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ORIGINAL PAPER

Performance evaluation of an operational lightning forecasting system in Europe

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Abstract This study presents the evaluation of 1 year of operational lightning forecasts provided for Europe, using the Weather Research and Forecasting model coupled with a cloud-top height-based lightning parameterization scheme. Three different convective parameterization schemes were employed for parameterizing sub-grid cloud-top heights and consequently driving the lightning scheme. Triggering of the lightning scheme was controlled by means of a model-resolved microphysics-based masking filter, while the formulation for deriving lightning flash rates was also modified, assuming a single "marine" equation instead of the original equations discriminating between continental and marine lightning. Gridded lightning observations were used for evaluating model performance on a dichotomous decision basis. Analysis showed that the lightning scheme is sensitive to the parameterization of convection. In particular, the Kain–Fritsch convective scheme was found to outperform the Grell–Devenyi and Grell–Freitas schemes, showing a statistically significant better performance with respect to lightning prediction. This was most evident during the warm season, while smaller differences among the schemes were recorded during the cold season. Further, for all examined convective schemes, it was found that the application of the masking filter is desirable for improving model performance in terms of lightning forecasting. Last, the reported results revealed that the refinement of the formulation of the lightning parameterization scheme, adhering to a "global" marine equation instead of distinguishing between land and sea lightning, may be necessary in order to obtain reliable lightning forecasts.

Keywords WRF · Lightning · Convective parameterization scheme · Sensitivity · Europe · Operational forecasting

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1 Introduction

Lightning is a typical feature of severe weather that raises significant concern for public safety. Every year, lightning kills thousands of people around the world and tens of thousands are injured (e.g., Mills et al. 2008; Navarrete-Aldana and Cooper 2014; Papagiannaki et al. 2013; Salerno et al. 2012; Zhang et al. 2011). Globally, it is estimated that lightning is responsible for approximately 6000–24,000 deaths per year (Cardoso et al. 2001; Holle 2008). Besides its potentially lethal impacts on human life, lightning has been also documented to be of significant interest for a broad spectrum of geoscience applications, including forest fire initiation (e.g., Drobyshev et al. 2010; Liu et al. 2016; Peterson et al. 2010) and ozone production (e.g., Cooper et al. 2007; Hudman et al. 2007; Ryu and Jenkins 2005).

Considering the importance of lightning as a natural hazard, it is understandable that there is a need for reliable and accurate lightning forecasts. To this end, several lightning parameterization schemes (LPSs) have been proposed during the past two decades. The most well documented and commonly used of such parameterizations is perhaps the one developed by Price and Rind (1992, 1993, 1994) (hereafter referred to as PR92), which relates lightning flash rates to the fifth-power of convective cloud-top height. Alternative approaches have been also developed, based on either bulk- or resolved-scale storm parameters that correlate well with lightning flashes. Examples of such parameters are the deep convective mass flux (Allen and Pickering 2002; Allen et al. 2010), the ice water content (Petersen et al. 2005), the convective available potential energy (CAPE) and other instability indices (Burrows et al. 2005; Tinnmaker et al. 2015; Zepka et al. 2014), the updraft volume (Deierling and Petersen 2008), and mixed-phase graupel flux (McCaul et al. 2009). Explicit lightning physics schemes, performing at cloud-resolving scales, have been also proposed (e.g., Fierro et al. 2013).

Aiming to provide qualitative lightning forecasts for the public, Yair et al. (2010) introduced the concept of the Lightning Potential Index (LPI), based on the fractional ice and super-cooled liquid water mixing ratios between the freezing level and the −20 °C isotherm. Bright et al. (2005) also followed a qualitative approach for developing the Cloud Physics Thunder Parameter (CPTP), based on CAPE and the temperature at the equilibrium level. Both LPI and CPTP differ from other lightning parameterizations in that they do not directly diagnose or predict flash rates or flash counts.

This study presents the evaluation of a modeling system, designed and implemented to provide operational lightning forecasts for increasing public awareness. The modeling system is based on the Weather Research and Forecasting (WRF) model and the cloud-top height-based PR92 LPS. Hence, one of the key goals of the study is to assess the capacity of PR92 to support a real-time numerical weather prediction (NWP) application. For this, we focus on the verification of daily 3-day lightning predictions, provided operationally for Central-South Europe during a 1-year period.

The present study extends the earlier works of Wong et al. (2013) and Giannaros et al. (2015), upon which it is conceptually based. In this context, the original WRF implementation of PR92 (Wong et al. 2013) was properly adapted to allow for using different convective parameterization schemes (CPSs) for driving the lightning scheme. The formulation of Price and Rind (1992), distinguishing between continental and marine lightning flash rates, was also modified with the aim to improve lightning forecasts. Further, the concept of the masking filter, introduced and preliminarily assessed by Giannaros et al. (2015), was evaluated on an operational basis, over the entire study period.

2 Methodology

2.1 Modeling system setup and implementation

The modeling system evaluated in the present study is based on the NWP WRF model, version 3.6.1 (Skamarock et al. 2008). Numerical simulations using parameterized convection were carried out on a single modeling domain, focusing on Central-South Europe with a horizontal grid spacing of 24 km and a mesh size of 185 × 125 grid points (Fig. 1). In the vertical, 28 unevenly spaced full sigma levels were defined and the model top was set to 100 hPa. Given that the specified vertical resolution can be considered to be rather coarse, there is in principle the possibility that the present results could be adversely affected. However, the testing of a newer version of the modeling system, employing a significantly larger number of vertical levels, revealed no important dependence of lightning forecasts on the vertical resolution.

Shortwave and longwave radiation were parameterized with the Dudhia (Dudhia 1989) and Rapid Radiative Transfer Model (RRTM; Mlawer et al. 1997) schemes, respectively. The Thompson parameterization (Thompson et al. 2008) was used for handling microphysics processes. For the planetary boundary layer, the Mellor–Yamada–Janjic (MYJ) parameterization (Janjic 1994) was employed, coupled with the Eta similarity scheme (Janjic 1996, 2002) for the representation of the surface layer. Land surface interactions were handled with the Noah land surface model (Tewari et al. 2004).

