

Application of an adaptive radiative transfer scheme in a mesoscale numerical weather prediction model

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Abstract

Since the computational burden of radiative transfer parameterisations is considerable, operational atmospheric models use various sampling, coarsening and interpolation techniques to reduce this load, which, however, introduce new errors. An adaptive radiative transfer scheme takes advantage of the spatial and temporal correlations in the optical characteristics of the atmosphere to make the parameterisation computationally more efficient. The adaptive scheme employed in this article generalises the accurate radiation computations made in a fraction of the spatial and temporal space to the rest of the field. In this study the scheme developed and presented in a previous article was extended to atmospheric heating rates and implemented in the numerical weather prediction model COSMO. Three case studies with different synoptic conditions were carried out with the operational COSMO-DE setup on a 2.8 km horizontal grid size. The performance of the adaptive scheme is compared with the performance of the currently operational COSMO-DE radiation configuration, where the radiation computations are performed quarter-hourly on 2x2 averaged atmospheric columns. The reference for both schemes are frequent radiation computations for the full grid. We show that the adaptive scheme is able to reduce the sampling errors in the radiation surface fluxes considerably and to conserve the spatial variability in contrast to the operational scheme. Deviations in

the three-dimensional heating rates are reduced for larger averaging scales. Physical relationships between the radiative quantities and cloud water or rain rates are better captured. It is shown that these improvements also lead to improvements with respect to the dynamical development of the model simulation, showing a smaller divergence from the reference model run.

1 Introduction

Radiative fluxes at the surface and atmospheric heating rates strongly influence the heat energy budget at the atmospheric interface to the soil-vegetation system and the temperature tendencies in the atmosphere, and thus boundary layer development and cloud processes. Therefore these fundamental energy sources and sinks need to be considered adequately in numerical weather prediction and climate models. In particular on the increasing resolutions of nowadays weather forecast models of a few kilometres in principle three-dimensional radiative transfer computations are required. Accurate radiative transfer (RT) computations based on the three-dimensional spectral radiative transfer equation are, however, extremely complex and computationally demanding. Consequently various parameterisations, with different degrees of simplifications, have been developed. In particular for the application in operational weather prediction models or for long period climate simulations large simplifications are inevitable to reduce computational costs. Common simplifications are the computation of radiative transfer reduced to flux densities on broad spectral bands for one-dimensional vertical atmospheric columns, assuming horizontal homogeneity. Also for the treatment of clouds in the RT parameterisation a number of assumptions are required, e.g. for the overlap of partial cloud cover in the vertical. Many input parameters required for the atmospheric radiative transfer, especially cloud characteristics, are, however, highly uncertain and also parameterised in operational models. Despite reductions in complexity, the radiation transfer parameterisation is for most applications still too demanding to be computed for each model timestep and the full

spatial grid. Different approaches have been implemented by the national weather services and climate centres to overcome this limitation by sampling in time and space. The most common strategy is temporal sampling, i.e. the radiation scheme is called at time intervals of more than one time step while keeping the fluxes and heating rates constant in between, either based on a medium solar zenith angle, or adjusted in each timestep according to the current solar zenith angle. Spatial sampling strategies interpolate between sparse computations or average atmospheric properties over multiple columns before passing the data to the RT parameterisation.

The Integrated Forecasting System (IFS) of the European Centre for Medium-Range Weather Forecasts (ECMWF) for example employs a comparatively sophisticated radiative transfer scheme since June 2007 (Rapid Radiative Transfer Model (RRTM) (Clough *et al.*, 2005; Mlawer *et al.*, 1997), in combination with the Monte Carlo Independent Column Approximation (McICA) (Pincus *et al.*, 2003)). To save computation time the radiation scheme is called only at large temporal intervals (once per hour or once per three hours, depending on model resolution) and on a coarsened grid, where the radiative effects are interpolated to the finer grid by a cubic interpolation scheme. The temporal interpolation for each dynamic model timestep is done by accounting for the correct solar zenith angle for shortwave flux and for changing surface temperatures for the longwave flux in each timestep (Morcrette, 2000; Morcrette *et al.*, 2008).

In the COSMO model (Steppeler *et al.*, 2003), the numerical weather prediction model (and regional climate model) of several European weather services, also the two-stream approximation is employed, based on code by Ritter and Geleyn (1992); see section 2. To save computation time the scheme is called either once per forecast hour or quarter-hourly, in the configurations COSMO-EU and COSMO-DE, respectively. In the latter configuration the atmospheric input parameters are first averaged over four columns, before carrying out the radiation calculations. The obtained surface radiation fluxes are adjusted taking the local albedo and surface temperature into account (Baldauf *et al.*, 2009).

Temporal and spatial sampling methods can, however, lead to errors. Temporally sampling neglects the varying local insolation due to changes in solar zenith angle and advection and evolution of clouds. Spatial averaging reduces spatial variability of radiative effects. Inconsistent situations may occur, when the radiative properties are not allowed to react to the changing atmosphere over several timesteps, thus raining clouds and strong solar fluxes are allowed to coexist in rapidly changing convective atmospheres. Morcrette (2000) studied the sampling effects on operational simulations and analyses for the IFS global model. He found a larger sensitivity with respect to temporal sampling, than to spatial sampling followed by subsequent interpolation. In 10-day forecasts he found temperature errors depending on the temporal frequency of radiation computations. This error increased with height, due to feedbacks between convective clouds and radiation, especially in the tropics. For longer, e.g. seasonal, predictions these errors grow, thus a higher temporal sampling is beneficial. The study also indicated, however, that changes in the microphysic scheme or in the cloud-overlap assumption have a larger influence than the spatial and temporal interpolation of radiation computations.

Several approaches have been developed to bypass this conflict between the need of frequent radiation computations and computational limits. Computation time can be reduced by training an artificial neural network (ANN) with a detailed radiation scheme offline (Chevallier *et al.*, 1998, 2000; Krasnopolski *et al.*, 2005). Krasnopolski *et al.* (2010) tested such ANNs in the National Center for Environmental Prediction (NCEP) Climate Forecast system (CFS) by comparing simulations with the original inherent radiation code (RRTMG) as control runs with simulations employing the ANN emulating the complex radiation code. The differences were small, and comparable to internal model variability, compiler changes etc. while a considerable speedup was achieved for the climate simulations. A drawback of this method is the need to re-train the ANN for any configurational changes such as the vertical resolution.

Pielke *et al.* (2005) proposed an approach based on look-up-tables. In this approach the radiative effects for all possible inputs are pre-calculated and stored to disk. As for

the ANN, this look-up-table needs to be recomputed for every change in the model setup, making the model inflexible. Furthermore, given the expected increase in the number of model levels, the number of possible combinations may soon become prohibitive.

