P7.11 A New Lightning Parameterization and its Implementation in a Weather Prediction Model

Johannes M. L. Dahl *† and Hartmut Höller and Ulrich Schumann
Deutsches Zentrum für Luft- und Raumfahrt, Institut für Physik der Atmosphäre, Oberpfaffenhofen, Germany

1. INTRODUCTION

A new lightning parameterization (in the following abbreviated DHS11) was developed and implemented into the mesoscale weather prediction model COSMO-DE (Steppeler et al., 2003). The DHS11 parameterization yields the total lightning frequency of a given thunderstorm cell (no distinction is made between cloud-to-ground and intra-cloud lightning).

Traditionally, the flash rate has been set linearly proportional to the electrification rate (such as the storm's generator power or generator current), while assuming a constant neutralization strength due to lightning discharges (such as lightning energy or lightning charge; e.g., Williams 1985; Price and Rind 1992, Yoshida et al. 2009 (henceforth abbreviated YMUK09); Blyth et al. 2001). The fact that either lightning energy or lightning charge are treated as constants in these approaches not only is unphysical, but also renders these approaches inconsistent with each other (Boccippio, 2002). In the new approach, the discharge strength is *predicted* and thus allowed to vary from storm to storm, which remedies the inconsistencies of the previous approaches (see Dahl et al., manuscript in preparation, for a detailed discussion). The DHS11 approach is based on a straightforward physical model: A two-plate capacitor represents the basic dipole charge structure of a thunderstorm, which is charged by the generator current and discharged by lightning.

This approach was implemented in the COSMO-DE model, which had not been equipped with a lightning scheme before. The currently existing lightning parameterizations within numerical models comprise a varying degree of sophistication, ranging from explicit simulation of the lightning channels (MacGorman et al., 2001; Mansell et al., 2002; Barthe et al., 2005) to simply predicting the flash rate, yielding e.g., lightning probabilities over a given region (McCaul et al., 2009). The approach pursued herein may be considered to be a compromise between these degrees of sophistication. While merely the flash rate is predicted, the individual flashes are pseudo-randomly distributed beneath each flashing cell, allowing for a comprehensive and detailed display of the modeled lightning activity during the simulation period.

To compare the predictions with observations, the LF/VLF lightning detection network, LINET, is used (Betz et al., 2009). This system is detecting signals in the LF/VLF range and uses a time-of-arrival technique to determine the three-dimensional position of the discharge. The reported LINET "strokes" are grouped into "flashes" such that all events that occur within one second and in an area with a radius of 10 km are binned into a single flash.

The DHS11 approach will be presented and compared to the approach by YMUK09 in section 2. Section 3 deals with the implementation of this approach into the COSMO-DE model, and in section 4 simulation results are presented. A discussion and conclusions are offered in section 5.

2. THE DHS11 APPROACH

The DHS11 approach (Dahl et al., manuscript in preparation) includes a theoretical part and an empirical part.

The theoretical approach is based on the idea that the flash rate is not only determined by the charging rate, but also by the discharge strength associated with each lightning flash (in other approaches, the discharge strength is constant; e.g., Blyth et al. 2001; Price and Rind, 1992). Using a simple two-plate capacitor model where the charging and discharging processes are balanced, the flash rate may be expressed as the ratio between charging rate and the discharge strength:

$$f = \gamma \frac{j}{\Delta\sigma} = \gamma j \frac{A}{\Delta Q}, \qquad (1)$$

*Corresponding author address: Dr. Johannes Dahl, Department of Marine, Earth, & Atmospheric Sciences, North Carolina State University, Campus Box 8208, Raleigh, NC 27695–8208. E-mail: johannes_dahl@ncsu.edu

†Current affiliation: Dept. of Marine, Earth, & Atmospheric Sciences, North Carolina State University, Raleigh, NC

where j is the charging-current density, $\Delta\sigma$ is the lightning charge per area, A is the area of the capacitor plates, and ΔQ is the lightning charge. Note that $j = \partial_t \sigma$. γ is a dimensionless factor between zero and one that accounts for the contribution of lightning to the discharging process.

The empirical part of the approach involves the parameterization of the four variables in Eq. 1,

$$f = f(\gamma, j, A \Delta Q). \tag{2}$$

in terms of the graupel-mass field.