The daily 0000 UTC 0.5° × 0.5° spatial resolution and 6-h temporal resolution Global Forecast System (GFS) data, provided by the National Centre for Environmental Predictions (NCEP), were used for initializing the modeling system. High-resolution (0.083° × 0.083°) sea-surface temperature analyses, provided by NCEP, were also employed during the initialization. Numerical forecasts were conducted operationally during the period spanning from October 1, 2014, through September 30, 2015. Forecasts were initialized at 0000 UTC on each day and extended to 84 h, allowing for a 12-h spin-

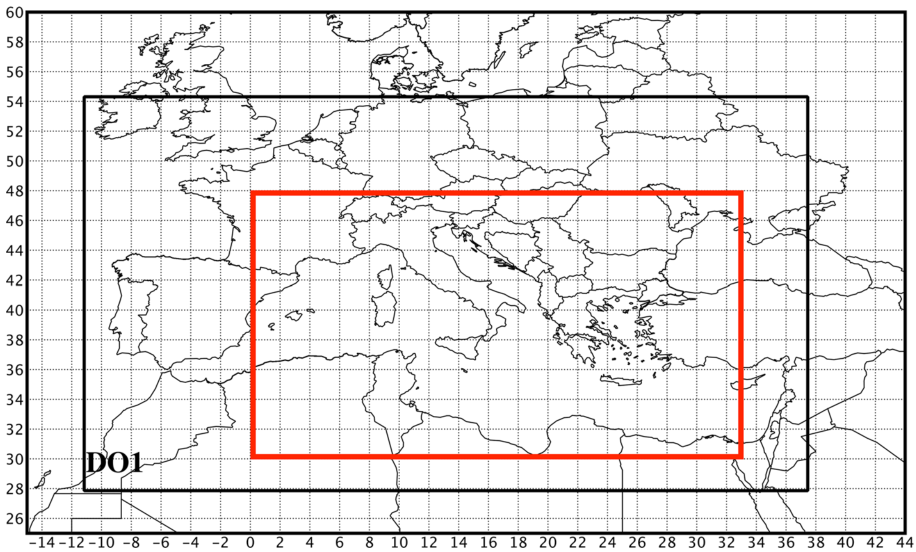


Fig. 1 WRF modeling domain (*black rectangle* denoted with DO1) and verification area (*red rectangle*)

up of the WRF model. The remaining 72 h of forecast data were used for the model evaluation. No data assimilation was carried out.

2.1.1 Parameterization of lightning

Lightning was parameterized using the cloud-top height-based PR92 LPS. The WRF implementation of this lightning scheme (Wong et al. 2013) initially required that a specific CPS be used, namely the Grell–Devenyi (GD) ensemble scheme (Grell and Devenyi 2002), in order to derive sub-grid cloud-top heights for computing flash rates. This restriction is lifted in the present study by proper modification of the lightning scheme's code. Consequently, the Kain–Fritsch (KF) scheme (Kain 2004) and the Grell–Freitas (GF) ensemble (Grell and Freitas 2014) scheme were used as alternatives to the GD parameterization.

To account for the resolution dependency of PR92, discussed in detail in Wong et al. (2013), the "calibration factor" approach of Price and Rind (1994) was used. Partitioning of the simulated total lightning flash rates into intra-cloud (IC) and cloud-to-ground (CG) was carried out with the empirical equation of Prentice and Mackerras (1977).

Following Giannaros et al. (2015), who provided a preliminary assessment of the PR92 LPS for Greece, a masking filter was applied for controlling the computation of lightning flash rates. The principal function of this filter can be summarized in preventing the production of lightning when the model-resolved column-integrated ice content (Q_{ice}) does not exceed a certain threshold value (2 g). For a detailed presentation of the development and assessment of this masking filter, the reader is advised to refer to Giannaros et al. (2015).

The above-presented adaptation of the PR92 lightning parameterization can be regarded as an ad hoc tuning procedure. In principle, this is necessary when diagnostic lightning prediction schemes are implemented. In developing their parameterization, Price and Rind (1992) established the fifth-order dependence of flash rates to the cloud-top height rather than to the radar echo top height. This basic assumption may not be applicable in all regions and seasons, since cloud tops exhibit sharp variations both spatially and temporally. For instance, the top of a convective cloud may be a few kilometers higher than the height to which significant radar echo exists, especially over ocean regions (Liu et al. 2007). Further, the atmosphere may occasionally be unstable to great heights, but with only small buoyancy, allowing deep clouds to form, with only weak updrafts. Such conditions hamper the process of charge separation within the cloud and, consequently, result in reduced lightning. On the other hand, the presence of increased concentrations of cloud condensation nuclei (CCN), particularly over land, may result in increasing lightning activity for the same cloud-top height (e.g., Mansell and Ziegler 2013). Ultimately, one should bear in mind that cloud-top height is generally a poor tracer for the intensity of convective and lightning activity and that tuning is almost always necessary when implementing parameterizations similar to PR92 (e.g., Wong et al. 2013).

2.2 Evaluation procedure and data

Hourly measurements of CG lightning flashes over Central-South Europe, confined to the geographical area between 0°N and 48°N, and 0°E and 33°E (Fig. 1), were used for the evaluation of the modeling system. Data were provided by ZEUS, a ground-based very low-frequency (VLF) lightning detection network operated by the National Observatory of Athens (NOA). ZEUS detects primarily CG lightning, with a detection efficiency of about

30 %, and only a few high-amplitude (IC) flashes, while over the verification area (Fig. 1) the location error approximates 6.5 km (Kotroni and Lagouvardos 2008; Lagouvardos et al. 2009). These characteristics suggest that the lightning data derived from ZEUS must be used with caution when investigating total lightning and, consequently, when studying the microphysical/convective evolution of thunderstorms. In this study, however, we focus on CG lightning as a natural hazard, not dealing with the examination of the structure and evolution of thunderstorms. Further, when compared to other long-range detection networks (e.g., WWLLN; Rodger et al. 2004), ZEUS shows a better detection efficiency and location error, while it has been shown to be capable of capturing the occurrence of lightning (as an event) with a success rate of 95 % (Lagouvardos et al. 2009). Therefore, the ZEUS lightning data are considered to be of sufficient quality for the purposes of this study.

To allow for comparisons against model data, lightning observations were aggregated to the 24-km WRF grid. In terms of data availability, 51 days were excluded from the verification procedure due to either missing lightning observations or modeling system failures. Overall, data availability for the 1-year verification period is considered to be adequate (i.e., ~86 %) to assess the robustness of forecast statistics presented herein. In particular, data availability during June, July, and August, which is the most active period in terms of lightning activity (e.g., Galanaki et al. 2015; Kotroni and Lagouvardos 2016), is about 95 %.