In Venema *et al.* (2007) (from now on VSAS07) two adaptive radiative transfer parameterisations are presented which exploit temporal and spatial correlations in the 3D optical property fields. Radiation calculations by the implemented RT scheme are performed in only a fraction of time and space. The so-called *temporal adaptive scheme* identifies the grid points in the model domain where the largest changes since the last radiation update have occurred and targets these columns for the next RT computations. These predictions utilise a simplified radiation scheme, based on multiple linear regression which uses vertically integrated atmospheric variables as predictors. The rest of the field is updated by computing the change in the radiative tendencies by the same simplified radiation scheme and adding them to the radiation effects from the last timestep. In the *spatial adaptive scheme*, only a small but fixed part of the field is updated by the internal radiation scheme at high temporal frequency. For the other columns a search for a nearby similar atmospheric column is carried out and the radiative effects of the most similar column are applied with a correction for solar angle and albedo. For training the scheme an optimisation algorithm had to be applied to find the weights for the weighted sum used to search for nearby similar columns. It was shown, however, that the scheme is not sensitive with respect to the exact values of these weights. Hence an advantage compared to neural networks, which emulate complex radiation schemes (e.g. Krasnopolski *et al.*, 2010) is that re-training is much less important for changes in the radiation scheme or the vertical resolution, the scheme can be applied as-is in other atmospheric models or in combination with other radiation codes. The obtained speedup, however, is potentially smaller than for neural networks because the complex radiation scheme is not emulated but only exploited more efficiently. The adaptive schemes in VSAS07 were, as a proof of principle, tested in an offline environment for the radiative net fluxes at the surface. In a case study it was shown that such schemes are able to predict the surface fluxes

much more accurately, without an increase in computational demands. In addition, the spatial difference fields of the adaptive approaches were characterised by notably smaller correlation lengths and a reduction in the number of calls to the complex scheme leads to only a small reduction in accuracy. The spatial adaptive scheme gave overall better results than the temporal adaptive scheme.

Manners *et al.* (2009) adopted this idea and developed two adaptive RT schemes in spectral space, they employ a reduced RT calculation at timesteps between calls to the full complex radiation scheme in the UK-Met Office Unified Model. Their *split time-stepping* approach divides the RT computation in bands with strong gaseous absorption terms, which are optically thick and hardly dependent on cloud characteristics, and in bands which are optically thin, thus where clouds have a strong influence. The latter RT calculations are updated with a higher temporal frequency to keep track of changes due to developing and advected clouds. Their second method, the *incremental time-stepping* method, uses a simple radiation scheme to compute temporal changes for the window region, i.e. the optically thin part of the atmospheric spectrum, where variability is mainly caused by variations in cloud properties. These increments are added to the results of the full complex scheme, which is computed at a lower temporal frequency.

For this paper we report results from the implementation of the spatial scheme in the operational weather forecast model COSMO. The spatial adaptive radiation parameterisation as introduced in VSAS07 has now been extended to be applied also to the vertical heating rates. The performance of this enhanced scheme is compared with the standard operational radiation update scheme.

Section 2 gives a short description of the COSMO model; followed by the description of the adaptive scheme and the experimental setup in 3. In section 3 we outline the performed simulations and experiments. Results are shown in section 4 and discussed in section 5.

2 The COSMO model

As an operational testbed for our scheme the COSMO model (version 4.0) has been chosen. This is the nonhydrostatic, limited-area mesoscale operational weather forecast model of the German and several other European meteorological services which is also used as a regional climate model. For the case studies the configurations of the operational COSMO-DE model have been adopted, this is the configuration for the daily weather forecasts by the German Weather Service (Baldauf *et al.*, 2009). The model domain covers Germany and parts of the neighbouring countries with 420x460 columns of a horizontal resolution of 2.8 km. This setup has 50 vertical layers and a time step of 25 seconds. The model is nested into the so-called COSMO-EU model, which has slightly different configurations with a horizontal grid spacing of 7 km, 40 vertical layers and a timestep of 40 seconds. The COSMO-EU model domain covers Europe and parts of the Atlantic Ocean and Northern Africa.

In both COSMO versions condensation and evaporation of cloud water is modelled by saturation adjustment, the treatment of grid-scale precipitation is based on a 1-moment bulk approach, a modified version of the Kessler type parameterisation (Kessler, 1969), which considers five prognostic water categories. Since clouds produced by the grid-scale scheme always cover the whole grid box, sub-grid scale cloudiness is required for radiation calculations. These clouds are analysed by means of an empirical function depending on relative humidity, height and convective activity. In COSMO-DE deep convection is assumed to be a grid-scale process and only shallow convection is parameterised by a mass flux scheme according to Tiedtke (1989). In COSMO-EU also the deep convection is parameterised by the Tiedtke-scheme.

The radiation scheme in the COSMO-models was developed by Ritter and Geleyn (1992) and is based on the one-dimensional δ -two-stream approximation of the radiative transfer equation. The spectrum is divided into broad spectral intervals, for which the radiative transfer calculations are carried out. Absorption, emission and scattering by

cloud particles, aerosols and gas molecules is accounted for. For clouds the maximum-random overlap assumption is applied. The cloud optical properties are parameterised based on a fit of the optical properties of eight cloud types provided by Stephens (1984). Aerosols are given by a constant climatology. Effects of three gases are considered: water vapour, carbon dioxide, which has a constant value of 330 ppm, and ozone, which is described by a climatological annual cycle. The radiation scheme provides net fluxes at the surface in the solar and thermal regime and three-dimensional heating rates for every vertical layer in a column. In COSMO-DE radiation computations are carried out every 15 minutes; these calculations are applied to 2x2 averaged columns, correcting the solar radiation surface flux by the local albedo and the thermal radiation flux by local ground temperature (Baldauf *et al.*, 2009). In COSMO-EU, radiation effects are calculated hourly and fluxes and heating rates are kept constant in between. The solar zenith angle used in the radiation computations is the zenith angle valid for the middle of the interval between two radiation updates.

3 Implementation and experimental design

3.1 Enhanced adaptive radiation scheme

The spatial adaptive scheme exploits spatial correlations in the radiative effects in the following way: The model domain is divided into small subdomains. At a high frequency the radiation effects at only one of the subdomain columns is updated by a call to the intrinsic radiation scheme; only in the first timestep of the model simulation the radiation routine is called once for the whole field. For grid points not updated a search is performed for a nearby similar, recently updated column. Similarity is evaluated by comparing a weighted sum of absolute differences in low cloud cover, total cloud cover, liquid water path, integrated water vapour, surface albedo, time since the last update of the respective column and distance between the two columns (see Table 1). This cost function has

now been extended by the spatial distance between the columns and the integrated water vapour compared to the version introduced in VSAS07. Having found the most similar column, the shortwave (SW), longwave (LW) and photosynthetic active radiation (PAR) surface fluxes and also the vertical column of atmospheric heating rates, i.e. the heating rate for each vertical level, are copied to the respective column. The solar fluxes and heating rates are corrected for solar zenith angle, and the surface fluxes also for the local albedo. For the longwave surface fluxes a correction according to local surface temperature has been applied (see Table 2).