The "graupel region" is defined as the region above the 263 K isotherm where the mass of graupel per volume (the "graupel mass") exceeds 0.1 g m^{-3}. The "ice region" is defined as the region where the sum of cloud ice and snow exceeds 0.1 g m^{-3}.

The idea underlying the parameterizations is that above the 263 K level, the graupel region contains negative charge and the ice region contains positive charge, which is based on the non-inductive graupel-ice charging mechanism (e.g., Saunders 2008). Moreover, the charging rate, j, is assumed to increase with the "graupel mass", and the discharge strength, ΔQ, is assumed to increase as the charge volume increases. The area of the capacitor plates is taken to equal the horizontal cross section though the centroid position of the graupel region. Details about these assumptions and about the following relations may be found in Dahl et al. (manuscript in preparation).

The parameterizations are given by:

$$\gamma = 0.9. \tag{3}$$

$$\Delta Q = 25 \cdot (1 - \exp(-0.013 - 0.027V)), \tag{4}$$

where ΔQ is given in C and the mean volume of the two charge regions, V, is given in km^3. The generator-current density includes the charge density, ρ, in the current and the charge velocity, which can be shown equal the mean terminal velocity of the graupel pellets, v_g:

$$j = \rho v_g, \tag{5}$$

The charge density is parameterized as follows:

$$\begin{aligned} \rho &= 4.467 \cdot 10^{-10} + 3.067 \cdot 10^{-9} m_g^m \quad (6) \\ &\quad \text{if } m_g^m \leq \ 3 \text{ g m}^{-3} \\ \rho &= 9.8 \cdot 10^{-9} \quad (7) \\ &\quad \text{if } m_g^m > \ 3 \text{ g m}^{-3} \end{aligned}$$

where m_g^m is the cell's maximum graupel mass in g m^{-3}. To determine the terminal graupel velocity, the size of the graupel pellets needs to be parameterized:

$$\begin{aligned} D_g &= 1.833 \cdot 10^{-3} + 3.333 \cdot 10^{-3} m_g^m \quad (8) \\ &\quad \text{if } m_g^m \leq \ 3 \text{ g m}^{-3} \\ D_g &= 0.012 \quad (9) \\ &\quad \text{if } m_g^m > \ 3 \text{ g m}^{-3} \end{aligned}$$

where D_g is the graupel diameter in m.

Experiments yielded the following formula to determine the terminal fall speed of graupel pellets as a function of their diameter (Heymsfield and Kajikawa, 1987):

$$v_g = 422.0 \cdot D_g^{0.89}, \tag{10}$$

where v_g is the magnitude of the terminal graupel fall velocity im m s^{-1}. The parameterizations are displayed graphically in Figs. 1 and 2.

See Dahl et al. (manuscript in preparation) for a detailed introduction to these parameterizations.

The YMUK09 approach is based on the assumptions that i) the flash rate varies linearly with the storm's electrical generator power, ii) the aspect ratio of all storms is identical, and iii) that the charge-separation velocity is proportional to the height (or width) of the storms. They found that

$$f_{ymuk} = 10^{-6.1 \pm 0.1} \bar{H}^{4.9 \pm 0.1}, \tag{11}$$

where f_{ymuk} is the flash rate in s^{-1} and $\bar{H}$ is the cold cloud depth in km.

We tested both approaches with the aid of a polarimetric radar POLDIRAD (Schroth et al., 1988)

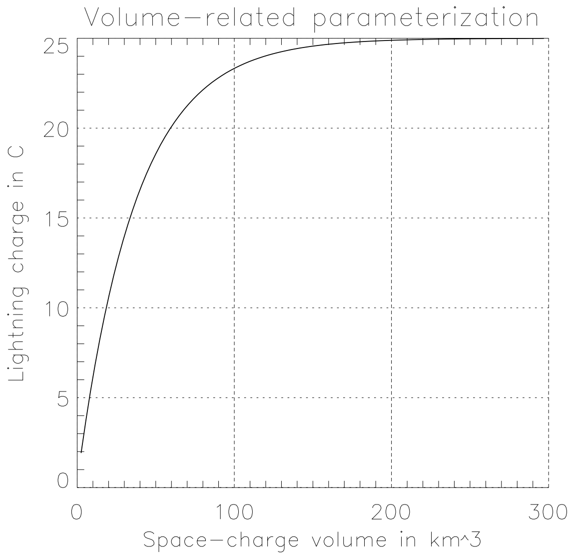

Figure 1: Charge in C deposited in a flash as a function of the volume of the space charge region.