The evaluation of the modeling system was conducted on a boolean decision basis (i.e., yes/no occurrence of lightning). Using contingency tables, the following verification scores were computed: (a) probability of detection (POD), (b) false alarm ratio (FAR), and (c) equitable threat score (ETS). In the above procedure, a single lightning threshold was considered: lightning counts >1. This approach was adopted since the principal requirement of this study is to assess the model's skill for successfully forecasting lightning occurrence rather than lightning in terms of absolute numbers. The statistical significance of differences in the scores has been verified using the bootstrapping-based hypothesis test approach of Hamill (1999), which is described in detail in Accadia et al. (2003, 2005) and Giannaros et al. (2016). The significance test was carried out assuming a 95 % ($\alpha = 0.05$) confidence interval.

3 Results

3.1 Overall performance and evaluation of the masking filter

To assess the overall performance of the modeling system and evaluate the masking filter, verification scores were first computed using the dataset for the entire study period. For this, the gridded ZEUS data were organized into 72-h intervals, beginning at T0 + 12 (T0 is the initialization time of the modeling system), out to T0 + 84, on each day of the 1-year period, and compared against the corresponding 72-h WRF data. As shown in Table 1, the selection of the CPS influenced model performance in terms of lightning forecasting. Compared to the control GD simulation, KF showed the largest, statistically significant, improvements in all scores. Rather small differences, statistically significant for POD and FAR but not for ETS, were computed between GD and GF, most probably due to the fact that both schemes are based on the same conceptual model for parameterizing convection (Grell and Devenyi 2002; Grell and Freitas 2014).

Table 1 Verification scores computed over the entire study period, without (NOFLT) and with (FLT) the implementation of the masking filter, for each of the examined CPS

CPS	NOFLT			FLT		
	POD	FAR	ETS	POD	FAR	ETS
GD	0.62	0.54	0.33	0.59*	0.45*	0.37*
GF	**0.69**	**0.58**	0.32	**0.66***	**0.51***	0.36*
KF	**0.71**	**0.52**	**0.37**	**0.68***	**0.47***	**0.40***

Scores appearing in bold font indicate a statistically significant difference (at $\alpha = 0.05$) between GF/KF simulations and the GD simulation (control). Scores with an asterisk indicate a statistically significant difference between the FLT and NOFLT (control) simulations, for each given CPS

In agreement with the earlier study of Giannaros et al. (2015), the results presented in Table 1 suggest that the implementation of the Q_{ice}-based masking filter improved lightning prediction. In particular, it is evident that the application of the filter restricted false alarms in all simulations (GD, GF, KF). A reduction in POD was also found, but the net effect of the masking filter on model performance was positive, as highlighted by the increase seen in ETS. More importantly, the corresponding differences (i.e., NOFLT [control] against FLT) were found to be statistically significant, highlighting the robustness of the masking filter approach.

In addition to the computation of verification scores, observed and modeled data were used to determine the number of grid points in DO1 (Fig. 1) affected by lightning on each day of the study period. The corresponding scatter plots are shown in Fig. 2. The reported correlation coefficients (R) indicate that even without the masking filter (Fig. 2a, c, e), the day-to-day variation of lightning activity over Europe was reproduced rather well. However, lightning occurrences were generally overestimated. This inadequacy of the modeling system was partially addressed when the masking filter was applied, resulting in improved R values for all three CPS (Fig. 2b, d, f).

With regard to the sensitivity of PR92 to the parameterization of convection, Fig. 2 confirms the previously reported superiority of KF over GD and GF. Furthermore, it now becomes evident that differences in the prediction of lightning activity do exist in between the simulations conducted with the GD and GF schemes. In particular, lightning forecasts derived with GF (Fig. 2c, d) were found to be better correlated with observations than the forecasts produced using GD (Fig. 2a, b). As will be shown (Sect. 3.3), the overall better performance of the model with the KF scheme is primarily due to the better representation of convective processes during the warm season.

3.2 Forecast lead-time

Figure 3 presents the variation of the computed verification scores with respect to the forecast lead-time. To calculate the scores, the gridded ZEUS and WRF data were aggregated into 24-h intervals, starting at T0 + 12 on each day of the 1-year verification period. Hence, three datasets were constructed, each containing data for the periods T0 + 12 − T0 + 36 (T24), T0 + 36 − T0 + 60 (T48), and T0 + 60 − T0 + 84 (T72). Given the demonstrated positive impact of the masking filter (Sect. 3.1), results presented hereinafter (Sects. 3.3, 3.4) are based on model data derived with the implementation of the masking filter (FLT).

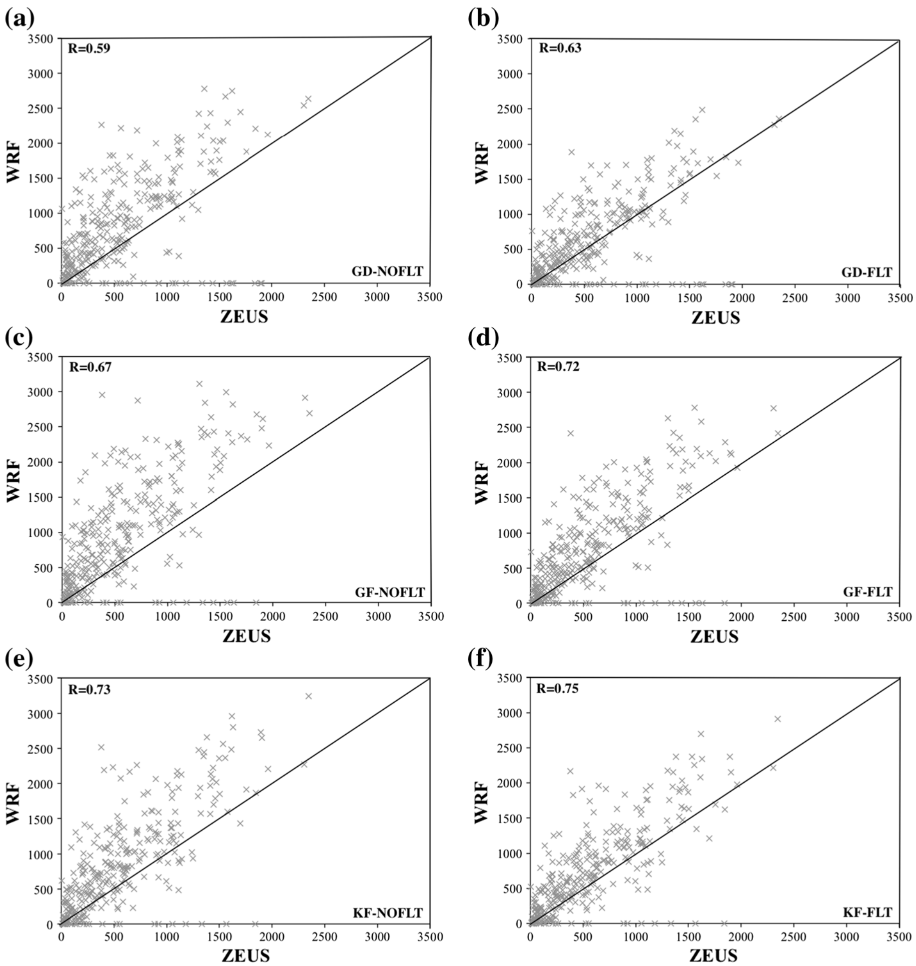


Fig. 2 Scatter plots of observed (ZEUS) versus modeled (WRF) daily lightning activity, represented by the number of grid points in DO1 (Fig. 1) with at least one lightning count, for each of the examined CPS (top, middle and bottom row) without (*left column*; NOFLT) and with (*right column*; FLT) the implementation of the masking filter. Pearson correlation coefficients (*R*) are shown within the plots

