme (Tiedtke, 1989) is used to parameterize shallow convection *(as did the operational deterministic and ensemble prediction system at that time)*.

   Summary:
   However, the predictability of this event was very low; neither the operational deterministic nor the ensemble prediction system *(both convection resolving)* captured the event with more than 12 hours lead time.

4. Line 35: First bullet point: what operational model is being discussed here? Second bullet point: Is the COSMO model being discussed here? Please be explicit about what model and associated configuration is being altered.

   We did not mean the operational model, but the COSMO model in an operational setup. We modified the text to make that clearer.

   Changes to paper:
   A series of different numerical simulations for the convective events of 8 and 9 June 2014 were performed *"with the COSMO model"*, the main findings were:

   - The ~~operational model~~ *COSMO model (in quasi operational set-up, without data assimilation)* initialized at 00:00 UTC reproduced the events on 8 June only, but not the mesoscale convective system (MCS) on 9 June.

5. Line 49: What is COSMO-DE? While the COSMO acronym has been properly described, I don't know what "DE" references.

   COSMO-DE is the name of operational configuration at DWD over Germany. This information is not needed here. So instead of explaining it, we just replaced *"COSMO-DE domain"* with *"model domain"*.

6. Lines 85-91: What benefit does "domain shifting" have over other traditional lateral boundary perturbation techniques (e.g., Torn et al. 2016)? I have not been convinced in the introduction that there is significant benefit in developing a new technique to perturb boundary conditions. Would it be appropriate to compare the described "domain shifting" technique with other perturbation techniques? Including this type of analysis would presumably shift the focus of your manuscript to an evaluation of ensemble-generation techniques for a specific MCS case study. Alternatively, the authors could instead focus on the true predictability of the event (rather than the domain shifting idea) and include some additional predictability analysis (e.g., ensemble sensitivity). See Schumacher and Davis (2010), Ancell and Hakim (2007), Bednarczyk and Ancell (2015), Hill et al. (2016), and Torn et al. (2016) for some examples of sensitivity analysis for precipitation and high-impact weather forecasts. (Major comment above)

   It was not our goal to evaluate different ensemble-generation techniques. Our case study is a first step, but needs evaluation with more cases before it can be compared to different methods to introduce uncertainties in the initial and boundary conditions. However, the study of Henneberg et al. (2018) showed, that by shifting the model domain, by ten to 30 grid points, an estimate of the uncertainty of the model results can be achieved with a sufficient large model spread. We believe that the large impact of these tiny changes need further evaluation with more cases, different extents of domain shifting, and other models. In several places in the manuscript, we now state that this method needs further evaluation and that suitability for representing uncertainties should be compared to traditional lateral boundary perturbation techniques.

   We are grateful for the examples of the sensitivity analysis. We performed such an analysis, the results are presented in the new section 4.5.

   Changes to paper:
   We include the sensitivity analysis in a new section 4.5, this includes explanation of the method and interpretation of the results and includes discussion of the newly added Figure 9.

7. I would suggest leaving the descriptive nouns out of the manuscript, and let the reader decide what is "surprising" or not (e.g., Line 92).

   We do believe that our technique of domain shifting of just 1 grid point provides surprising or at least unexpected results for this particular case. Given the large model domain and the minor changes at the boundaries, we would not have anticipated such a large dependency. Therefore we like to keep our phrasing in the current form.

   Changes to paper:
   none

Section 4

1. What is the source of radar observations? Would be appropriate to add this into the manuscript for reproducibility.

   The radar observation come from the radar network of the German Weather Service, the product is called RADOLAN. We added this sentence at the beginning of section 4.1.

Changes to paper
"Here we compare our simulations to radar-derived precipitation from the precipitation analysis algorithm RADOLAN (Radar Online Adjustment), which combines weather radar data with hourly surface precipitation observations of about 1300 automated rain gauges to get quality-controlled, high-resolution (1 km) quantitative precipitation estimations."

2. Line 144: should be (Fig. 4a)

   Done

3. Lines 158-159: I actually do not agree with this statement. I think the reference forecast has some glaring errors that do not make this a particular good forecast. Consider revising or removing this statement.

   We agree with the reviewer that the bow-like structure is not well-defined in our simulations. We therefore removed that sentence. Otherwise, we think that the model is doing a reasonable job, despite the differences already described in the text.

   Changes to paper:
   ~~However, the model succeeds in producing the bow-like structure of precipitation, typical of storms with an intense rear-inflow jet.~~

4. Lines 179-181: All the eastward shift simulations have poorer prediction though.

   We agree with the reviewer as the precipitation in the E-run is more to the North and does not extend as much to the East as the other successful runs.

   Changes to paper:
   "However, as the precipitation in the E run is more to the North and does not extend as much to the East as the other successful runs, all the eastward shift simulations have poorer prediction."

5. Lines 270-272: I think a reasonable counter argument could be that the W run initiated the convection well to the east (east of the red circle) and therefore had an earlier impact over Germany than the reference run, making it a "poor" forecast. Additionally, this forward storm system appeared to greatly impact the CAPE field in Figure 9, which seemingly had an impact on the development of upstream convection in the red circle. Furthermore, there is clearly a neutral to slightly negatively-tilted mid-tropospheric trough to aid in the propagation of short-waves (hard to tell where these might exist in the coarse resolution of Figure 1): what role did mid-tropospheric dynamics play in this system? I suggest a more thorough evaluation of the simulations and discussing all aspects of the environment more thoroughly, including any convection that might have influenced convection initiation (CI) in the focus area.

   The reviewer is right about the fact that in the W run, a convective cell occurs east of the red circle. We already mentioned this at the end of section 4.5:

   "The isolated cell, to the north west of these plots between 1000-1100 UTC, does not appear to be important to the decay of the cell of interest. It is located approximately 150 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."

   Our main counter argument would be that this convection does indeed reduce the CAPE locally, but the reduction in CAPE does not reach the region where the cell of interest is decaying. At 1130 UTC, the cell in the W run is decaying although further downstream there is still a tongue

of air with higher CAPE values as in the REF run. Moreover, in the SE run there is no cell to the east of the system of interest, and convection dies out anyway, in spite of the unaltered CAPE field downstream. We therefore conclude 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.

Changes to paper:
none

6. Line 284: The sea surface temperatures have not been described in detail yet. How do we know these SSTs are the limiting factor? We do not know what the SSTs from each simulation are or how they dynamically are impacting the simulation convection. Seems like a reaching statement without any evidence and I would suggest revising or providing more concrete, quantitative support.

   The surface temperature and CAPE are depicted in Fig. R.2. The sea surface temperature is much lower than the land surface temperature, at least in the northwestern coast of France where no significant amounts of rain was simulated in the last hours. As a result of these lower temperatures, CAPE is significantly reduced over sea. Along the coastline, there is a strong gradient in temperature (23 → 15 deg C) and CAPE. These statements also hold true for the remaining model runs. We added some remarks on that in the text, but decided not to provide an extra figure.

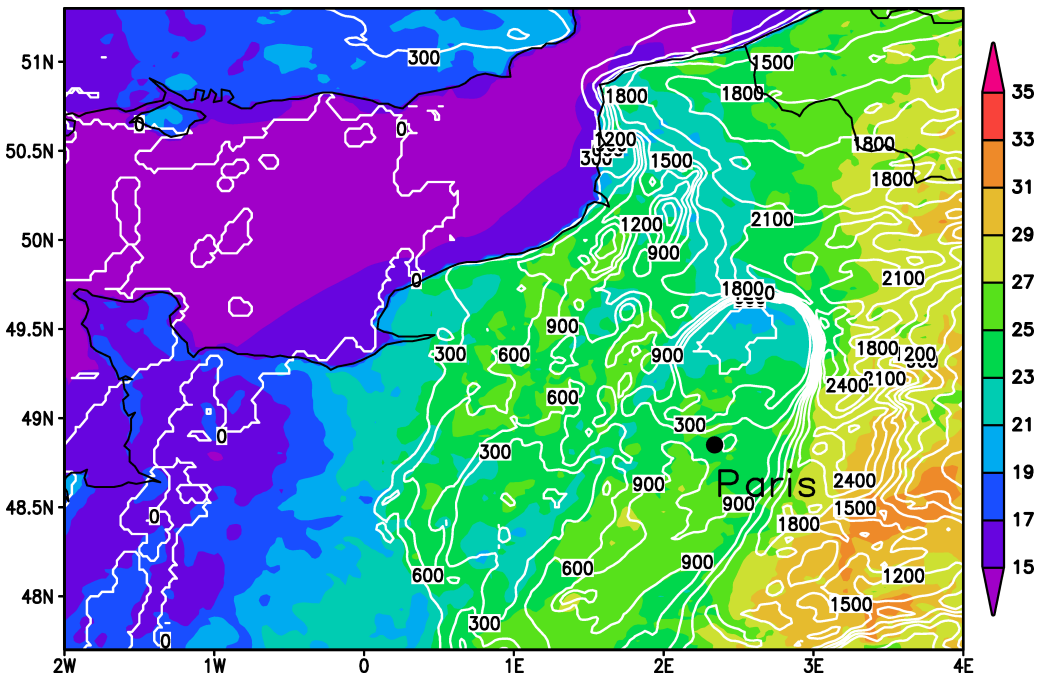

Figure R.2: Surface temperature of the REF run at 1000 UTC (colours, in deg C) and CAPE (white contours, in $\mathrm{J\,kg^{-1}}$).