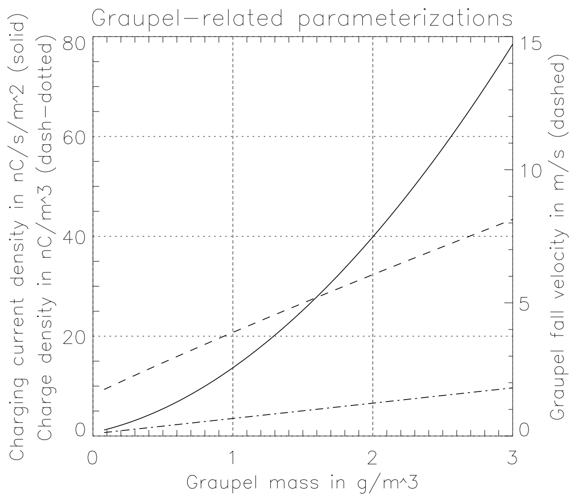

Figure 2: Parameterizations based on the graupel mass. The dashed line represents the terminal fall velocity of the graupel in m s^{-1} (right scale), the dash-dotted line represents the charge density in the generator current in nC m^{-3}, and the solid line represents the resulting generator current density in nC s^{-1} m^{-2}.

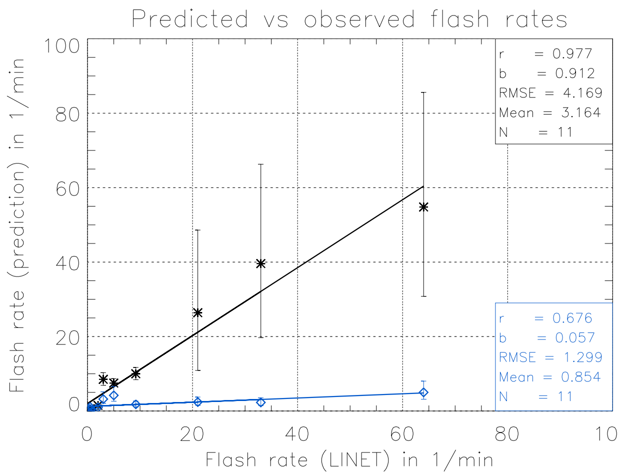

Figure 3: Scatter diagram showing observed (abscissa) and predicted (ordinate) flash rates, Blue symbols refer to the YMUK09 parameterization and black symbols refer to the DHS11 parameterization. r is the correlation coefficient, b is the slope of the regression line, MEAN is the mean error in $\min^{-1}$, RMSE is the root mean squared error in $\min^{-1}$, and N is the number of investigated cases. The error bars in the DHS11 data refer to an uncertainty in determining the diameter of the cells ($\pm$ 1 km for cells with diameters $<$ 10 km and $\pm$ 5 km for cells with diameters $>$ 10 km). The error bars in the YMUK09 data pertain to the uncertainties reported in Yoshida et al. (2009).

situated about 25 km southwest of Munich in southern Germany. Fig. 3 depicts observed and predicted lightning frequencies for a variety of discrete thunderstorms, ranging from shallow and weakly electrified polar-air convection to long-lived and severe supercells. The results of both approaches, DHS11 and YMUK09, are shown. The YMUK09 approach, depending only on the cold-cloud depth, exhibits little variability and underestimates the average flash rate by a factor of about 20, while the DHS11 approach produces rather accurate results for the set of investigated discrete storms (the correlation coefficient and the slope are greater than 0.9). These cases do not include mesoscale convective systems.

3. DESCRIPTION OF THE MODEL AND THE NEW ALGORITHM

COSMO-DE is a fully compressible, convection-resolving numerical weather prediction model (Steppeler et al., 2003). In this study a single-moment, 6-category bulk microphysics scheme was used, which includes the graupel category. The time-independent grid is terrain-following, becoming quasi-horizontal with increasing altitude. The vertical resolution varies from about 50 m in the lowest model layers to about 1000 m towards the domain top, which is at 22 500 m. The horizontal resolution is about 2.8 km (0.025°). The model domain includes Germany and parts of the adjacent countries, and it is nested in the domain of the European-scale model COSMO-EU. The time integration was performed using a two-time-level Runge-Kutta scheme with a large time step of 25 s.