The results shown in Fig. 3 indicate that the predictive ability of the modeling system drops with increasing forecast lead-time. For each of the three CPS, POD was found to decrease by approximately 10 % from T24 to T72 (Fig. 3a). On the other hand, FAR was found to increase (∼ 7 %) in the simulations conducted with KF, remaining fairly constant when either GD (∼ −2 %) or GF (∼ 2 %) was employed. With regard to ETS, simulations with the KF scheme were found to exhibit the largest decrease (∼ 12 %) from T24 to T72, whereas lower reductions were computed for GD (∼ 5 %) and GF (∼ 8 %).

The deterioration of model performance with increasing lead-time is in principle associated with the basic uncertainties of NWP (e.g., Cuo et al. 2011; Leutbecher and Palmer 2008). Initial conditions are of particular importance, and these can be only determined within a certain accuracy. Given that NWP models have, by their nature,

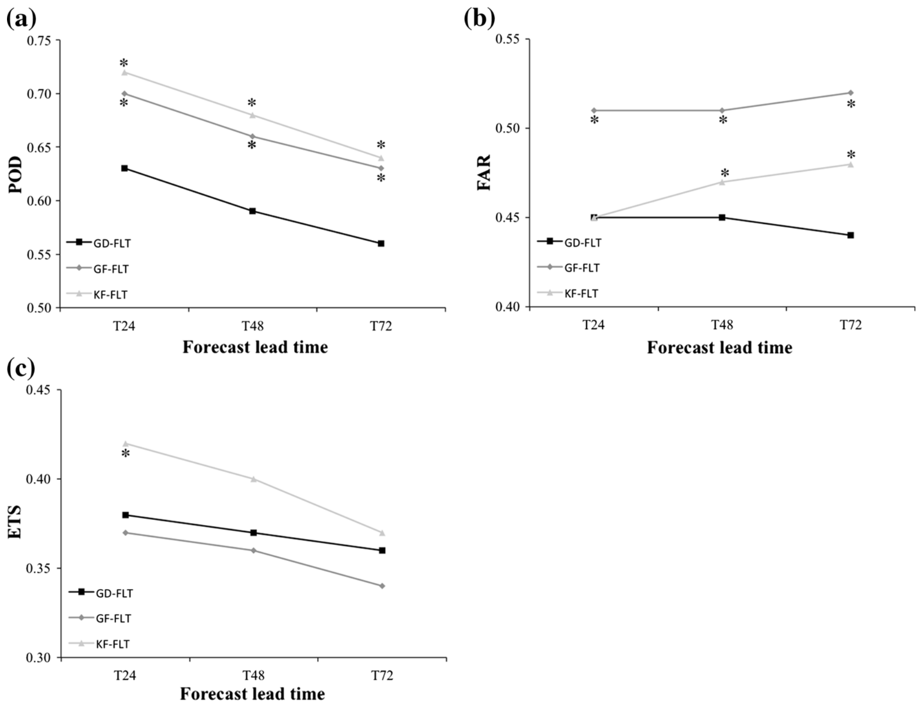


Fig. 3 Variation of model performance metrics with respect to the forecast lead-time: **a** POD, **b** FAR, and **c** ETS. Verification scores were computed using model data derived with the implementation of the masking filter (FLT). The *asterisk* above or below a data marker indicates a statistically significant difference (at $\alpha = 0.05$) between GF/KF simulations and the GD simulation (control), for the given forecast lead-time

inadequacies in representing physical processes, these initial errors may amplify during a forecast, thus resulting in a model performance that drops with increasing lead-time.

The results presented in Fig. 3 also suggest that KF is generally a better option for driving PR92, compared to GD and GF. This was most pronounced in the very short-range (T24) forecasts, while for the T72 lightning forecasts, the computed ETS scores indicate rather small differences in between the three convective schemes. Indeed, a statistically significant improvement in ETS for T24 is only evident for KF (Fig. 3c).

3.3 Seasonal variations

To investigate model performance on a seasonal basis, the 1-year study period was split into two seasonal periods: (a) the warm period, ranging from May through September, and (b) the cold period, ranging from October through April. This particular seasonal categorization was selected based on past studies focusing on convection and lightning activity (e.g., Giannaros et al. 2015; Kotroni and Lagouvardos 2001; Mazarakis et al. 2009). Further, it allows for examining model performance under different meteorological conditions associated with the lightning occurrence (e.g., dynamically versus thermally driven convection).

The results presented in Table 2 reveal interesting aspects of model performance differentiation due to employment of different CPS. One can easily notice that the

Table 2 Verification scores computed over the warm and cold seasonal periods, for each of the examined CPS

CPS	POD		FAR		ETS	
	W[a]	C[b]	W	C	W	C
GD	0.55	0.63	0.46	0.44	0.34	0.40
GF	**0.64**	**0.68**	**0.52**	**0.50**	0.34	**0.37**
KF	**0.72**	0.64	0.46	**0.47**	**0.41**	0.39

The calculation of the performance metrics was carried out using gridded observed and modeled (with the implementation of the masking filter) lightning data, aggregated to 72-h intervals, beginning at T0 + 12 on each day of the verification period. Scores appearing in bold font indicate a statistically significant difference (at $\alpha = 0.05$) between GF/KF simulations and the GD simulation (control)

[a] Warm period

[b] Cold period

performance of each CPS is quite similar, one to the other, during the cold period of the year. In this period, the development of storm systems, which may potentially lead to the occurrence of lightning, is primarily driven by synoptic-scale forcing. Hence, the role of the CPS is restricted. This, in turn, restricts the differentiation of model performance in terms of lightning forecasting.