Changes to paper:
"The sea surface temperatures along the French coast lie around 15°C and are much lower than the land surface temperatures (around 23°C, not shown). This temperature distribution is similar in all model runs for the preconvective environment."

References:

Ancell B. C. and G. J. Hakim, 2007: Comparing Adjoint- and Ensemble-Sensitivity Analysis with

Applications to Observation Targeting. Monthly Weather Review, 135, 4117-4134

Bednarczyk C. N. and B. C. Ancell, 2015: Ensemble sensitivity analysis applied to a southern Plains convective event. Monthly Weather Review, 143, 230-249

Gebhardt C., S. E. Theis, M. Paulat, and Z. B. Bouallgue, 2011: Uncertainties in COSMO-DE precipitation forecasts introduced by model perturbations and variation of lateral boundaries. Atmospheric Research, 100, 168-177.

Hill A. J., C. C. Weiss, and B. C. Ancell, 2016: Ensemble senstivity analysis for mesoscale forecasts of dryline convection initiation. Monthly Weather Review, 144, 4161-4182.

Limpert G. L. and A. L. Houston, 2018: Ensemble senstivity analysis for targeted observations of supercell thunderstorms. Monthly Weather Review, 146, 1705-1721.

Romine G. S, C. S. Schwartz, J. Berner, K. R. Fossell, C. Snyder, J. L. Anderson, and M. L. Weisman, 2014: Representing forecast error in a convection-permitting ensemble system. Monthly Weather Review, 142, 4519-4541.

Schumacher R. S. and C. A. Davis, 2010: Ensemble-Based Forecast Uncertainty Analysis of Diverse Heavy Rainfall Events. Weather and Forecasting, 25, 1103-1122.

Torn. R., G. J. Hakim, and C. Snyder, 2006: Boundary conditions for limited-area ensemble Kalman filters. Monthly Weather Review, 134, 2490-2502.

Torn R., G. S. Romine, and T. J. Galarneau, Jr., 2016: Sensitivity of dryline convection forecasts to upstream forecast errors for two weakly forced MPEX cases. Monthly Weather Review, 145, 1831-1852.

Additional changes to the paper:

1. We included a new sentence in the introduction about two recent papers:

   "Recent studies of Schneider et al. (2019) and Keil et al. (2019) have also shown that different assumptions for the amount of cloud condensation nuclei could be included in convective-scale ensemble forecasting, but only if the model employs a double-moment microphysics scheme."

2. Old Figure 9 was enhanced by increasing the size, length, and density of the wind arrows.

3. Information about the financial support was added.

Responses to the reviewers

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

by Christian Barthlott and Andrew I. Barrett November 26, 2019

Dear Editor,

This letter accompanies our revised manuscript. We are grateful for the reviewer's helpful comments, and hope our revision addresses them all. Below we detail the changes made in our revision. We include the text of the reviews in black, our responses are in blue.

Reviewer 2

This study presents the results of a simple experiment to test the sensitivity in simulating a high impact precipitation event over Germany by shifting the model domain by seemingly inconsequential amounts. While the study focuses on the impact of the domain shifts, essentially the ensemble model setup is an exercise in perturbing the initial conditions/lateral boundaries and thus the intrinsic predictability of convective storms. The main result of the ensemble was that members that initialized convection in France and then subsequently moved over cooler, ocean air resulted in weaker convection that dissipated before being able to intensify into the observed MCS in Germany. On the other hand, members that kept the convection over land where it was able to tap into a more favorable environment produced convective systems that were reasonably well forecasted over Germany.

In general, this paper needs provide a clearer link to previous studies that have investigated the impact of perturbing the initial conditions/lateral boundaries. I am still unconvinced that shifting the domain would be a more promising avenue to "account for uncertainties in the initial and boundary conditions" than other techniques (see the work from Ryan Torn and colleagues since the mid-2000s). Additionally, I believe more analysis is needed than a cursory comparison of precipitation and environmental parameters. What preempted the deviations in convection evolution over land/sea? Plots and discussions of differences in upper-level vorticity, MSLP, and even SSTs would improve the analysis. Once these two chief concerns have been addressed, I will provide a more thorough review, including specific comments and suggestions, prior to publication.

- The first point we want to address is similar to the reply to the first and second comment of Reviewer #1. We do not believe that our technique is a new method to generate ensembles with perturbed initial/boundary conditions in operational convective-scale ensemble forecasting. However, we were surprised to see such a large influence of these tiny changes on the simulation results and strongly believe that this method should be tested for more cases (also with different extents of domain shifting) and other models. It may also be that the high sensitivity is a feature of days with low predictability only, which would be a useful information to have. Therefore, a more systematic evaluation is left for future work. The goal of this paper was not to assess the impact of other perturbation techniques, as we already mentioned the poor forecast quality of the operational COSMO-DE-EPS of the German Weather Service in the introduction. It is of special interest to see, if other cases with low predictability (i.e. forecast busts) show the same sensitivity. However, we think that such an analysis would not fit into the present paper and is therefore left for future work. For these reasons, we did not refer much to other techniques to perturb initial and boundary conditions in our manuscript.

  Changes to paper

Abstract:
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~~ *the sensitivity to similarly small initial condition perturbations* should be evaluated ~~for different cases, models~~ *across other cases, model* and weather regimes.

Summary:
The results of this work suggests that ~~the method of~~ model domain shifting could be used to ~~account for~~ *quantify how* uncertainties in the initial and boundary conditions ~~by introducing a small disturbance at model initialization~~ *contribute to the predictability of an event*. 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 example in weather regimes with strong synoptic forcing and more stratiform precipitation and in other models such as ICON...

- The upper-level dynamics are similar in all model runs in the early stage of the convection over France. Hoskins et al. (1978) demonstrated that the traditional form of the quasi-geostrophic omega equation can be rewritten using the Q-vector and that regions of upward (downward) vertical motion are associated with Q-vector convergence (divergence). In Fig. R.1, there are no noticable differences in the Q-vector divergence, nor does the model simulate any variations in geopotential height. This indicates that the large scale forcing is similar for these model runs. We included a statement on that at the end of section 4.6.

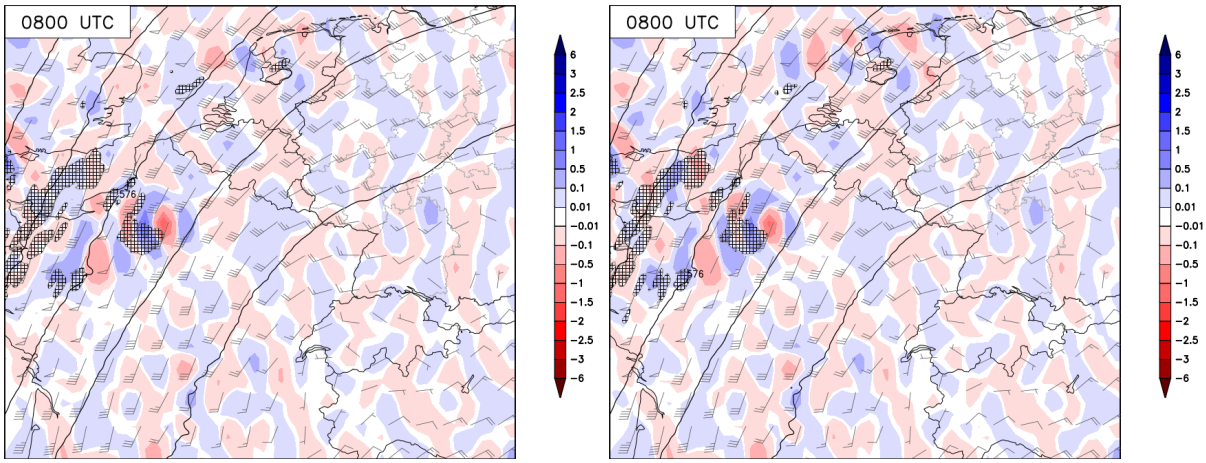

Figure R.1: Q-vector divergence (colours), 500 hPa geopotential height (contour lines), and precipitation rate (hatched) for the W run (left) and the REF run (right) at 0800 UTC.