3.1 The DHS11 implementation

To implement the DHS11 parameterization, only knowledge about the spatial distribution of the graupel-mass and ice-mass fields, as well as of the temperature is necessary.

The variables that need to be determined by the algorithm are:

- The 263 K level,
- The centroid position of each graupel region,
- The horizontal cross-sectional area through each graupel region at the height of the centroid location,
- Each storm's maximum graupel mass,
- The thickness of each graupel and ice region.

If these quantities are known, the DHS11 flash rate can be determined. In the first step each graupel region is identified using a "blob-identification" or "labeling" algorithm (Hoshen and Kopelman, 1976), which was originally designed in the context of percolation theory. This algorithm was parallelized as in Constantin et al. (1997). Subsequently, the centroid position of these regions are determined, and the existence of ice crystals above each graupel region is verified. If an ice region exists over the graupel region, then these regions are considered as part of a cumulonimbus cloud, and it is assumed that electrification is occurring. Else, the cloud is not considered to have the potential of producing lightning. The next step involves the determination of the cross-sectional area of the graupel region at the height of its centroid. This area represents the area of the capacitor plates.

To parameterize the charge deposited in the lightning channels, the "charge volume" is needed. This quantity is determined by the arithmetic mean of the volumes of the ice and graupel regions. Since the plate area has been determined already, only the average thickness of the charge regions needs to be determined. This is achieved by calculating the arithmetic mean of the thickness of the graupel and ice regions. This mean is determined at the centroid location of the graupel region.

Once the location of each cell and its properties (location, diameter, maximum graupel mass, charge volume) are known, the flash rate is calculated for each cell. The next step is to determine the accumulated flashes of each cell between two calls of the lightning scheme. If it is called every 900 s (15 min), the accumulated number of flashes of the cell labeled k, is

$$n_k = 900 \cdot f_k, \tag{12}$$

where n_k is the total number of flashes of the kth cell and f_k is the flash rate of the kth cell in s^{-1}. The distribution of the flashes beneath the cell first involves the determination of the time of occurrence of every flash. The entirety of flashes occurring in the given time interval between two calls of the scheme is pseudo-randomly distributed within this interval. This way, fluctuations of the individual flash rates are simulated.

Next, the n_k flashes per cell are spatially distributed around each cell. This distribution is realized in plane polar coordinates. Again a pseudo-random number generator is used to spread the flashes within a certain radius, R, around each cell. This radius is expressed as angular distance in degrees[1] and is given by the equivalent circular radius of the graupel area,

$$R = \frac{180°}{\pi r_e}\sqrt{\frac{A}{\pi}}, \tag{13}$$

[1]This is because the horizontal gridpoint locations in COSMO-DE are defined in (rotated) geographical coordinates.

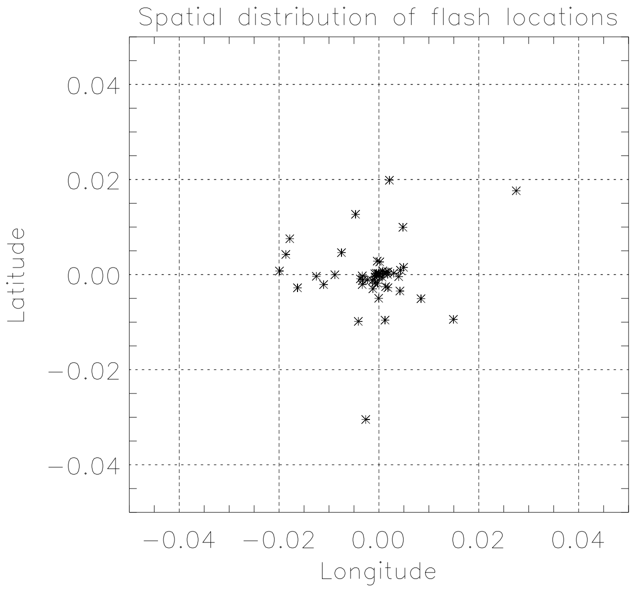

Figure 4: Flash locations for $n_k = 50$. The locations are marked by asterisks and the units of the x- and y-axes are degrees. The centroid of the cell is located at (0,0). 0.05° correspond to about 5.6 km.