Conversely, when the synoptic-scale forcing is weak, as is the general case during the warm season, the role of the CPS is enhanced and differences in model performance arise. Indeed, as shown in Table 2, the examined parameterizations perform differently, with respect to lightning forecasting, during the warm period of the year. Most notably, the computed POD scores indicate that the KF scheme significantly outperformed GD and GF in successfully capturing the occurrence of lightning. This could be attributed, at least to a part, to the trigger function of this particular scheme that eventually allows for an improved spatiotemporal simulation of convection, and consequently lightning activity. In brief, KF employs low-level vertical motion for triggering convection and CAPE as the closure (Kain 2004). Hence, it allows for a better representation of convective processes associated with thermodynamic vertical motions induced by heating at the lower boundary, which typically occurs during the warm season. On the other hand, the GD and GF schemes employ a plethora of closure assumptions and trigger mechanisms that, by means of ensemble techniques, are used for initiating and describing convection (Grell and Devenyi 2002; Grell and Freitas 2014). Both schemes are conceptually based on the original model of Grell (1993), which has been shown to perform better under conditions of large-scale forcing (e.g., Liang et al. 2004; Pei et al. 2014) than under thermally driven forcing.

3.4 Marine versus continental lightning

As discussed by Wong et al. (2013), the PR92 LPS considers different formulations for deriving lightning flash rates over land and sea. Therefore, it is of particular interest to examine model performance with respect to forecasting the occurrence of continental and marine lightning. For this purpose, the gridded ZEUS data were first separated into two groups based on the location of occurrence, either over land or over the sea. Model performance metrics were then computed separately for each group.

To draw the overall picture of model performance over land and sea, verification scores for each CPS were computed over the entire 1-year period (refer also to Sect. 3.1, Table 1). Results are presented in Fig. 4. Most notably, FAR scores for marine lightning were found to be significantly lower than for continental lightning (Fig. 4b). Particularly for GD and KF, the “marine FAR” was computed to be as low as about its half value over the land. Smaller differences, not exceeding 20 %, were computed for POD, which suggest better predictive ability over the land than over the sea (Fig. 4a). Overall, however, the ETS scores depicted in Fig. 4c suggest better prediction of lightning over the sea than over the land, especially when GD or KF was employed.

The above results suggest that irrespective of the employed CPS, marine lightning was better forecasted than continental lightning. Thus, it is reasonable to assume that the reason for this lays in the formulation of PR92, rather than in differences attributed to the convective schemes. To evaluate this speculation, the original WRF implementation of PR92 was appropriately modified. In particular, instead of distinguishing between continental and marine lightning, a “global” marine equation (Eq. [1] in Wong et al. 2013) was used for deriving flash rates over both land and sea. More details on the distinction between continental and marine lightning, and the corresponding mathematical formulations, are available in Wong et al. (2013).

Table 3 summarizes the performance of the modeling system after the modification of PR92. It presents the verification scores that were calculated over the warm and cold period of the year, as well as over the 1-year period. Clearly, the predictive ability of the modeling

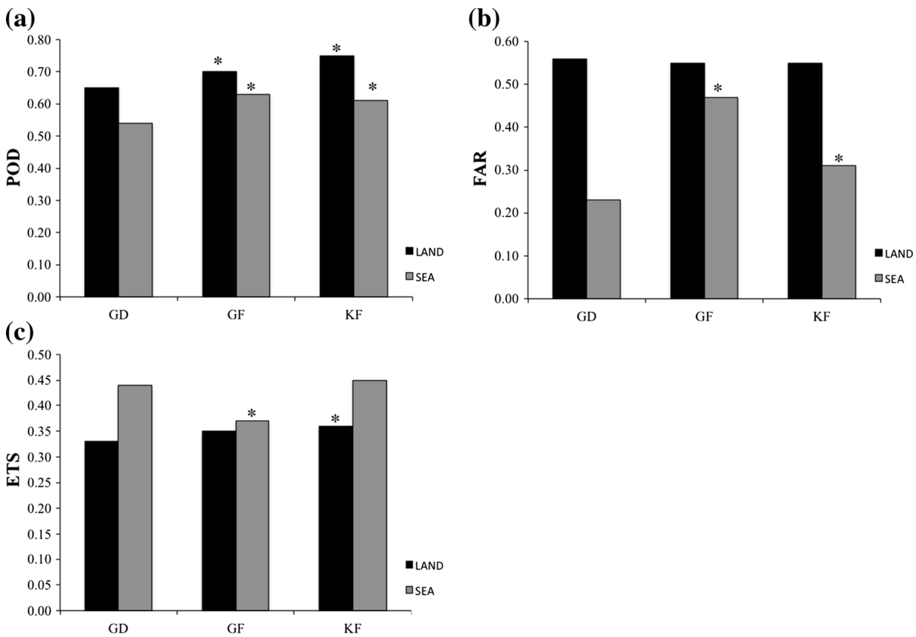


Fig. 4 Model performance metrics for continental (land) and marine (sea) lightning, for each CPS, computed over the entire study period: **a** POD, **b** FAR, and **c** ETS. Model data with the implementation of the masking filter were used for the calculations. The *asterisk* above or below a data column indicates a statistically significant difference (at $\alpha = 0.05$) between GF/KF simulations and the GD simulation (control), for the given sub-dataset (i.e., land/sea). For each of the given CPS, the differences between “land” and “sea” scores were found to be statistically significant (at $\alpha = 0.05$)

Table 3 Verification scores computed over the warm and cold seasonal periods, and the entire study period, for each CPS, after the modification of the PR92 LPS

CPS	POD			FAR			ETS		
	W[a]	C[b]	Y[c]	W	C	Y	W	C	Y
GD	0.52*	0.55*	0.53*	0.37*	0.28*	0.32*	0.37*	0.43	0.40*
GF	**0.62***	**0.60***	**0.61***	**0.47***	**0.42***	**0.44***	0.37*	**0.39**	**0.38**
KF	**0.71**	**0.58***	**0.63***	**0.40***	**0.35***	**0.37***	**0.45***	0.42	**0.44***

The calculation of the performance metrics was carried out using gridded observed and modeled (with the implementation of the masking filter) data, aggregated to 72-h intervals, beginning at T0 + 12 on each day of the verification period. Scores appearing in bold font indicate a statistically significant difference (at $\alpha = 0.05$) between GF/KF simulations and the GD simulation (control). Scores with an asterisk indicate a statistically significant difference between the FLT_LAND and FLT simulations, for each given CPS

[a] Warm period

[b] Cold period

[c] Year

system was overall improved. Most notably, comparing the metrics of Table 3 against those shown in Tables 1 and 2, one can notice that the use of the marine equation for computing continental lightning flashes resulted in significant reductions in FAR. These reductions are evident for all examined CPS, although higher for GD and KF than GF, and for both seasonal periods, as well as on an annual basis. POD was also found to decrease, but the relative changes were computed to be lower than in the case of FAR, suggesting that the modification applied to PR92 successfully dealt with reducing falsely predicted lightning rather than negatively affecting correct predictions. This is also reflected in ETS, the values of which were computed to be higher by approximately 10 %, on average, compared to the forecasts provided with the original PR92.