Changes to paper
"In addition to this analysis, we further want to point out that the upper-level dynamics are similar in all model runs in the early stage of the convection over France. Hoskins (1978) showed that the traditional form of the quasi-geostrophic omega equation can be rewritten using the Q-vector and that regions of upward (downward) vertical motion are associated with Q-vector convergence (divergence). We calculated the divergence of the Q-vector at 500 hPa and found no noticable differences between successful and unsuccessful runs, nor does the model simulate any variations in geopotential height (not shown). This indicates that the large scale forcing is similar for these model runs and not responsible for the simulation result differences. "

- We also analysed SST as suggested. Our reply is the same as for Reviewer #1 (minor comment 6): The surface temperature and CAPE are depicted in Fig. R.2. The sea surface temperature

is much lower than the land surface temperature, at least in the northwestern coast of France where no significant amounts of rain was simulated in the last hours. As a result of these lower temperatures, CAPE is significantly reduced over sea. Along the coastline, there is a strong gradient in temperature (23 → 15 deg C) and CAPE. These statements also hold true for the remaining model runs. We added some remarks on that in the text, but decided not to provide an extra figure.

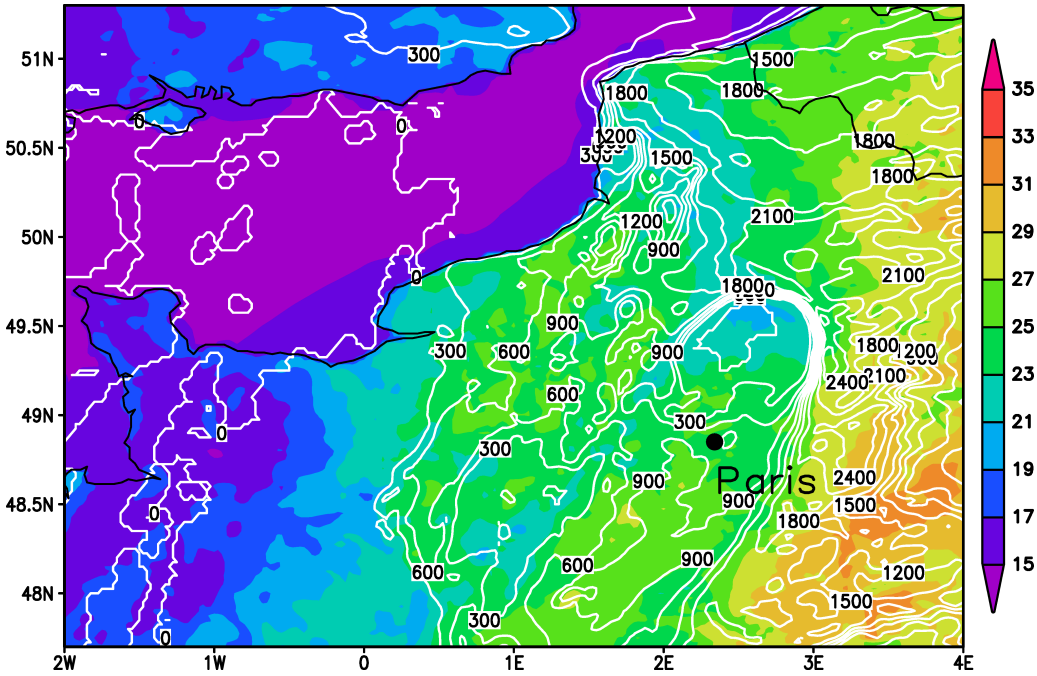

Figure R.2: Surface temperature of the REF run at 1000 UTC (colours, in deg C) and CAPE (white contours, in $\mathrm{J\,kg^{-1}}$).

Changes to paper:
"The sea surface temperatures along the French coast lie around 15°C and are much lower than the land surface temperatures (around 23°C, not shown). This temperature distribution is similar in all model runs for the preconvective environment."

- Furthermore, we conducted an ensemble sensitivity analysis and included those results in a new section.

Changes to paper:
We include the sensitivity analysis in a new section 4.5, this includes explanation of the ensemble sensitivity analysis method and interpretation of the results and includes discussion of the newly added Figure 9.

Additional changes to the paper:

1. We included a new sentence in the introduction about two recent papers:

   "Recent studies of Schneider et al. (2019) and Keil et al. (2019) have also shown that different assumptions for the amount of cloud condensation nuclei could be included in convective-scale ensemble forecasting, but only if the model employs a double-moment microphysics scheme."

2. Old Figure 9 was enhanced by increasing the size, length, and density of the wind arrows.

3. Information about the financial support was added.

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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 ($2.8\,\mathrm{km}$) resolution on a large ($1668\times1807\,\mathrm{km}$) 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~~ the sensitivity to similarly small initial condition perturbations should be evaluated ~~for different cases, models~~ across other cases, model 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 with the COSMO model, the main findings were:

- The ~~operational model~~ COSMO model (in quasi operational set-up, without data assimilation) 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~~ model 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 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). Recent studies of Schneider et al. (2019) and Keil et al. (2019) have also shown that different assumptions for the amount of cloud condensation nuclei could be included in convective-scale ensemble forecasting, but only if the model employs a double-moment microphysics scheme. Because of the fundamental uncertainties of the simulations due to nonlinearities of the model equations, several studies have noted the 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 experiments 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) 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 interactions 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.

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 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.

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

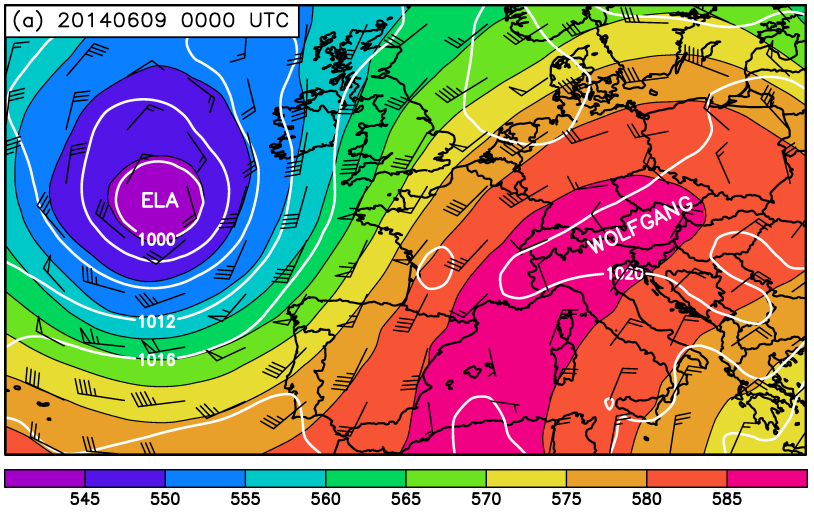

Figure 1. Global Forecast System analyses at 9 June 00:00 UTC showing 500 hPa geopotential height (gpdm, shading), sea-level pressure (hPa, white contours), and 500 hPa wind barbs.