where r_e is the earth's radius. Gauss-weighting is applied to reduce the lightning occurrence towards the edge of the cell:

$$r_i = R_k \cdot \exp(-ai)^2, \qquad \text{where } i = 1, \ldots, n_k; \tag{14}$$

r_i is the angular distance in degrees of the ith discharge from the cell centroid. R_k is the plate radius (also expressed as angular distance), and $a = (\sigma\sqrt{2})^{-1}$ with $\sigma = 0.4 \cdot n_k$. The suffix, k, refers to the label of the cell. Fig. 4 shows how lightning locations are distributed around a centroid position located at the geographical coordinates $(\lambda, \phi) = (0, 0)$ for $n_k = 50$. This procedure is repeated for every cell.

This completes the algorithm, and after minor post-processing the final output contains a list that includes

- the time in UTC,
- the longitude in degrees,
- the latitude in degrees

of every simulated discharge.

1) COSMO-DE-specific additions

As pointed out by Bryan et al. (2003), a horizontal grid resolution of 2.8 km is insufficient to simulate convective clouds realistically. We found that in the COSMO-DE model, the convective clouds generally tend to be too wide, roughly by a factor of two. Moreover, the graupel particles in the microphysics scheme are best described as “densely-rimed snow” or “light graupel particles”, as the autoconversion from riming snow to graupel is initiated rather early. This may also contribute to excessively wide graupel regions (Axel Seifert, personal communication). Although this problem could have been circumvented by introducing larger thresholds to define the graupel regions, this would have filtered out weak convective clouds, yielding overall unrealistic results. The solution was to reduce the area of the graupel region, A, before inserting it into the flash-rate equation. In turn, the graupel mass was somewhat increased:

$$m_{gc} = 1.2 \cdot m_g \tag{15}$$

and

$$A_c = 0.25 \cdot A, \tag{16}$$

where m_{gc} is the corrected graupel mass and A_c is the corrected area. Clearly, these corrections are quite crude, and they are merely employed to make the DHS11 approach applicable to COSMO-DE.

4. SIMULATION RESULTS OF 22 AUGUST 2008

An isolated supercell developed over southeastern Germany in the afternoon of 22 August 2008. This case covers the high-intensity end of the spectrum of isolated thunderstorms, both in terms of storm organization and flash production. On its eastward track, the storm evolved into a severe hailstorm, as reported by eye witnesses and supported by radar data (not shown). In the evening hours, another cell appeared in close vicinity to the original cell both in the model and in reality.

First we compare the the lightning rates of these two simulated cells with their observed counterparts. The mean modeled and observed lightning frequencies were compared within several time intervals. The results are summarized in Tab. 1. The flash rates of the two cells in the different periods range from about 10 min^{-1} to about 60 min^{-1} and are accurately reproduced, including the slight strengthening trend of the cells. The periods were selected such that the observed cells were in the domain where LINET data were available and that the simulated cell had reached a quasi-steady state.

Note that between 1930 and 1945 UTC, the two observed cells were so close to each other, that only one “flash cell” was identified. If the flash rate belonging to this region is compared with the sum of the flash rates of the two modeled storms, an agreement to within about 3 % is achieved.

Table 1: Comparison of the flash rates of the simulated (COSMO) and observed (LINET) supercells on 22 August 2008. f is short for flash rate.

Source	Time Interval	f (cell 1)	f (cell 2)
LINET	1900-1930 UTC	12 min^{-1}	38 min^{-1}
COSMO	1900-1930 UTC	10 min^{-1}	33 min^{-1}
LINET	1915-1945 UTC	64 min^{-1}	-
COSMO	1915-1945 UTC	17 min^{-1}	45 min^{-1}
LINET	1930-1945 UTC	22 min^{-1}	58 min^{-1}
COSMO	1930-1945 UTC	23 min^{-1}	54 min^{-1}