3.5 Subjective evaluation

Besides the quantitative verification (Sects. 3.1, 3.2, 3.3, 3.4), the performance of the modeling system was subjectively evaluated for selected cases of the 1-year study period. For this purpose, maps of observed and forecasted lightning, aggregated to 24-h intervals, were constructed and intercompared. For clarity, the results reported herein refer to two cases, one for the cold and one for the warm period of the year (see Sect. 3.3). The presented maps depict a parameter that has been named to be the "level of lightning activity" (LLA). Briefly, for each grid point of the modeling domain, LLA is defined as the number of observed/modeled lightning flash counts divided by the domain-wide maximum of observed/modeled lightning flash counts. Thus, LLA can be considered as a measure of the relative intensity of lightning activity, observed or modeled, at a particular grid point, with respect to the maximum observed or modeled lightning activity. Forecasting maps for LLA are currently produced operationally, on a daily basis, at NOA and can be accessed via the Web at http://www.thunderstorm24.com.

◀**Fig. 5** Level of lightning activity in past 24 h (10 November 1200 UTC to 11 November 1200 UTC 2014) derived from **a** ZEUS lightning detection network and WRF forecasts with **b** GD, **c** GF and **d** KF schemes. For each CPS, plots derived without (b–d1; NOFLT) and with (b–d2; FLT) the masking filter, and with the masking filter and the modified PR92 equation for continental lightning (b–d3; FLT_LAND), are presented. The *color scale* is common to all plots

3.5.1 Cold period case: November 10–11, 2014

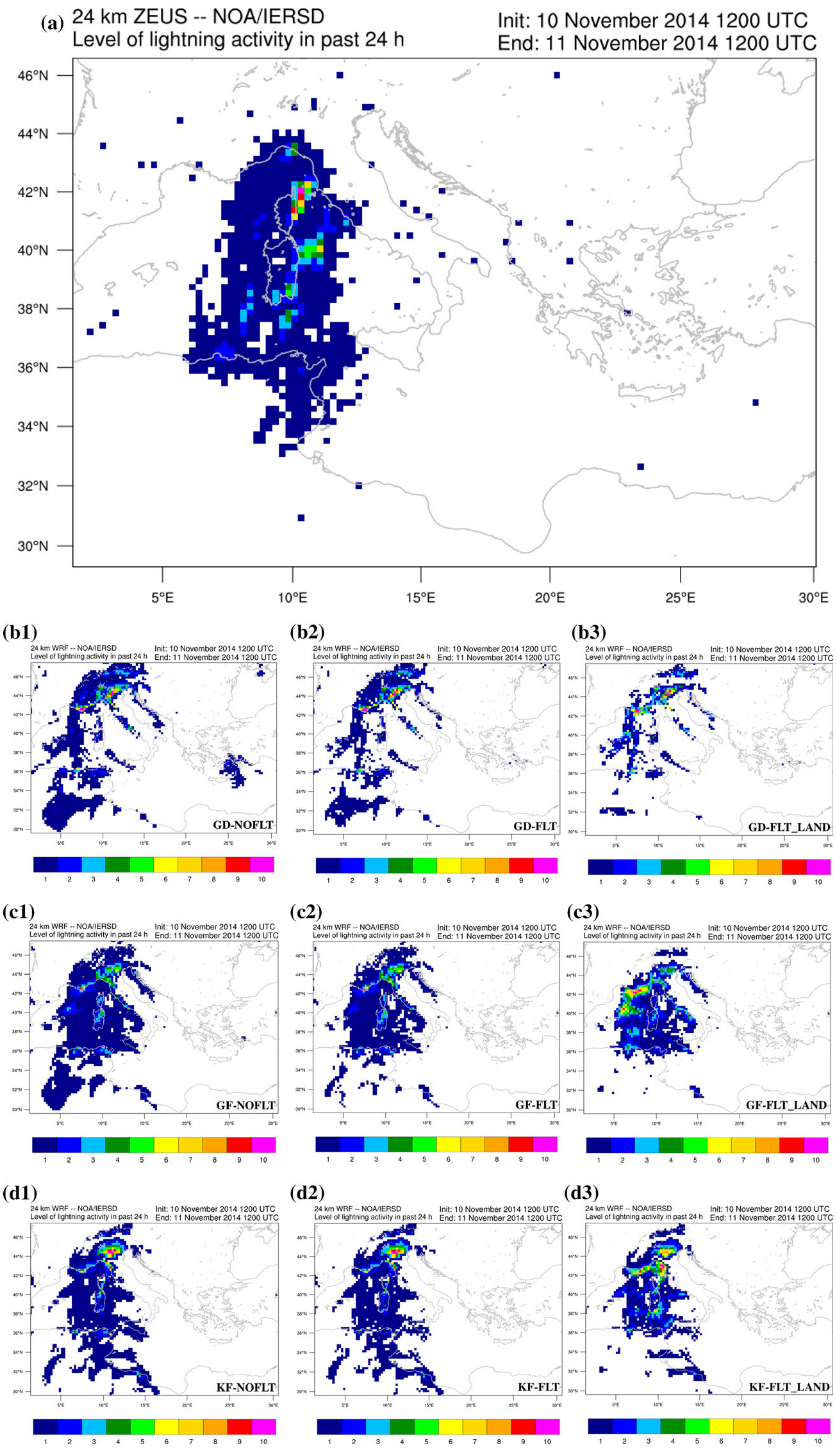
The event of November 10–11, 2014, was selected as a typical example of convection occurring in the cold period of the year. This particular event was characterized by the occurrence of mostly marine lightning over the Central Mediterranean Sea (Fig. 5a), as it is typically the case during autumn (e.g., Galanaki et al. 2015; Kotroni and Lagouvardos 2016; Price and Federmesser 2006).