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 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 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 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

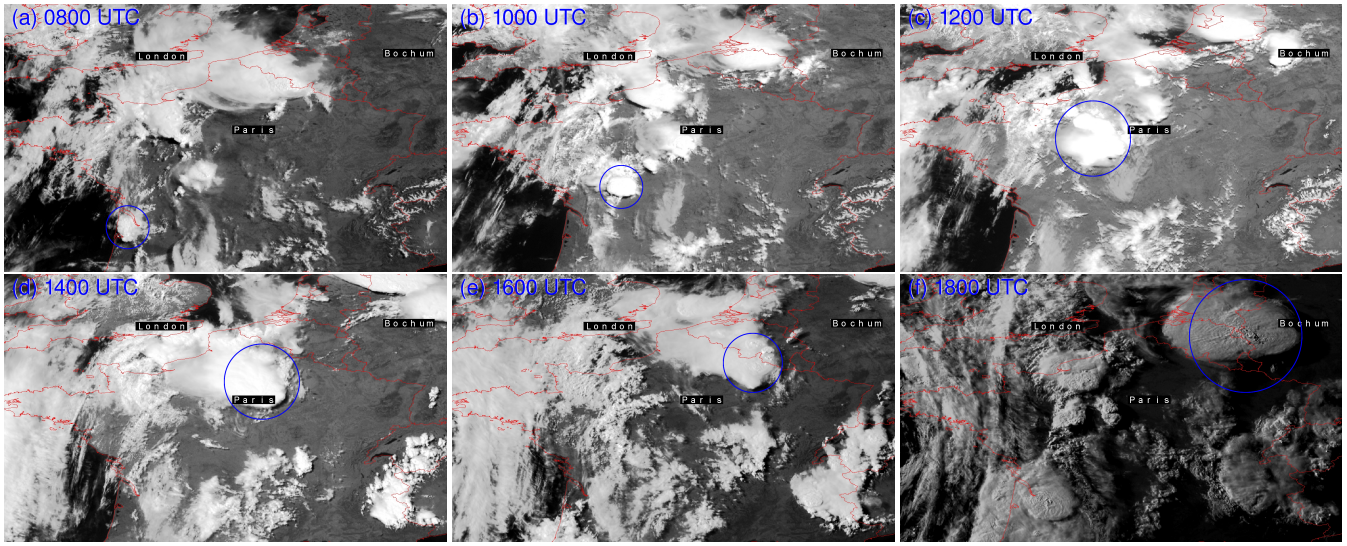

Figure 2. Meteosat visible satellite pictures of northern France and western Germany from 08:00–18:00 UTC (raw data courtesy of EUMETSAT). The convective system investigated here is marked by the blue circles.

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.

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

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

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 previous simulations of this case, the changes suggested by Barrett et al. (2019) to minimise timestep-dependent results from 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 ~~.~~(as did the operational deterministic and ensemble prediction system at that time). A 1D turbulence parameterization based on the prognostic equation for the turbulent kinetic 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.

3.2 Model domain choices

The model domain contains 600×650 grid points, which corresponds to an area of about 1668 km×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 where the model domain is shifted by one grid point in eight different directions (Table 1). All other model settings remained unchanged.

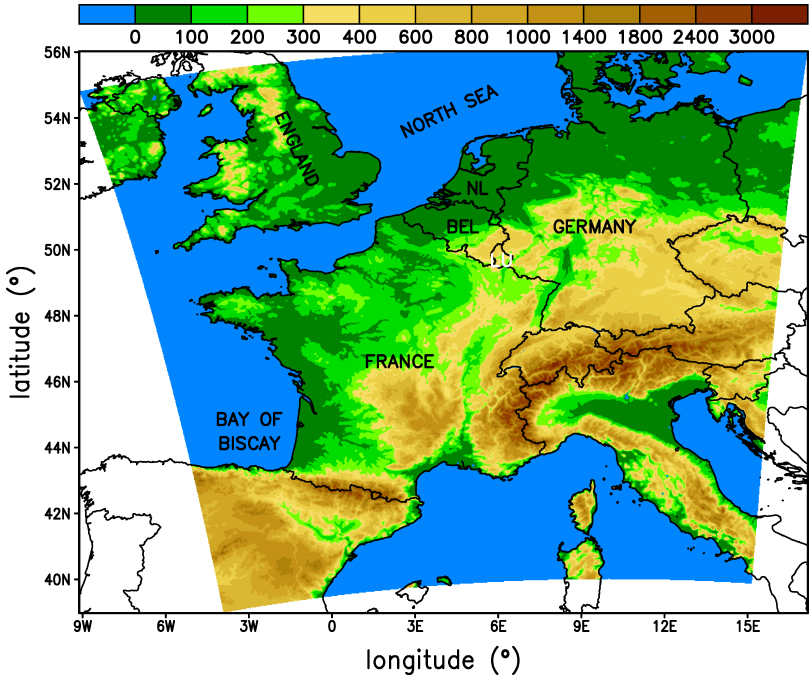

Figure 3. COSMO simulation domain and model orography (in m asl) of the reference run.

4 Results

4.1 Reference run

Here we compare our simulations to radar-derived precipitation from the precipitation analysis algorithm RADOLAN (Radar Online Adjustment), which combines weather radar data with hourly surface precipitation observations of about 1300 automated rain gauges to get quality-controlled, high-resolution (1 km) quantitative precipitation estimates. 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. 4~~b~~a). However, the simulated 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 poor performance of the model. Unfortunately, this radar composite also suffers from missing data at some locations (e.g. over Belgium southwest from Cologne) and also different calibrations or Z-R-relationships (obvious from the strong precipitation gradient about 100 km north of Cologne).

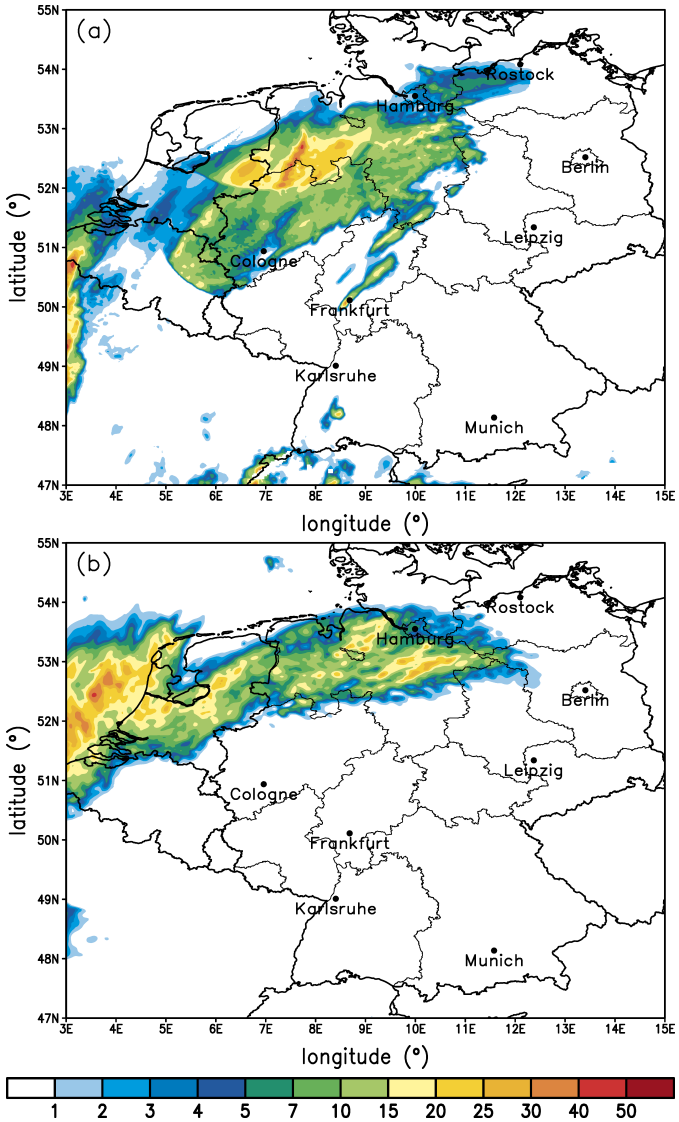

Figure 4. Radar-derived (a) and simulated (b) accumulated precipitation in mm on 9 June 2014 (17:00–24:00 UTC).

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 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.