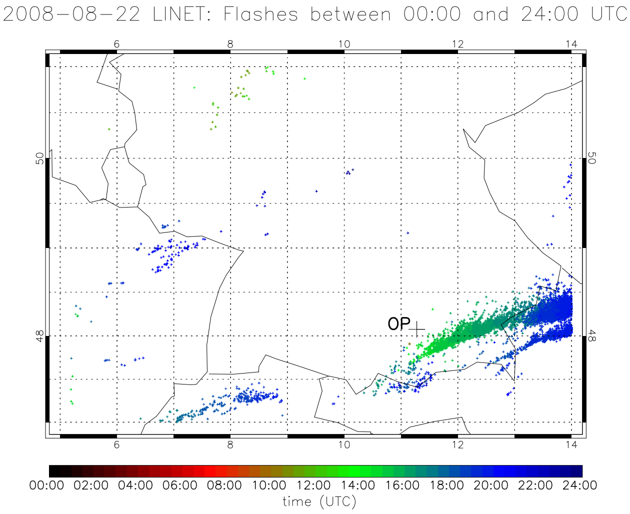

Figure 5: LINET flashes on 22 August 2008. The plus signs represent discharge locations; time is color-coded.

Now we consider the total lightning activity associated with all thunderstorms that occurred over southern Germany on 22 August 2008. The evolution of the lightning activity on that day based on LINET measurements is depicted in Fig. 5. The supercell is represented by a broad “lightning track” that extends from southern Germany into Austria. Fig. 6 shows the simulated lightning activity. For this overview plot, a larger domain was chosen, to display the path of the simulated supercell, which is displaced to the south and east in the simulation. Moreover, the model initiated scattered convection with much lightning over the western part of the LINET subdomain (black rectagle in Fig. 6), where only minimal lightning activity was observed in reality.

The temporal evolution of the observed lightning activity over southern Germany on that day is shown in Fig. 7. The same plot, but for modeled lightning, is displayed in Fig. 8. The total number of accumu-

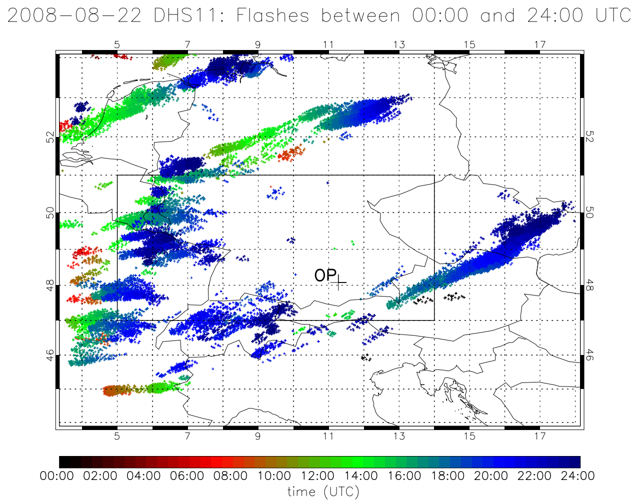

Figure 6: COSMO-DE flashes on 22 August 2008 for central Europe. The plus signs represent discharge locations and the time is color-coded. The black rectangle denotes the LINET domain used in this study.

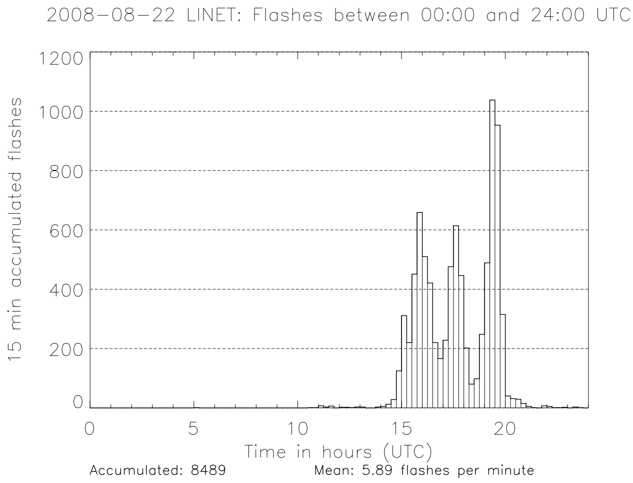

Figure 7: Histogram plots of observed lightning activity over southern Germany on 22 August 2008, showing the 15-min accumulated flashes.