Among the examined CPS, GD showed the worst performance with respect to the reproduction of the spatial distribution of lightning activity (Fig. 5b). Most notably, marine lightning was poorly forecasted. On the other hand, employment of GF (Fig. 5c) and KF (Fig. 5d) yielded a more realistic spatial pattern for LLA. For both schemes, it is worth noticing the positive impact of the masking filter, whose implementation resulted in reducing falsely forecasted lightning activity over the African part of the domain (Fig. 5c2, d2). In addition, the adoption of the modification for computing continental lightning (Sect. 3.3) further improved LLA forecasts (Fig. 5c3, d3). It is evident that KF outperformed GF, providing an overall better forecast for the spatial distribution of lightning activity. For instance, the areas of higher LLA east of Corsica and Sardegna (Fig. 5a) were better captured by KF (Fig. 5d3) than by GF (Fig. 5c3). Further, in the GF forecast (Fig. 5c) lightning was erroneously forecasted to occur along the west coast of Italy and over the Adriatic Sea, whereas the KF forecast (Fig. 5d) was found to be in better agreement with observations (Fig. 5a) over both of the above geographical regions. Last, it is worth noticing that all simulations reproduced a secondary maximum of LLA over the northwest coast of Italy, which is not present in the observations. Examination of the synoptic setup and the driving large-scale model (i.e., GFS) revealed a precipitation maximum over the area of interest, associated with the presence of a stationary front (not shown). Hence, the disagreement between the model and the observations could be partially attributed to the overestimation of the large-scale forcing influence on convective and, consequently, lightning activity.

3.5.2 Warm period case: August 12–13, 2015

The event of August 12–13, 2015, was chosen as representative of conditions that typically occur in summer. As shown in Fig. 6a, this specific case was marked by the occurrence of continental lightning over parts of Greece, Italy, France, and Spain. Compact marine lightning activity was also observed southwest of Greece.

Looking at Fig. 6, it is easy to notice that the KF CPS outperformed GD and GF in reproducing the spatial distribution of lightning activity. This is particularly true when focusing on marine lightning. Both GD (Fig. 6b) and GF (Fig. 6c) generally failed in capturing lightning activity over the sea area southwest of Greece, whereas KF provided a spatial pattern (Fig. 6d) closer to the observed (Fig. 6a). Similarly to what has been previously noted for the cold period case (Sect. 3.5.1), the implementation of the masking filter and the modified equation for deriving continental lightning reduced erroneously forecasted lightning, especially over the northern parts of the Balkan Peninsula and the


(a)
24 km ZEUS -- NOA/IERSD
Level of lightning activity in past 24 h
Init: 10 November 2014 1200 UTC
End: 11 November 2014 1200 UTC
46°N
44°N
42°N
40°N
38°N
36°N
34°N
32°N
30°N
5°E
10°E
15°E
20°E
25°E
30°E
(b1)
(b2)
(b3)
(c1)
(c2)
(c3)
(d1)
(d2)
(d3)
24 km WRF -- NOA/IERSD
Level of lightning activity in past 24 h
Init: 10 November 2014 1200 UTC
End: 11 November 2014 1200 UTC
GD-NOFLT
GD-FLT
GD-FLT_LAND
GF-NOFLT
GF-FLT
GF-FLT_LAND
KF-NOFLT
KF-FLT
KF-FLT_LAND
1 2 3 4 5 6 7 8 9 10

African coast, irrespective of the employed CPS. Considering the magnification of LLA over this maritime area, as seen when comparing Fig. 6d1–d3, this could be attributed to the reduction of predicted lightning over the northwesternmost part of the domain due to the implementation of the masking filter and the modification for continental lightning. As a result, the secondary maximum of LLA over the region southwest of Greece was magnified.

4 Conclusions

The significance of lightning for public safety and other geoscience applications has driven important progress in the development of predictive parameterizations for this natural hazard. PR92 (Price and Rind 1992, 1993, 1994) is one such parameterization that has been recently implemented in the WRF model (Wong et al. 2013). It has been preliminarily evaluated by Giannaros et al. (2015) for Greece, and despite the fact that it is considered to be a purely diagnostic lightning scheme, it showed promising potential in terms of its suitability for real-time weather forecasting applications.

In this general context, this paper presents the evaluation of an operational modeling system for lightning forecasting in Europe, built upon the WRF model and the PR92 LPS. Different parameterizations for convection were examined as potential drivers for the lightning scheme, while a modification in the computation of marine and continental lightning was also applied and assessed. The analysis focused primarily on the qualitative aspect of lightning forecasting, employing ground-based observations.

Overall, the reported results suggest a successful implementation of the WRF-based modeling system for lightning forecasting in Europe. Confirming the preliminary results of Giannaros et al. (2015), the verification of 1 year of operational data revealed that the implementation of a masking filter is necessary for obtaining reliable lightning forecasts. The positive impact of the Q_{ice}-based filter was evident in all simulations, irrespective of the employed CPS.

Regarding the sensitivity of PR92 to the parameterization of convection, the KF CPS was found to generally outperform the GD and GF schemes. The largest differences between the examined CPS were found in the warm season of the year, when the synoptic-scale forcing is generally weak and the role of the convective schemes is more important. As discussed, the superiority of KF could be possibly attributed to its trigger function that allows for a better representation of the observed convection and consequently lightning. Nevertheless, further investigation is required prior to drawing final conclusions about the actual reasoning.

This study also revealed the possible need for revisiting the PR92 LPS. In particular, it was found that, irrespective of the implemented CPS, lightning forecasts are overall more successful over the sea than over the land. Replacement of the continental lightning equation with the equation used for computing marine flash rates improved model performance. The improvement was evident during both the warm and the cold period of the year, as well as for the entire 1-year period.

Drawing the wider picture, the presented work highlights the limitations imposed on forecasting lightning, when diagnostic schemes, such as the PR92, are used. The use of various storm parameters, including cloud-top height, makes the results of any diagnostic scheme dependent on the ability of the driving NWP model to reproduce storm characteristics (Barthe et al. 2010). In turn, the representation of storms in any NWP model is a