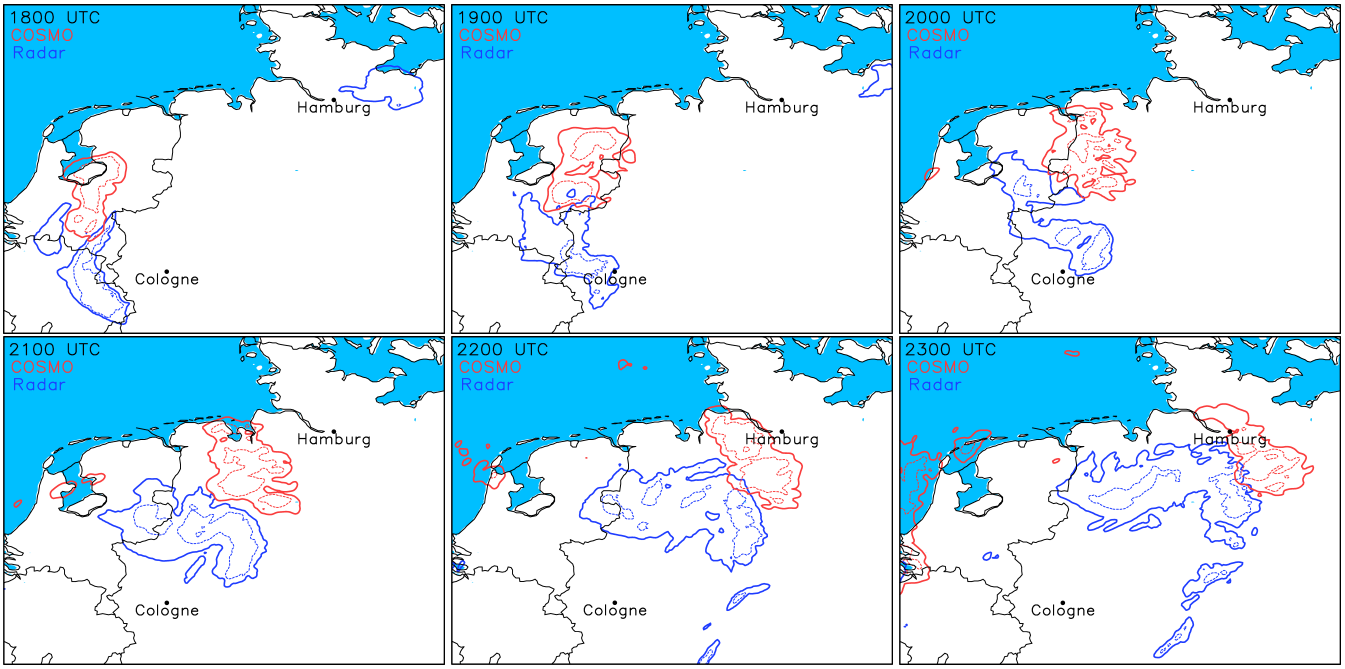

Figure 5. Radar-derived (blue contours) and simulated (red contours) 30-min precipitation of 1 mm (solid) and 5 mm (dashed) on 9 June 2014.

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 06:00 UTC. The track of the system in the REF run is marked by the red 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 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.

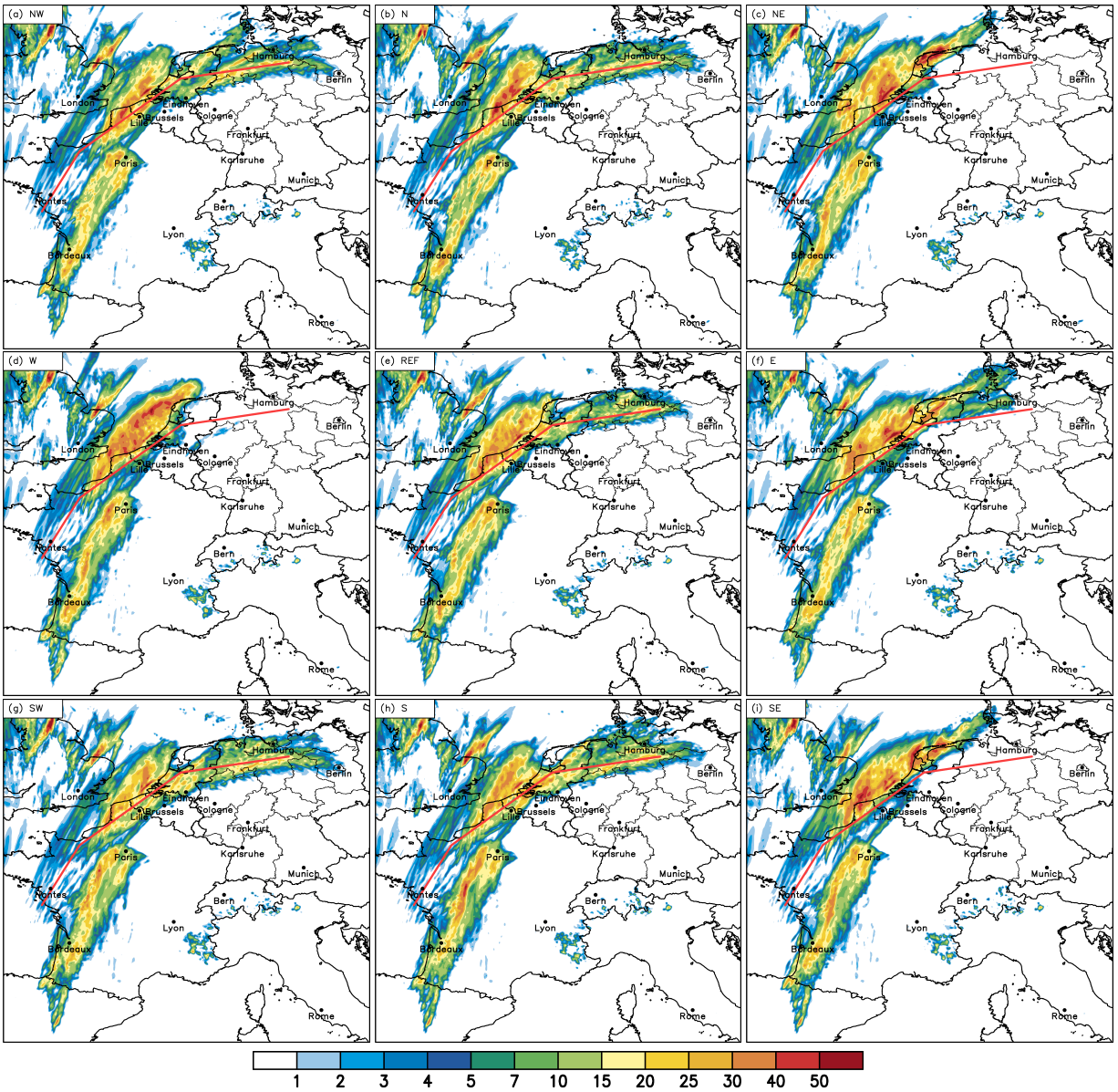

Figure 6. 24-h precipitation (00:00–24:00 UTC on 9 June) amount in mm. The red line indicates the approximated storm track of the REF run.

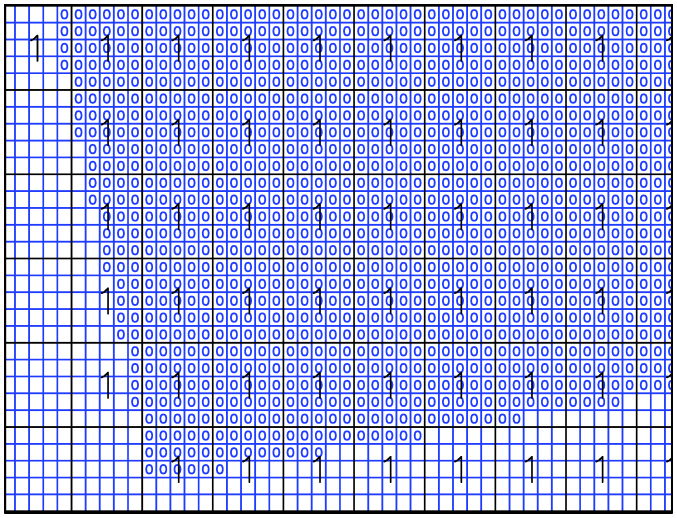

Figure 7. Southwest corner of the simulation domain with illustration of IFS grid (black) and COSMO grid (blue). Numbers of 1 indicate IFS grid points whereas 0 indicates COSMO grid points.

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 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. However, as the precipitation in the E run is more to the North and does not extend as much to the East as the other successful runs, all the eastward shift simulations have poorer prediction.

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 $\Delta x = 2.8\,\mathrm{km}$. 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).

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

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 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 $\mathrm{g\,kg^{-1}}$ for specific humidity, and 0.1 $\mathrm{m\,s^{-1}}$ 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).