3.2 Setup

The spatial adaptive scheme is compared with the standard operational radiation configuration of COSMO-DE, i.e. with radiation calculations carried out for 2x2 averaged columns every 15 minutes. For clarity of notation the scheme will be referred to as “2x2” scheme from now on. The adaptive scheme is called every 2.5 minutes, applying the intrinsic radiation scheme only for one out of 5x5 atmospheric columns, while the extrinsic generalisation is applied for the other columns (see Fig. 1). This setup requires about the same computation time as the standard COSMO-DE setup. Update patterns for the adaptive approach, i.e. the sequence in which the pixels are updated, are given in VSAS07 for regions of different size: the ordering is such that subsequently updated columns have a large distance between them.

The most accurate results with respect to radiation would be obtained by radiation computations for the full domain on a high temporal frequency. This optimal but much too expensive setup has been taken as reference for testing our adaptive scheme and the standard COSMO-DE 2x2 configuration. All comparisons and deviations shown in the following are based on intrinsic radiation computations carried out every 2.5 minutes on the full model domain. The considered radiation configurations are listed in Table 3.

For the comparisons we developed a COSMO model version in which the different

radiation options are computed diagnostically, i.e. the dynamics are driven by one of the three radiation options, which is for most comparisons the reference setup. The radiation effects of the other two schemes are computed in addition and provided as model output.

The highest errors in radiation effects are expected to occur in situations with heterogeneous atmospheric conditions, i.e. small-scale convective cloud patterns, where the atmospheric state of the columns change rapidly and hence frequent radiation calculations are most important. Three days have been chosen for the comparison of the radiation options, which span a range from mainly convective to stratiform clouds. The first day is a convective summer day, 21 June 2004, when instable air masses were centred over Central Europe under an elevated trough, and a large number of showers and thunderstorms covered the whole model domain. The second day is a slightly less heterogeneous autumn day, 19 September 2001, where a low-pressure system over the North Sea led to convective activity in parts of the model domain. As a third case the schemes have been tested for a winter day (22 December 2005) with stratiform, very homogeneous and slowly changing cloud conditions. Germany was under the influence of an occlusion front belonging to a low pressure system centred over Scandinavia. During the day the front and its broad stratiform cloud band crossed the model domain from north-west to south-east and led to moderate rain in lower and snow in higher altitudes.

For these three cases the COSMO-DE runs were forced by COSMO-EU operational analyses as initial and boundary values, obtained from the German Meteorological Service.

4 Results

4.1 Radiative fluxes and heating rates

For the three case studies described above, COSMO model runs were carried out, where frequent intrinsic radiation computations of the full domain served as reference and provided the radiative effects for driving the dynamics and soil-surface parameterisations

of the model. For the comparison the radiation properties resulting from the adaptive radiation computations and the standard 2x2 column-averaging quarter-hourly radiation updates used by default in COSMO-DE were computed as well, hence the three different radiation computations are based on the same atmospheric fields and can be compared directly, without effects which would result from diverging dynamics in different model runs.

According to Figure 2 the adaptive scheme reduces the hourly averaged root mean square difference (RMSD) for the summer case by about 25% in both the shortwave and longwave regime; also the bias is largely decreased. The instantaneous (2.5 min) deviations (deviations always compared to the reference) of the COSMO-DE radiation scheme show a quarter-hourly cycle due to the 15-minute update cycle. Deviations are low directly after a new computation of the full field and increase during the following 15 minutes. The instantaneous deviations of the adaptive scheme are lower throughout the time. The deviations of the COSMO-DE fluxes do not reach zero at a new calculation at a quarterly hour interval because of two reasons: Firstly, the solar zenith angle is taken as at the middle of the update interval, which leads to deviations from the reference values, and secondly errors arise due to the averaging over four columns.

The root mean square differences and biases for the surface fluxes for all three cases are listed in Table 4. The adaptive scheme almost always outperforms the 2x2 standard scheme. The differences are generally smaller for the more homogeneous cases, but about the same relative improvement compared to the 2x2 scheme is achieved by the adaptive scheme as for the summer day.

The daily cycle of the deviations for the atmospheric heating rates is depicted in Figure 3. The RMSD for the shortwave heating rates hardly differ between the adaptive and the 2x2 scheme, while for the longwave the adaptive scheme has the higher RMSD. The systematic deviations are small, but the adaptive scheme clearly outperforms the 2x2 standard scheme (lower panel in Figure 3). Only during sunset the solar radiation shows high systematic deviations, probably due to the fast changing path lengths of the sun

through the atmosphere leading to very different transmissivities. The average vertical profile of RMSD and bias (see Figure 4) shows that the adaptive scheme leads to larger random differences for the cloud level, while the values for the systematic differences, which are however much smaller than the RMSD, can be improved. This behaviour can be traced to the weighted difference function used to search for the most similar column, which is mainly based on vertically integrated atmospheric properties. Hence columns of heating rates may be copied which have the same integrated cloud properties, but differ in the vertical position of the clouds. Such differences are penalised twice in the root mean square difference, once in the level where radiation is overestimated and once in the level where it is underestimated. The systematic deviations over the whole field, however, are small. In the 2x2 standard COSMO-DE radiation scheme systematic differences can occur due to the averaging of the atmospheric properties, which can lead to biases due to the nonlinearity of radiative transfer processes, especially through clouds.

Table 5 summarises the daily mean values of the heating rate differences for the three case studies. Averaged over the day, the COSMO-DE radiation scheme performs better than the adaptive scheme for the longwave RMSD. The average bias over the day is small, although instantaneous biases can be much larger. The reason is the shape of the diurnal cycle of the bias (Fig. 3), which shows an overestimation (underestimation) for the shortwave (longwave) heating rates in the morning and vice versa in the afternoon for all case studies, averaging to a small value close to zero over the day. The hourly biases of the 2x2 scheme are almost always higher than for the adaptive scheme.

An interesting characteristic of the difference fields is the temporal autocorrelation, i.e. the correlation of the differences with time lag. Buizza *et al.* (1999) showed that temporally persistent perturbations have a remarkable influence on model dynamic development (in their study model runs with temporally correlated perturbations increased the divergence of the model runs in an ensemble), while noise which varies randomly from timestep to timestep has no noticeable influence. In our study the temporal correlations of the difference fields could be reduced by about 34% and 45% for the shortwave and

longwave surface fluxes, respectively. The spatial autocorrelations of the difference fields have also been computed in this study, showing that the correlations in the difference fields are also slightly lower for the adaptive scheme than for the 2x2 scheme (not shown).