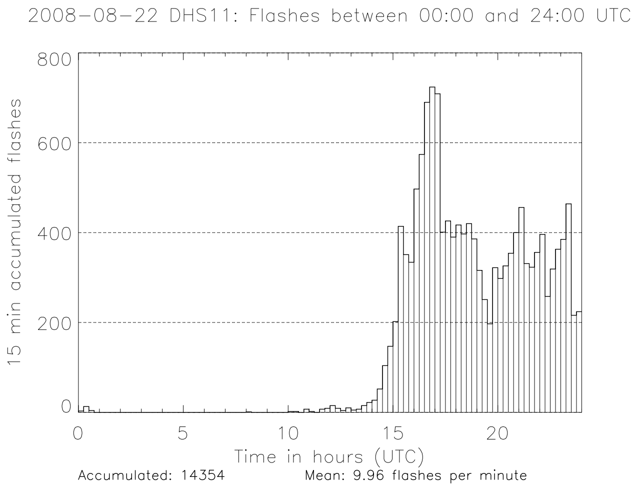

Figure 8: Histogram plots of simulated lightning activity over southern Germany on 22 August 2008, showing the 15-min accumulated flashes.

lated flashes in the southern German domain was 8489 (observed) vs 14 354 (simulated). This difference is due mainly to convection that developed in the simulation in the western parts of the domain in the evening hours. The fact that the lightning activity commences in the afternoon hours was correctly simulated.

5. DISCUSSION AND CONCLUSIONS

The DHS11 approach incorporates several simplifications, the most notable of which are the presence of only two charged regions, and the fact that these regions have equal horizontal extents. In addition, some uncertainties exist with the parameterizations of the charging current density and the lightning charge. However, application of the DHS11 approach to observed thunderstorms justifies these simplifications, at least as long as only discrete (non-MCS) cases and the total lightning frequency are considered. If details such as lightning polarity and IC/CG ratios were to be determined, a more sophisticated approach would be required. Moreover, only isolated (non-MCS) storms were considered. The approach by YMUK09, which is based on constant lightning-energy dissipation, does not reflect the observed range of lightning frequencies. This is because the cold-cloud depth did not vary much in the observed cases, rendering it an inaccurate predictor for the flash rate.

The comparison of the simulated and observed storm on 22 August 2008 suggests that after correcting the horizontal extent of the graupel regions, the lightning scheme is able to accurately reproduce the individual flash rates. Other cases with weaker flash rates were equally well handled (not shown).

Although no MCSs were considered, it seems unlikely that MCSs in COSMO-DE exhibit realistic flash rates (despite the ah-hoc MCS correction). The DHS11 approach very likely is too simple to account for the complicated charge structures of MCSs.

When comparing the overall lightning activity over southern Germany on 22 August 2008, the picture is dominated by the wrong placement and timing of the modeled convection. However, it is not surprising that COSMO-DE does not capture every detail of the convective development, given the long simulation periods before convective initiation occurs (usually more than 12 h). Other mesoscale models have similar problems, which directly affect the quality of the lightning predictions (e.g., McCaul et al., 2009).

Despite the shortcoming of the model to capture the details of the convective evolution, the lightning forecasts are still useful in the forecasting context. The simulations may be considered to offer one possible scenario given a certain environment. The information provided by the new lightning scheme allows for a display of the overall thunderstorm activity throughout the simulation period in one graphic. Such a comprehensive picture cannot be gained by using other model fields. Radar-reflectivity fields only provide an instantaneous picture and accumulated precipitation fields may include non-convective precipitation in convection-resolving models.

In summary, the DHS11 approach remedies physical inconsistencies of previous theoretical approaches to predict the lightning frequency. The DHS11 predictions are more accurate than those based on YMUK09, who assume constant energy dissipation during every discharge.

The DHS11 approach was implemented in the COSMO-DE model, which is now equipped with a lightning module. A cluster-labeling algorithm identifies contiguous graupel and ice regions, which are used to define potentially electrified cumulonimbus clouds. Subsequently, the geometries of the cells, their maximum graupel mass, and their centroid locations are specified. With this information, the number of flashes per cell within the activation periods of the lightning scheme, is determined. In the last step, the flashes are randomly distributed in time and in space around the centroids of the cells, yielding the time and the horizontal location of every flash as output. The overall lightning evolution in the model depends on the placement and timing of the simulated cells. Although the individual cells may exhibit realistic flash rates, the lightning simulations are dominated by placement and timing errors of the modeled convection.