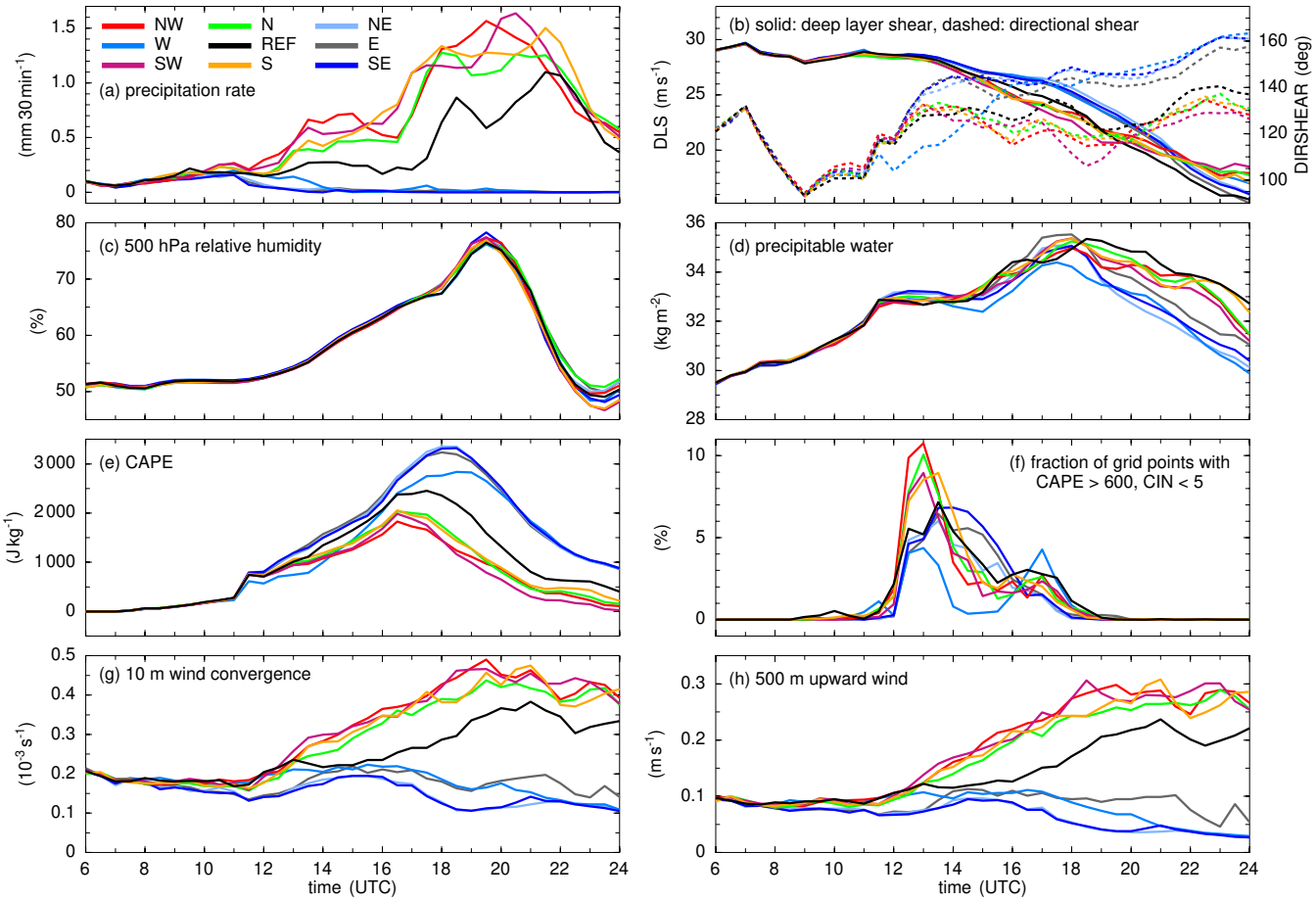

Figure 8. Time series of convection-related parameters averaged over a 3°×2.5° box surrounding and following the convective system. Shear parameters are based on surface and 6-km altitude winds.

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 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 $\mathrm{m\,s^{-1}}$. 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 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 been consumed. This leaves the runs without an MCS over Germany with the highest CAPE values in the early evening (2500-3300 $\mathrm{J\,kg^{-1}}$). 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 $\mathrm{J\,kg^{-1}}$ and CIN is lower than 5 $\mathrm{J\,kg^{-1}}$ (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 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 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 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 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 Ensemble sensitivity analysis

The above analysis has shown that whether the simulation is successful or not can be quantified based on small differences in the environment close to the developing convective cell. However, from this analysis we cannot tell what causes these changes in the pre-convective environment. Here we use ensemble sensitivity analysis to help identify the origin of these differences. This analysis determines geographical areas, model variables and times that are correlated with a successful simulation. Although the correlations do not provide evidence of a causal relationship they do provide a starting point for understanding the diverging simulations, as shown in the below analysis and also by Barrett et al. (2015), Bednarczyk and Ancell (2015), Hill et al. (2016), Torn et al. (2017).

Following the above papers, we define the ensemble sensitivity S as

$$S = m\ a\ \sigma_x\ = \frac{\mathrm{cov}(y,x)}{\mathrm{var}(x)}\ a\ \sigma_x \tag{1}$$

where m is the regression coefficient between the test variable x and the response function y as calculated at each grid point. A scaling factor a is used to de-emphasise noise in the analysis based on the correlation coefficient r; $a = 0$ where $r^2 < 0.4$ and $a = 1$ otherwise. Finally the sensitivity is scaled by the ensemble standard deviation of the test variable σ_x, calculated individually at each grid point, to normalise the calculated sensitivity which enables comparison of sensitivities to different model variables.

We attempted to use ensemble sensitivity analysis on numerous model variables at surface, 850, 500 and 250 hPa levels. However, because the model initial states are nearly identical, the ensemble sensitivity analysis is unable to identify any relationships between convection intensity and typical large-scale drivers of convection before the convection develops. Only after the convection develops can signals be seen in the e.g. upper-level pressure, wind and divergence fields as they are directly modified by the convection. Therefore the analysis below focusses on near-surface model fields.

In Fig. 9, we show the ensemble sensitivity of surface precipitation over Germany to temperature (T) and zonal wind (u) at 200 m above the ground, at 09:00, 11:00 and 13:00 UTC. The precipitation values used are the mean in the box bounded by 7 W, 14 W, 52 N, 53.5 N, which is 4.4–6.7 mm in the successful ensemble members 1.0 mm in the E-shifted member and less than 0.1 mm otherwise. The resulting sensitivity S has units of mm per standard deviation change in x (here T or u). Hence the ensemble sensitivity is interpreted as the change to precipitation for a one standard deviation increase in variable x at that grid point.

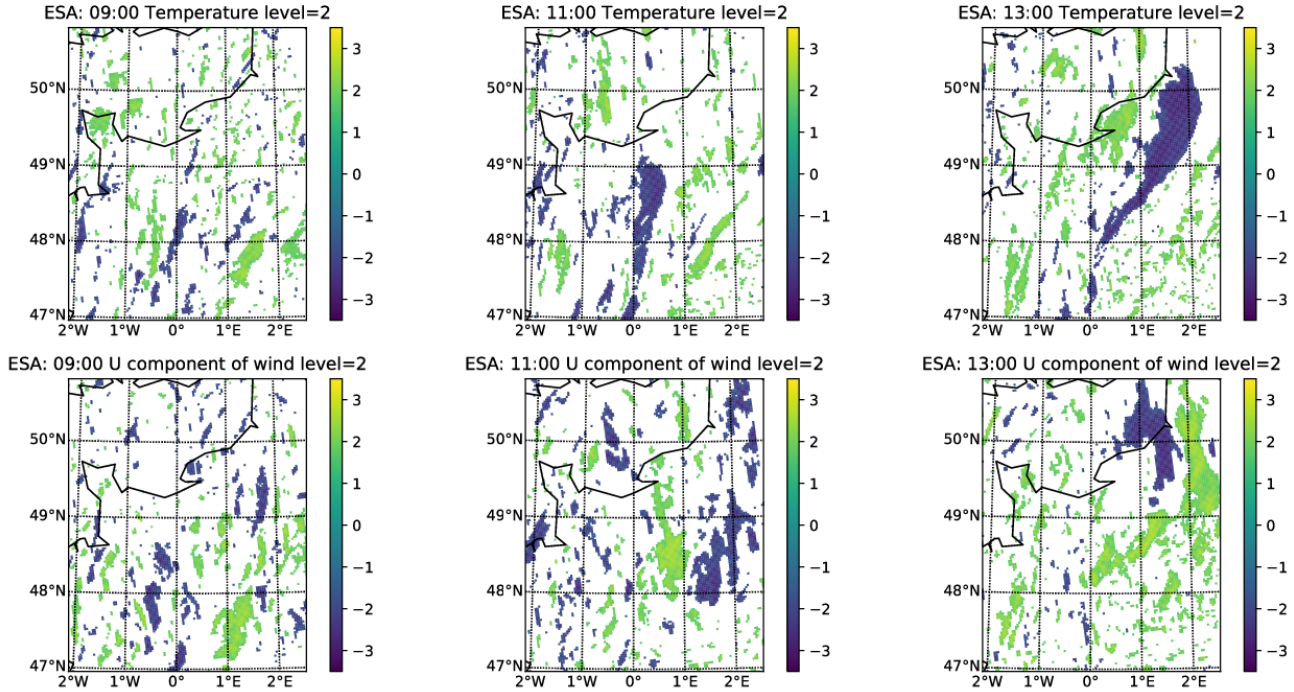

Figure 9. Ensemble sensitivity of preciptation over Germany to temperature (top row) and zonal wind component (bottom row) both at 200 m above the surface. The units are mm per standard deviation change in the ensemble, with positive values indicating that ensemble members produced more precipitation over Germany when the temperature or wind speed in the marked locations was larger in the ensemble. A signal of increased precipitation for lower temperatures and increased wind speed develop throughout the morning, consistent with a large developing cold pool.