Averaging the radiation fields to larger scales and computing the root mean square differences on these larger scales (as depicted in Figure 5) shows that the differences to the reference of the adaptive scheme decrease more strongly with increasing scale than for the 2x2-averaged radiation. This holds not only for the radiation fluxes at the surface, but in particular also for the atmospheric heating rates. On the smallest scale the results for the adaptive scheme are worse in terms of differences of the heating rates, however the RMSD on the pixel scale is not as relevant as on larger scales, where the adaptive scheme is more accurate.

Table 6 shows that the mean standard deviations, i.e. the spatial variability of the radiation fields, are underestimated by the 2x2 averaging scheme. Due to the smoothing of the 2x2-column-averaging especially small convective clouds are smoothed out (see also section 4.3).

4.2 Test case with 7 km resolution

Many mesoscale weather forecast models operate on resolutions on the 10 km scale. The operational COSMO-EU model configuration of the German weather service on this scale as mentioned above has a grid spacing of 7 km. On this resolution the relative advection speed is smaller than for the 2.8 km model resolution, thus e.g. cloud cover in the columns changes less rapidly than on the smaller scale. Hence for lower resolutions the problems caused by infrequent radiation calculations are expected to be less important. The convective summer test case as described above has been simulated with 7 km resolution with COSMO-EU settings. For this case the standard COSMO-EU update practise of computing the radiation just once per forecast hour and keeping the radiation fields fixed in between has additionally been simulated and compared to the quarter-hourly 2x2

averaging option and the adaptive scheme. The reference radiation update interval and also the time step of the adaptive schemes were set to 6 minutes. Again the total number of radiation calculations in the four methods under considerations were forced to be equal by choosing the configuration accordingly.

For these 7km model simulations the adaptive scheme again outperforms the 2x2 column-averaging scheme for the surface fluxes in terms of root mean square differences (Figure 6), although the relative improvement is smaller than on the smaller scale considered in the previous section. In the heating rates the 2x2 averaging scheme leads to better results than the adaptive approach (not shown). However, the by far worst results for both fluxes and heating rates, are obtained by the hourly update scheme.

4.3 Physical consistency

In addition to the quantitative performance in terms of deviations of the radiation fields also consistency of radiative effects within the model with other variables and other physical parameterisations is of importance. To illustrate physical relations between radiative effects and cloud characteristics, the mean solar surface flux as a function of the atmospheric liquid water content is depicted in Figure 7 (left). For increasing liquid water path (LWP) the solar surface net fluxes decrease strongly for the reference and the adaptive radiation, whereas for the 2x2 averaging scheme this behaviour is less pronounced. Also the probability density function for a specific LWP value (Figure 7, right) is much wider, less peaked and shifted to higher values for the 2x2 scheme, illustrating that too high radiation fluxes may occur for thick clouds. Again this relation is much better captured by the adaptive scheme.

To study the physical consistency more quantitatively one could compute this probability density function for each LWP value, yielding a 2D histogram of LWP and solar surface net flux and subsequently calculate the RMSD between this histogram for the reference radiation and one of the other schemes. The disadvantage of a histogram is,

however, that the RMSD can depend on the bins widths chosen. Therefore, we have chosen to compute this error measure on the 2D empirical cumulative distribution functions (ECDF). The two-dimensional ECDF is obtained from a two-dimensional histogram by integrating in both directions. In this way, small random errors do not have a strong influence, but systematic deviations do.

In Figure 8 the root mean square differences of these ECDFs with respect to the ECDF of the reference radiation are depicted, for LWP and surface radiation net fluxes (left) and rain rate and surface net fluxes (right), respectively. Evidently, the differences between the 2x2-column averaging scheme and the reference is much larger, both for shortwave and longwave net fluxes, than for the adaptive scheme. This illustrates that the radiative variables computed by the adaptive radiation scheme are more consistent with other model variables, here shown exemplary for the liquid water path and rain rate. Also the relations of the surface net fluxes with cloud cover and ground temperature are captured more accurately (not shown). For the 2x2 scheme the LW differences show a peak in the first hours of the model run; this peak is even more pronounced in the other two case studies (not shown). This indicates that after initialisation the changes in cloud characteristics are fast, due to spin-up processes caused by the initialisation being based on coarser scale analyses (7 km grid spacing).

4.4 Effects on model dynamics

Very important for the evaluation of different radiation parameterisations is in particular the effect on the model dynamics. It is desirable that the inherent errors, inevitably caused by any radiation scheme, which samples in time and space due to computation time limits, has as little as possible negative influence on the model dynamics, i.e. the weather development. To investigate this aspect we carried out three single model runs, one driven by the high-frequent reference radiation computations, one driven by the adaptive radiation computations and one with the quarter-hourly 2x2 averaging COSMO-DE scheme. For a

numerical weather forecast model it is of great interest how much the two computationally cheaper model runs diverge from the reference model run. In Figure 9 the RMS difference for three variables, which are not only important in daily weather forecasts, but also good indicators of the dynamical behaviour of the model is displayed (for the summer case): the surface pressure, the total precipitation (sum since model initialisation) and 2 m temperature, normalised with the standard deviations of the respective reference field to remove effects which are caused by the diurnal cycle alone. The differences in total precipitation and 2 m temperature are caused by differences in cloud formation and movement. The root mean squared differences are larger for the 2x2 radiation update configuration for all three variables, indicating that the model run with the adaptive radiation diverges less. These dynamical effects have been investigated for a second day to ensure robustness of the results. Again the same behaviour as shown exemplary in Fig. 9 was observed, i.e. a slightly stronger divergence of the model run with the 2x2 radiation scheme (not shown).

5 Discussion

The concept of adaptive parameterisations for radiative surface fluxes had been introduced first in VSAS07. In this study the spatial adaptive scheme has been extended to heating rates and the scheme has been implemented and tested in the COSMO-DE model with the same setup as used for daily weather forecast simulations by the German meteorological service on 2.8 km horizontal resolution. The results for three case studies with different synoptic conditions were compared with radiative effects computed with the standard radiation setup based on four (2x2) averaged columns computed once per 15 minutes. Such spatial and temporal sampling strategies are common in operational atmospheric models, which are subject to computer time limits. This study shows that the adaptive concept provides the envisioned benefits in a real model implementation, which was also demonstrated for a spectral adaptive RT parameterisation by Manners *et al.* (2009). We showed that the adaptive scheme produces better results in terms of

random and systematic deviations for the surface fluxes. The deviations for the longwave three-dimensional heating rates did not show these improvements on the smallest scale, but for both, fluxes and heating rates, considerable improvement is achieved for larger averaging scales, which are dynamically more important. The 2x2 averaging scheme leads to too low variability of the radiation fields due to the smoothing by the 2x2 filter, whereas the adaptive scheme does not decrease the variability, but matches the reference standard deviations well.