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References

Barthe, C., G. Molinie, and J. Pinty, 2005: Description and first results of an explicit electrical scheme in a 3D cloud resolving model. *Atmos. Res.*, **76**, 95–113.

Betz, H., K. Schmidt, and P. Oettinger, 2009: LINET – An International VLF/LF Lightning Detection Network in Europe. *Lightning: Principles, Instruments and Applications, Eds. H.-D. Betz, U. Schumann, and P. Laroche*, Springer, 115–140.

Blyth, A. M., H. J. Christian, K. Driscoll, A. M. Gadian, and J. Latham, 2001: Determination of ice precipitation rates and thunderstorm anvil ice contents from satellite observations of lightning. *Atmos. Res.*, **59**, 217–229.

Boccippio, D., 2002: Lightning scaling relations revisited. *J. Atmos. Sci.*, **59**, 1086–1104.

Bryan, G. H., J. C. Wyngaard, and J. M. Fritsch, 2003: Resolution requirements for the simulation of deep moist convection. *Mon. Wea. Rev.*, **131**, 2394–2416.

Constantin, J., M. Berry, and B. Vander Zanden, 1997: Parallelization of the Hoshen-Kopelman algorithm using a finite state machine. *Int. J. High. Perform. C.*, **11**, 34.

Grewe, V., 2009: Impact of lightning on air chemistry and climate. *Lightning: Principles, Instruments and Applications, Eds. H.-D. Betz, U. Schumann, and P. Laroche*, Springer, 537–549.

Heymsfield, A. and M. Kajikawa, 1987: An improved approach to calculating terminal velocities of plate-like crystals and graupel. *J. Atmos. Sci.*, **44**, 1088–1099.

Hoshen, J. and R. Kopelman, 1976: Percolation and cluster distribution. I. Cluster multiple labeling technique and critical concentration algorithm. *Phys. Rev. B*, **14**, 3438–3445.

MacGorman, D., J. Straka, and C. Ziegler, 2001: A lightning parameterization for numerical cloud models. *J. Appl. Met.*, **40**, 459–478.

Mansell, E., D. MacGorman, C. Ziegler, and J. Straka, 2005: Charge structure and lightning sensitivity in a simulated multicell thunderstorm. *J. Geophys. Res.*, **10**, D12 101.

Mansell, E. R., D. R. MacGorman, C. L. Ziegler, and J. M. Straka, 2002: Simulated three-dimensional branched lightning in a numerical thunderstorm model. *J. Geophys. Res.*, **107**, 10.1029.

McCaul, E., Jr, S. J. Goodman, K. M. LaCasse, and D. J. Cecil, 2009: Forecasting lightning threat using cloud-resolving model simulations. *Wea. Forecasting*, **24**, 709–729.

Pickering, K., H. Huntrieser, and U. Schumann, 2009: Lightning and NO_x production in global models. *Lightning: Principles, Instruments and Applications, Eds. H.-D. Betz, U. Schumann, and P. Laroche*, Springer, 551–571.

Price, C. and D. Rind, 1992: A simple lightning parameterization for calculating global lightning distributions. *J. Geophys. Res.*, **97**.

Saunders, C. P. R., 2008: Charge separation mechanisms in clouds. *Space Sci. Rev.*, **137**, 335–353.

Saunders, C. P. R. and S. Peck, 1998: Laboratory studies of the influence of the rime accretion rate on charge transfer during crystal/graupel collisions. *J. Geophys. Res.*, **103**.

Schroth, A. C., M. S. Chandra, and P. F. Meischner, 1988: A C-Band coherent polarimetric radar for propagation and cloud physics research. *J. Atmos. Ocean. Tech.*, **5**, 803–822.

Steppeler, J., G. Doms, U. Schaettler, H. W. Bitzer, A. Gassmann, U. Damrath, and G. Gregoric, 2003: Meso-gamma scale forecasts using the nonhydrostatic model LM. *Meteorol. and Atmos. Phys.*, **82**, 75–96.

Williams, E. R., 1985: Large-scale charge separation in thunderclouds. *J. Geophys. Res.*, **90**, 6013–6025.