Working backwards in time from the right hand column to the left, we can see that the ensemble reproduces the MCS better in members where the temperature across northern France (49–50 N, 1–2 E) is lowest and where the wind speed is highest just east of the low temperatures. This is a clear sign of increased precipitation across Germany in ensemble members with a strong surface cold pool in the locations marked by the sensitivity. In the middle column, we see that this signal is already evident at 11:00 UTC near 48.8 N, 0.4 E and in the left column at 09:00 UTC (near 47.8 N, 0.75 W) but only in the wind field at this time as the cold pool is yet to develop. A convective system exists near this location in all ensemble members at 09:00 UTC but the location at 09:00 UTC appears to be the decisive factor with a location farther to the east apparently favored.

This disturbance at 09:00 UTC can be tracked farther back to the western french coast (46 N, 1 W) already at 04:00 UTC (not shown). However, neither the ensemble sensitivity analysis nor more detailed investigation into the convective disturbances at this time showed any systematic structure of the convective cells that were decisive in the successful simulation of the MCS later in the day. The important aspect appears to be that by 09:00 UTC that a line of convection begins to form on the outflow of this convection, as seen in the lower-left panel of figure 9, and that changing the position of that cell by only around 10 km determines whether the convective cell evolves into the MCS which later affects Germany, or not.

The ensemble sensitivity analysis has helped highlight interesting areas in the development timeline of the convective cells. However, due to the disparate locations of the convective cells, the grid-point correlations required for ensemble sensitivity analysis do not help explain how these cells differ in their development. In the next section we evaluate in more detail how the developing convective cells interacted with their environment and what caused the differing convective evolutions.

4.6 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 runs, namely the ones with the model domain shifted towards the W and the SE. Figure 10 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 11:00 UTC at the latest. The simulations all have weak, disorganised convection over northwestern France and 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 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 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 sea surface temperatures along the French coast lie around 15°C and are much lower than the land surface temperatures (around 23°C, not shown). This temperature distribution is similar in all model runs for the preconvective environment. The proximity of the cell to the colder sea surface appears to have a decisive influence on the further life cycle of convection. 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 10:00-11:00 UTC, does not appear to be important to the decay of the cell of interest. It is located approximately 150 km upstream. The cell is stronger in the W run leading to a slight reduction

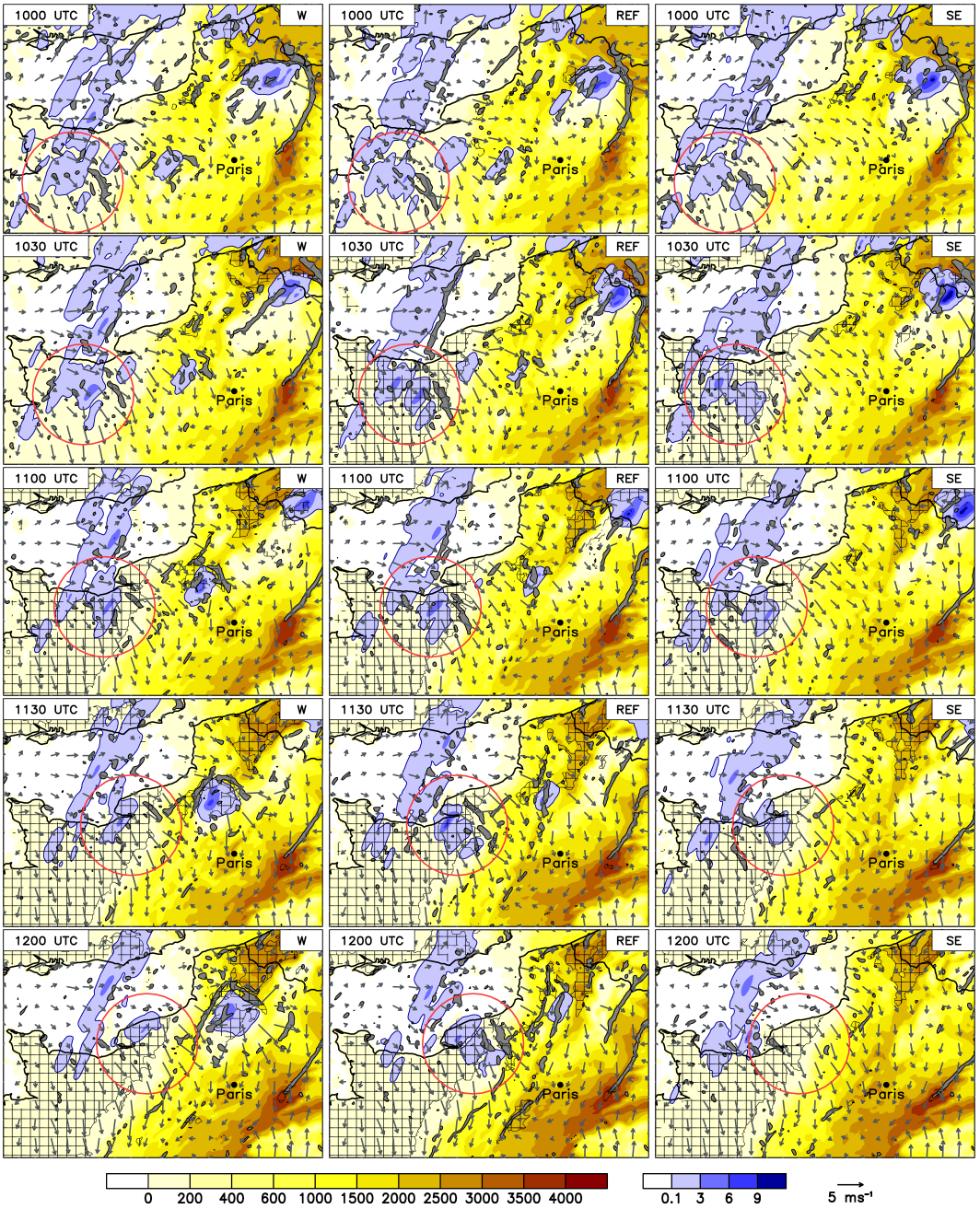

Figure 10. Convective available potential energy (colour shading, in $\mathrm{J\,kg^{-1}}$, 30-min precipitation rate (blue colour shading, in $\mathrm{mm\,(30\,min)^{-1}}$, and 10-m wind field (arrows) between 14:00–18:00 UTC on 9 June. Gray areas indicate low-level wind convergence larger than $0.35{\cdot}10^{-3}\ \mathrm{m\,s^{-1}}$ 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.