Evaluating model consistency based on relationships between radiation surface fluxes and rain rates or cloud water content leads to the conclusion that the adaptive scheme is better in conserving these physical relations by capturing changes in cloud cover, while for the 2x2 scheme these correlations are on the one hand smoothed out due to averaging, on the other hand fast moving and developing clouds can not be tracked by the quarter-hourly updates. The adaptive scheme benefits from some new calculations made at high frequency in each region and thus does not miss rapid developments. The search of similar atmospheric columns assures that the heating rates and surface fluxes are taken from similar cloudy or cloudfree columns, leading to consistent radiative and atmospheric characteristics.

Simulations with the different radiation options have also been carried out for the operational COSMO-EU model, which runs on a larger model domain with 7 km horizontal grid spacing. Here the operational setting where updates are computed only once per forecast hour and kept constant in between shows the worst results, indicating that also for that scale either the adaptive or the 2x2 scheme would be more appropriate.

Crucial for weather forecasts is the question, which CPU-time saving configuration has the least deteriorating effect on the dynamical model development. To answer this question single model runs were carried out where the different radiation quantities of the adaptive and 2x2 averaging schemes were not just computed diagnostically, but were actively used to force the model. We found that the model runs with the operational quarter-hourly 2x2 averaged radiation diverges more from the reference model run with

highly frequent calls to radiation scheme than the model run employing the spatial adaptive scheme. Thus it can be concluded that the benefits of the adaptive scheme (improved surface fluxes, heating rates at coarse scales and physical relations between variables) are more important than the slightly worse results for the heating rates on the smallest scale. All this is achieved without an increase in computation time, but based on a more intelligent way of exploiting the available computation resources and distributing the information from the complex radiation scheme to the rest of the field.

As further improvement of the scheme a combination of the spatial adaptive scheme with the temporal adaptive scheme proposed in VSAS07, is planned. In that scheme the grid points for which a call to the complex radiation scheme is carried out are not fixed, but a very simple radiation scheme based on a multiple linear regression is used to find the columns that have undergone the largest atmospheric changes since the last update. This gives even better information on the radiative quantities in regions where the clouds are developing and moving rapidly. Furthermore, remaining differences between the best matching nearby column and the true atmospheric profile can be corrected by the simple radiation scheme. We also aim for an improvement of the results for the heating rates, potentially by better correction methods or a search algorithm which not only incorporates vertically lumped measures.

The adaptive approach has been tested on the meso- γ -scale, because for high horizontal resolutions the problem of fast moving clouds becomes an important task; the persistence assumption made in many operational codes leads to highly inconsistent situations. However, it has been shown, e.g. by Morcrette (2000) for longer, seasonal simulations, that deviations due to sampling of radiation computations build up in time. They can have considerable impact on the dynamical development of the model, leading to a too cold stratosphere through cloud-radiation-convection interactions for his simulations with the ECMWF model. Thus, also for larger scale models, especially for climate simulations where the heat budget is of particular importance, the use of adaptive radiation computations as a tool to provide better radiative fluxes and heating rates without increasing

computational burden, should be considered.

We applied this concept to radiative transfer, because it is one of the most expensive parameterisation in terms of computation time. However, the general idea of combining complex parameterisation with more simple schemes to spread the accurate information in time and space (or spectral space) to save computational resources can also be applied to other parts of the model physics or also model dynamics. The mode-splitting approach by Klemp and Wilhelmson (1978) for example, which is applied in many atmospheric models and computes the fast atmospheric waves on intermediate time steps between the coarse model time steps for advective and physical processes, is based on a similar idea.

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1	18	14	7	11	1	18	14	7	11
25	10	20	23	17	25	10	20	23	17
15	6	2	13	4	15	6	2	13	4
12	21	16	9	19	12	21	16	9	19
5	8	24	3		5	8	24	3	22
1	18	14	7	11	1	18	14	7	11
25	10	20	23	17	25	10	20	23	17
15	6	2	13	4	15	6	2	13	4
12	21	16	9	19	12	21	16	9	19
5	8	24	3	22	5	8	24	3	22

Figure 1: Illustration of the spatial adaptive parameterisation setup tested in the COSMO-DE model configuration: Every 6 timesteps (i.e. 2.5 minutes) one out of 5x5 columns is updated by a call to the intrinsic radiation scheme (in this example the dark shaded grid boxes). The update sequence is indicated by the numbers 1-25 in the grid boxes. For the other grid boxes (for example the grid box without number) a search for a similar, recently updated atmospheric column is carried out, in a search region of 5x5 surrounding columns (light shaded pixels). The radiation fluxes and heating rates found are then copied.

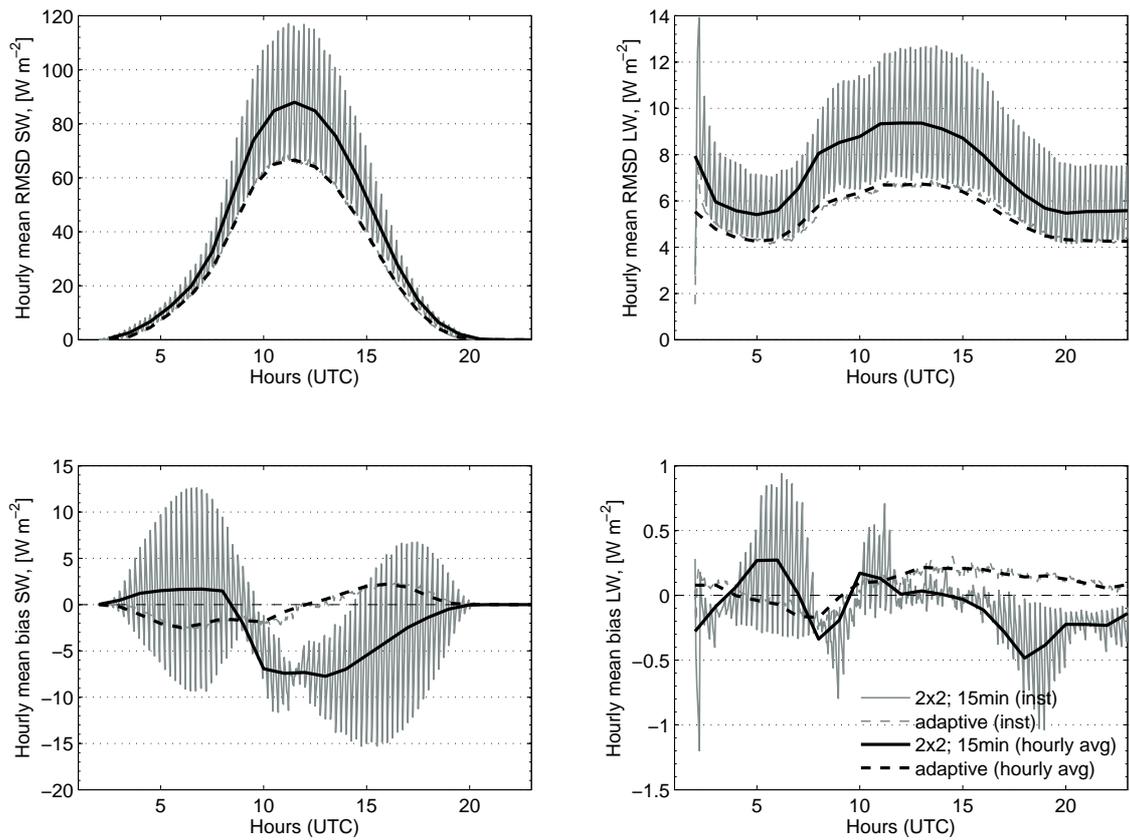


Figure 2: Top: Instantaneous (grey) and hourly averaged (black) root mean square differences in surface net radiation fluxes for shortwave (left) and longwave (right) for the 2x2 COSMO-DE scheme (solid) and for the adaptive scheme (dashed), for 21 June 2004. Bottom: The same for the biases. For the adaptive scheme the instantaneous and hourly averaged differences are almost identical.