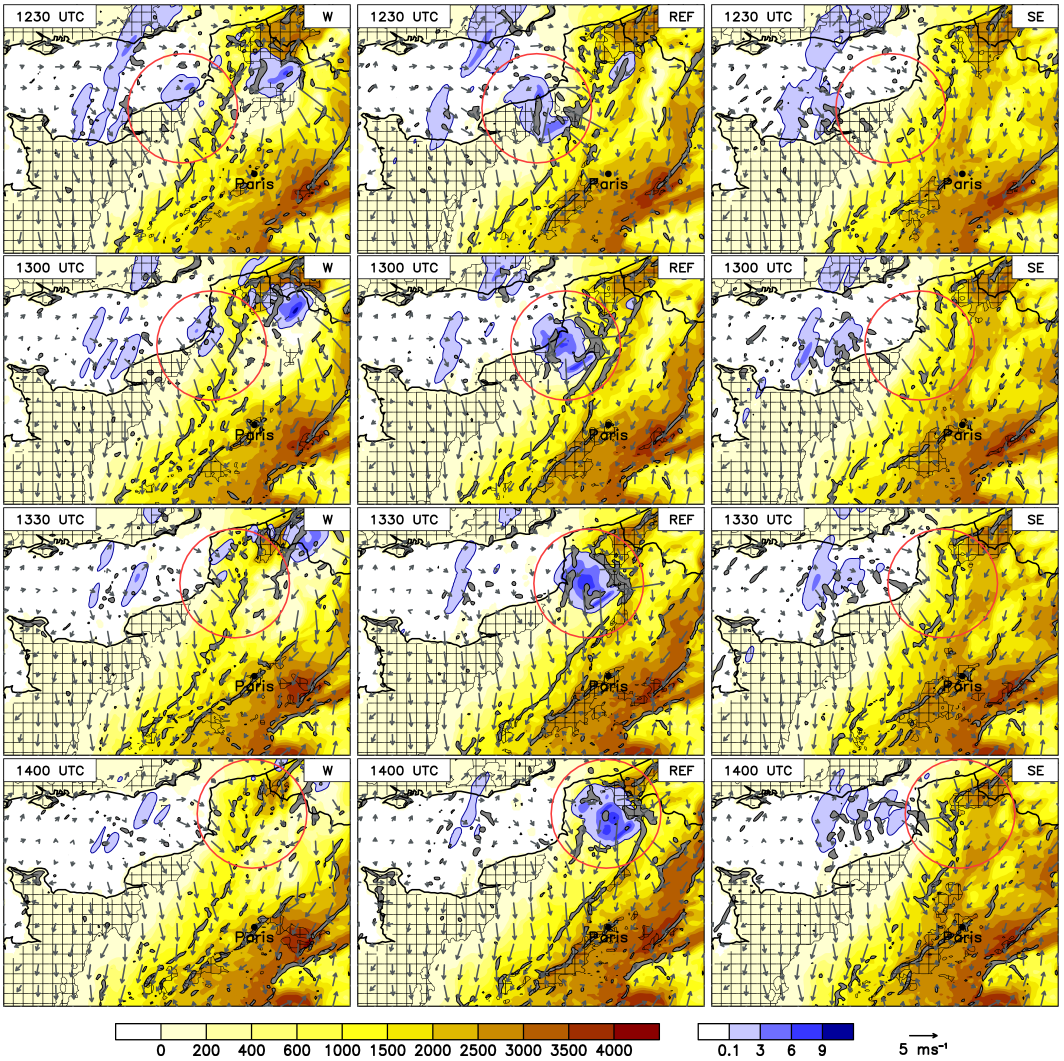

Figure 10. Continued.

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.

In addition to this analysis, we further want to point out that the upper-level dynamics are similar in all model runs in the early stage of the convection over France. Hoskins et al. (1978) showed that the traditional form of the quasi-geostrophic omega equation can be rewritten using the Q-vector and that regions of upward (downward) vertical motion are associated with Q-vector convergence (divergence). We calculated the divergence of the Q-vector at 500 hPa and found no noticable differences between successful and unsuccessful runs, nor does the model simulate any variations in geopotential height (not

shown). This indicates that the large scale forcing is similar for these model runs and not responsible for the simulation result differences.

4.7 Further MCS evolution

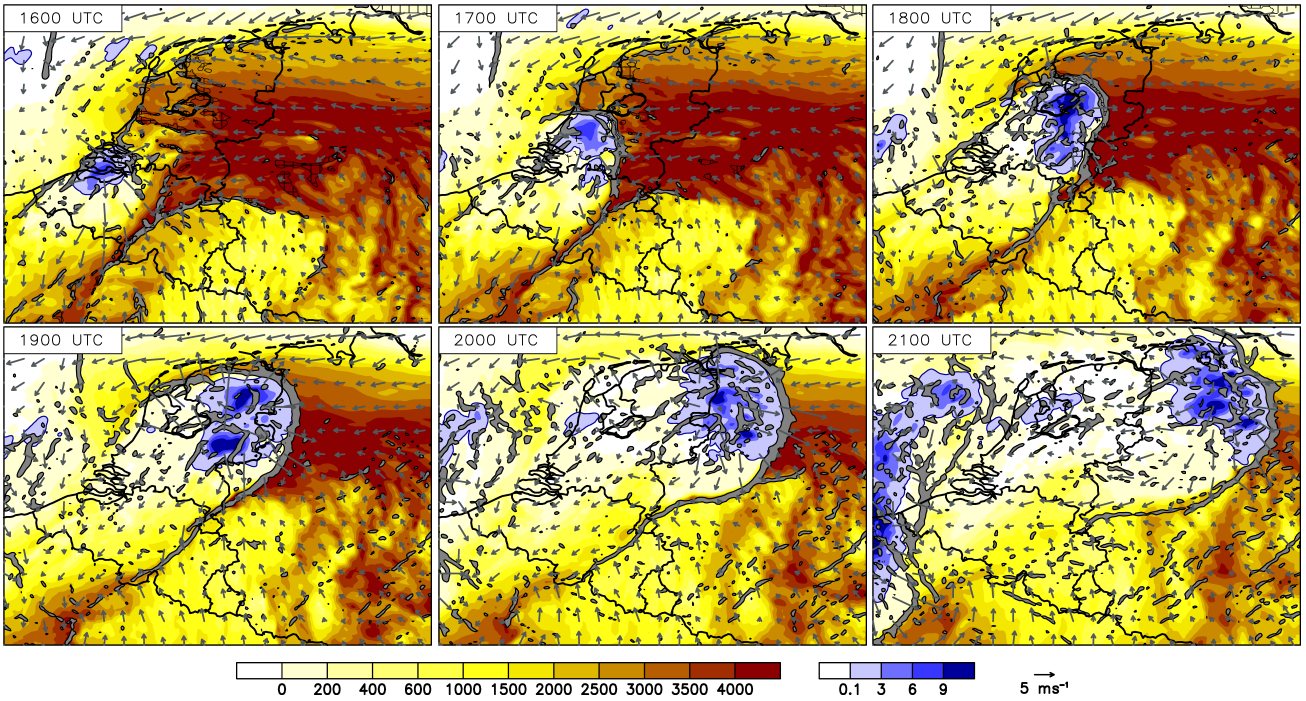

Figure 11. As Fig. 10, but between 16:00–21:00 UTC.

Having established a possible explanation for the decay of the precursors of the MCS in the previous section, we now analyze the further evolution of the system into a MCS using the reference simulation (Fig. 11). To the east of the system, the model simulates an east-west oriented region of high low-level equivalent potential temperature in the north-central part of Germany, which corresponds to CAPE values between 3000–4000 $\mathrm{J\,kg^{-1}}$. This CAPE-rich air is advected with easterly winds towards the convective system over the Netherlands. Colliding with the cell's outflow, a strong low-level mass and moisture convergence occurs, which fosters the evolution into a MCS. As already discussed in section 4.4, the 0-6 km deep layer shear shows suitable conditions for highly-organised convection (27–30 $\mathrm{m\,s^{-1}}$). The maximum rain intensities reach locally up to 22 $\mathrm{mm\,(30\,min)^{-1}}$ with a weakly defined bow-like structure of precipitation, typical of storms with an intense rear-inflow jet. In the wake of the MCS, CAPE is almost entirely consumed. From 23:00 UTC onwards, the MCS is decaying while further travelling towards Poland (not shown).

5 Summary and conclusions

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 due to the advection of warm and moist air. However, the predictability of this event was very low; neither the operational deterministic nor any member of the ensemble prediction system (both convection resolving) 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, 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 $1668\,\mathrm{km} \times 1807\,\mathrm{km}$.

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 also revealed similar conditions in its preconvective environment. The ensemble sensitivity analysis was unable to reveal differences in the upper-level flow between ensemble members, although low-level differences associated with a developing cold pool were identified. 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 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 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~~ quantify how uncertainties in the initial and boundary conditions ~~by introducing a small disturbance at model initialization~~contribute to the predictability of an event. 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 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 authors contributed equally to the writing of the paper.

Competing interests. The authors declare that they have no conflict of interest.

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