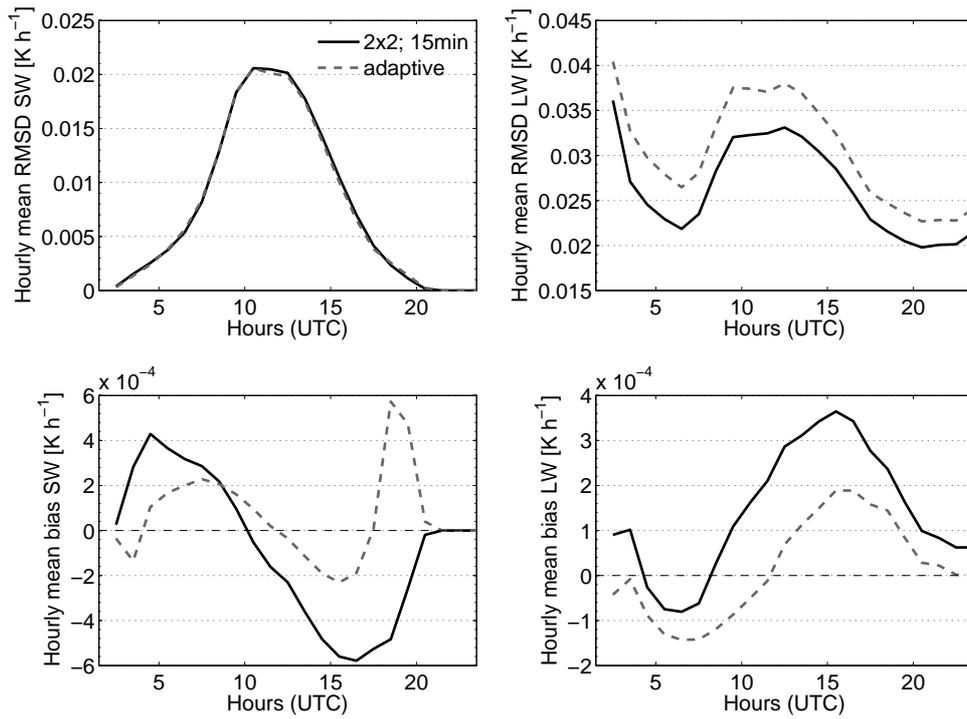


Figure 3: Diurnal cycle of mean root mean square differences (top) and bias (bottom) for columns of atmospheric heating rates for the summer case 21 June 2004. Left: shortwave; right: longwave.

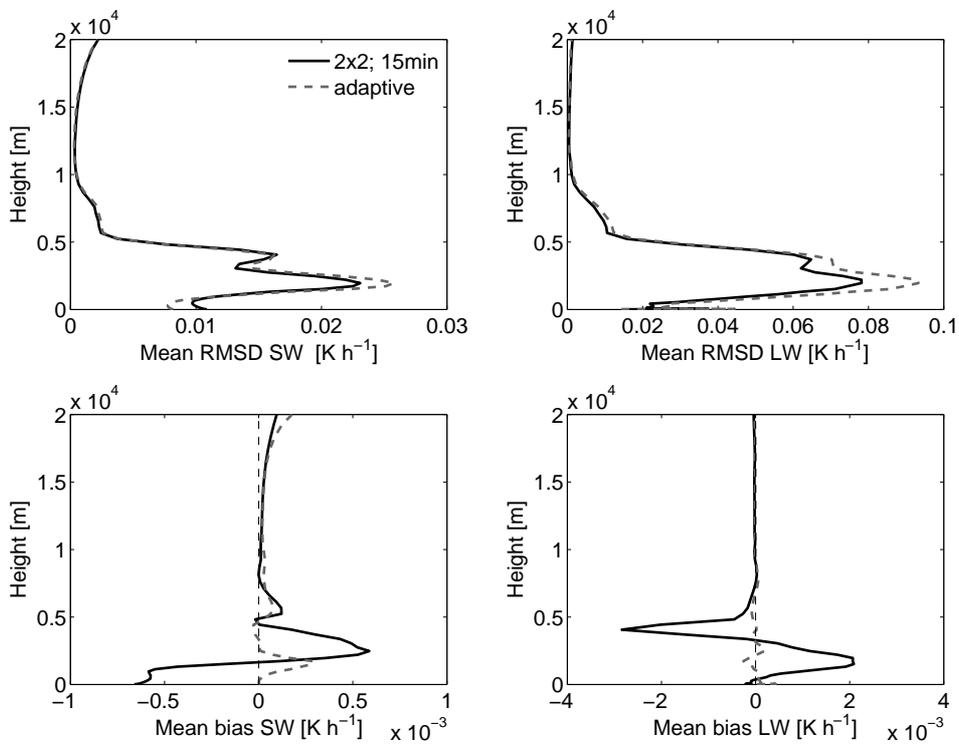


Figure 4: Mean profile of root mean square differences (top) and bias (bottom) of atmospheric heating rates for the summer case 21 June 2004. Left: shortwave, Right: longwave.

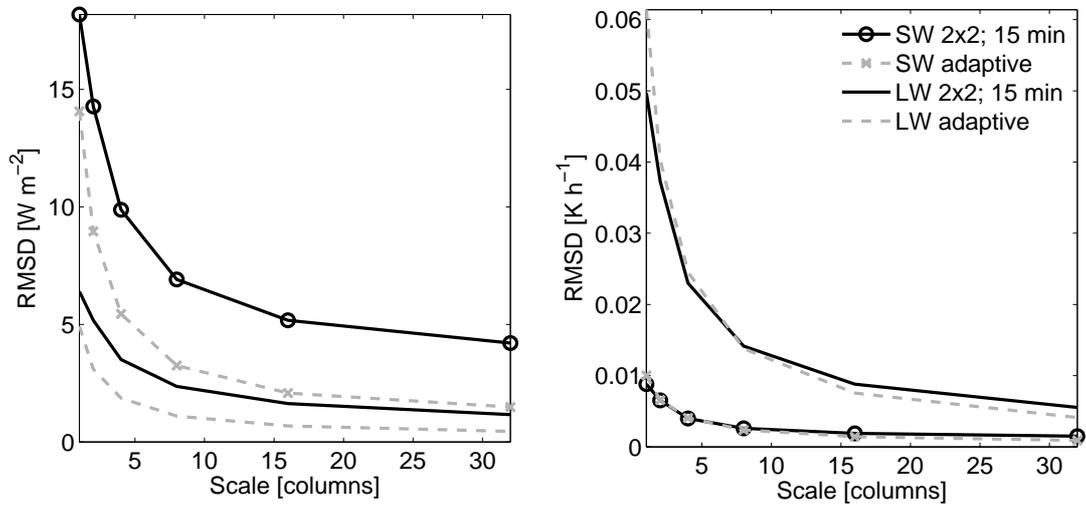


Figure 5: Root mean square differences computed for different spatial scales, based on results for all three case studies. Left: surface fluxes; right: heating rates.

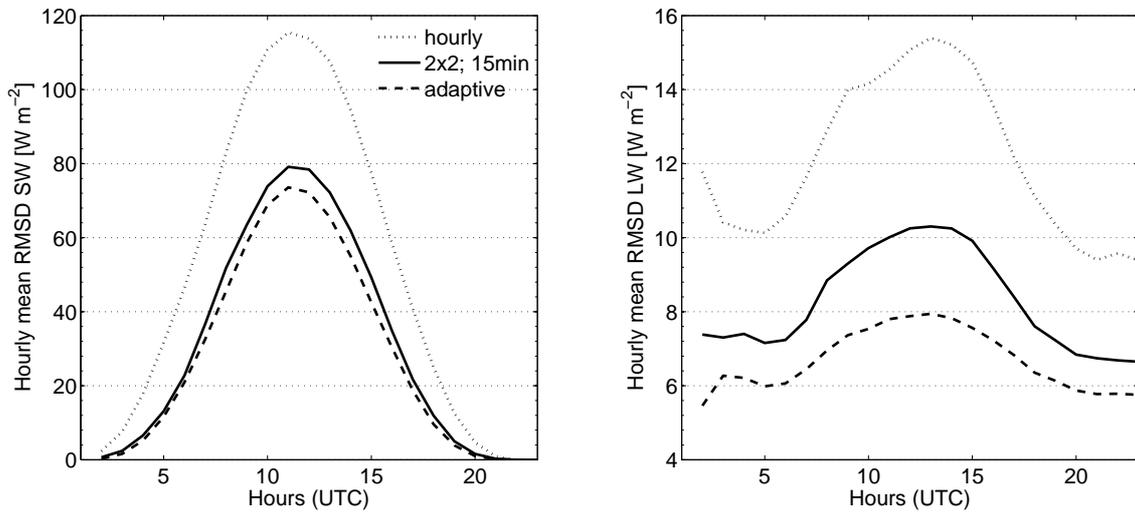


Figure 6: RMSD for surface radiation net fluxes for a model run with 7 km resolution (left: shortwave, right: longwave) again for the summer case. Additionally shown are the deviations for hourly radiation updates for the whole field.

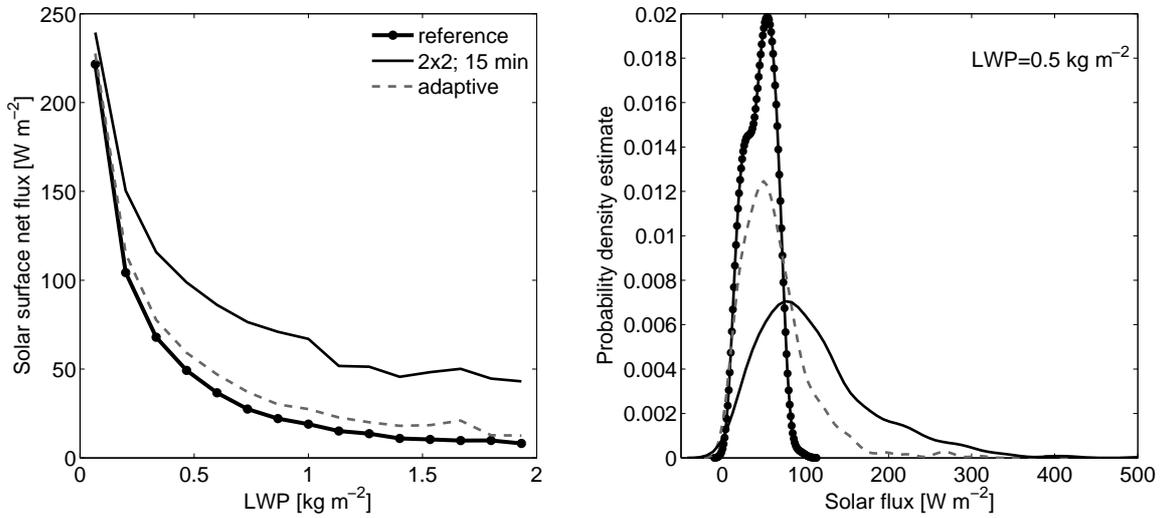


Figure 7: Left: Mean shortwave surface net fluxes for different LWP values. For legibility cloudfree columns have been omitted. Right: Estimated probability density function of shortwave fluxes for a LWP value of 0.5 kg m^{-2} , based on a normal kernel function. Data taken from 1200 to 1700 UTC on 21 June 2004.

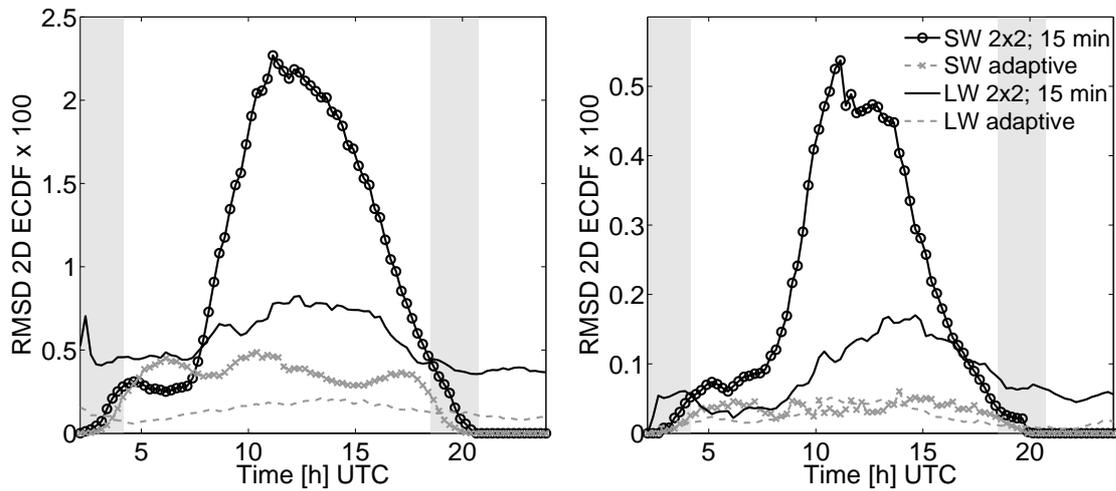


Figure 8: Left: RMS difference between the ECDFs for logarithmic LWP and surface radiation fluxes of the 2x2-column-averaging scheme and the spatial scheme for the summer case study. The light grey bars denote sunrise and sunset, respectively. Right: The same for rain rates and radiation fluxes.

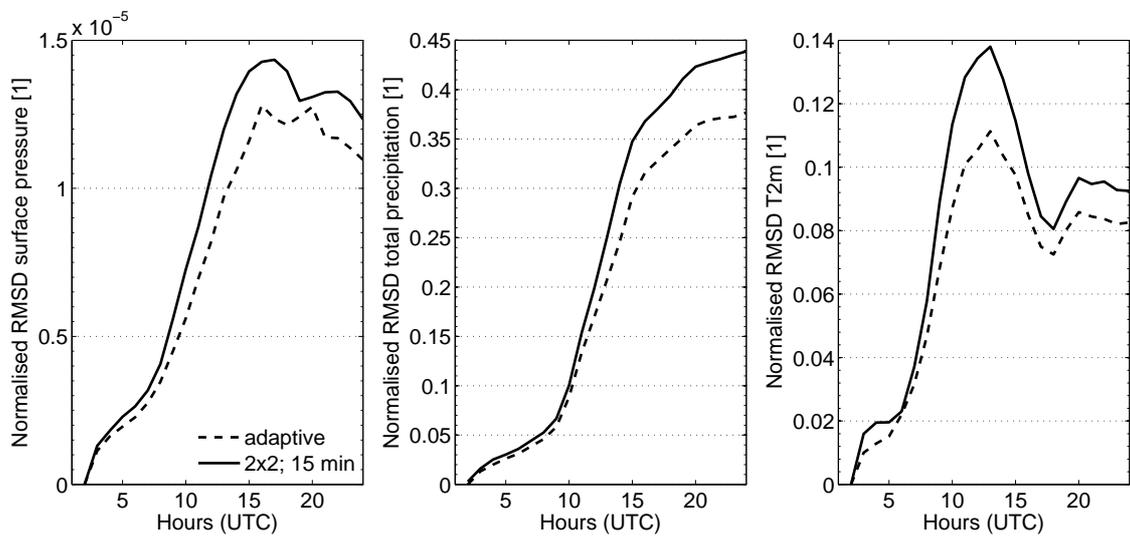


Figure 9: Root mean square difference of surface pressure, total precipitation and 2 m temperature for model runs driven by different radiative forcing for 21 June 2004. The deviations are normalised with the standard deviations of the reference field for the respective variable.

Table 1: Cost function for finding a nearby radiatively similar atmospheric column. The weights are optimised for minimal errors for the heating rates.

Cost function	$\delta = w_1\Delta CCL + w_2\Delta CCT + w_3\Delta LLWP + w_4\Delta IWV + w_5\Delta\alpha + w_6\Delta t + w_7 dist$
Weights	$w_1 = 0.37; w_2 = 7.85; w_3 = 2.1734 kg m^{-2^{-1}}; w_4 = 2.0801 kg m^{-2^{-1}}; w_5 = 13.69; w_6 = 0.267 s^{-1}; w_7 = 0.744;$

CCL: low level clouds (below 800 hPa) [1]; *CCT*: total cloud cover [1]; *LLWP*: logarithm of liquid water path [$kg m^{-2}$]; *IWV*: integrated water vapour [$kg m^{-2}$]; α : surface albedo [1]; t : time since last update [s]; *dist*: distance between grid points [1].

Table 2: Correction applied to the radiation variables after copying a recently updated column in the spatial adaptive scheme.

Variable	Correction
SW heating rates	$H_{SW} = H_{SW} \frac{\cos(\Theta_x)}{\cos(\Theta_c)}$
SW and PAR surface radiation flux	$F_{SW} = F_{SW} \frac{\cos(\Theta_x)}{\cos(\Theta_c)} \frac{1-\alpha_x}{1-\alpha_c}$
LW heating rates	no correction
LW surface radiation flux	$F_{LW} = F_{LW} + (\sigma(1 - \alpha_{IR})(T_{G,c}^4 - T_{G,x}^4))$

Θ : solar zenith angle, α : surface albedo, σ : Stefan Boltzmann constant, T_G : ground temperature, α_{IR} : infrared albedo; the indices c and x denote the value from the copied and the actual local grid point, respectively.

Table 3: Overview of radiation configurations.

Radiation scheme	Call frequency [min]	Number of columns updated
Reference	2.5	all
Adaptive	2.5	1/25
COSMO-DE	15	1/4 (averaging 2x2 columns)

Table 4: Daily mean root mean square differences (RMSD) and systematic deviations (bias) for shortwave and longwave surface net fluxes.

Day	RMSD [W m^{-2}]				Bias [W m^{-2}]			
	SW		LW		SW		LW	
	2x2	adapt	2x2	adapt	2x2	adapt	2x2	adapt
21-06-2004	31.43	23.80	7.15	5.34	-2.01	-0.20	-0.09	0.07
19-09-2001	19.62	15.81	6.53	5.08	-0.60	-0.17	-0.05	0.08
22-12-2005	2.36	1.71	5.25	4.14	-0.08	-0.04	0.11	0.07

Table 5: As Table 4 but for the atmospheric heating rates.

Day	RMSD [10^{-3} K h^{-1}]				Bias [10^{-3} K h^{-1}]			
	SW		LW		SW		LW	
	2x2	adapt	2x2	adapt	2x2	adapt	2x2	adapt
21-06-2004	7.8	7.7	26.2	30.4	-0.008	0.006	0.014	0.002
19-09-2001	6.1	6.3	29.1	33.8	-0.007	0.009	0.008	-0.002
22-12-2005	1.3	1.2	29.0	32.9	-0.003	0.004	0.003	-0.004

Table 6: Mean standard deviation of radiation effects obtained from the different radiation update schemes.

Case	Flux [W m^{-2}]						Heating rate [K h^{-1}]					
	SW			LW			SW			LW		
	ref	adapt	2x2	ref	adapt	2x2	ref	adapt	2x2	ref	adapt	2x2
21-06-2004	143	142	135	30.9	31.1	30.1	0.056	0.056	0.053	0.090	0.090	0.082
19-09-2001	116	116	113	35.3	35.4	34.6	0.044	0.044	0.043	0.092	0.093	0.084
22-12-2005	49	49	49	39.1	39.2	38.9	0.028	0.028	0.027	0.127	0.127	0.120