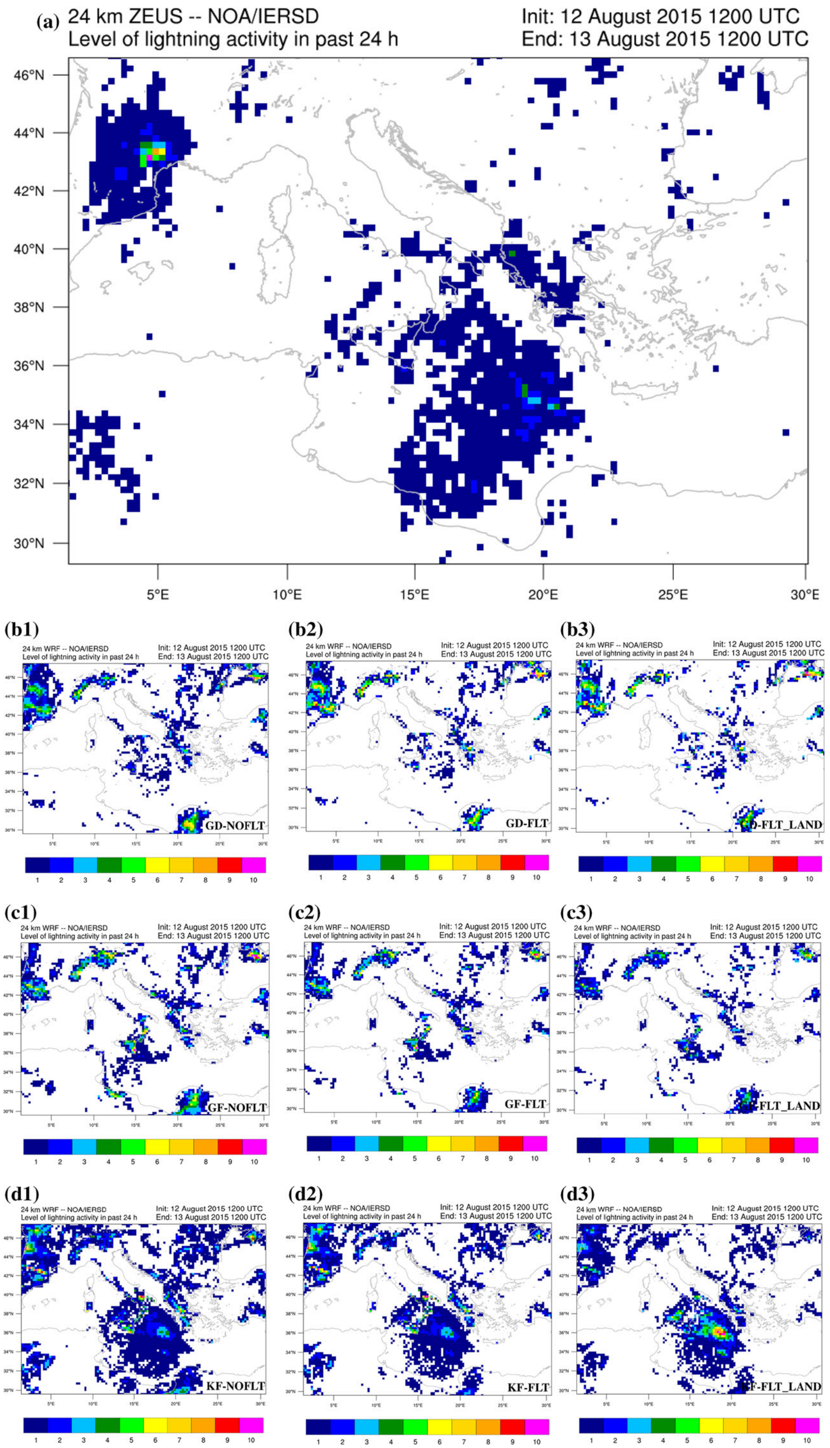


Fig. 6 Same as Fig. 5 but for the period from 12 August 1200 UTC to 13 August 1200 UTC 2015

matter of scale, which also introduces uncertainties in diagnosing lightning. Hence, ad hoc tuning is highly necessary in order to obtain realistic forecasts with a lightning scheme of similar nature to the one used in this study (Wong et al. 2013; Giannaros et al. 2015). Alternatively, explicit lightning schemes, operating at cloud-resolving scales, may be used. Such schemes are based on charge separation parameterizations and, thus, have a stronger physical foundation compared to diagnostic schemes. Additionally, they can take advantage of lightning data assimilation techniques, which have been shown to improve the quality of the resulting forecasts (e.g., Lynn et al. 2015). It is anticipated that the progress in operating forecasting systems at convection-allowing resolutions will promote shifting entirely from diagnostic to explicit lightning schemes in the near future.

Summarizing, the results of the current study are promising, but further work is certainly required. To the authors' knowledge, this is the first study that provides a detailed verification of lightning forecasts from the point of view of parameterized-convection operational weather forecasting, utilizing real-time data from a 1-year period. Hence, more similar studies are required to compare results against and identify the strengths and weaknesses of each approach. More importantly, however, the present study should be extended in the future to include other sources of data that could provide different insights on model performance. For instance, it would be of great interest to use observed cloud-top height data to further analyze the performance of the different CPS in terms of lightning forecasting.

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References

Accadia C, Mariani S, Casaioli M, Lavagnini A (2003) Sensitivity of precipitation forecast skill scores to bilinear interpolation and a simple nearest-neighbor average method on high-resolution verification grids. Weather Forecast 18:918–932

Accadia C, Mariani S, Casaioli M, Lavagnini A, Speranza A (2005) Verification of precipitation forecasts from two limited-area models over Italy and comparison with ECMWF forecasts using a resampling technique. Weather Forecast 20:276–300

Allen DJ, Pickering KE (2002) Evaluation of lightning flash rate parameterizations for use in a global chemical transport model. J Geophys Res 107:D02066

Allen DJ, Pickering KE, Duncan B, Damon M (2010) Impact of lightning NO emissions on North American photochemistry as determined using the global modeling initiative (GMI) model. J Geophys Res 115:D14062

Barthe C, Deierling W, Barth MC (2010) Estimation of total lightning from various storm parameters: a cloud-resolving model study. J Geophys Res 115:D24202

Bright D, Wandishin M, Jewell RE, Weiss SJ (2005) A physically-based parameter for lightning prediction and its calibration in ensemble forecasts. Conference on Meteorological Applications of Lightning Data, San Diego, CA, USA

Burrows WR, Price C, Wilson LJ (2005) Warm season lightning probability prediction for Canada and the Northern United States. Weather Forecast 20:971–988

Cardoso I, Pinto O Jr, Pinto IRCA, Holle R (2001) A new approach to estimate the annual number of global lightning fatalities. 14th International Conference on Atmospheric Electricity, Rio de Janeiro, Brazil

Cooper OR, Trainer M, Thompson AM et al (2007) Evidence for a recurring Eastern North America upper tropospheric ozone maximum during summer. J Geophys Res 112:D23304

Cuo L, Pagano TC, Wang QJ (2011) A review of quantitative precipitation forecasts and their use in short- to medium-range streamflow forecasting. J Hydrometeorol 12:713–728

Deierling W, Petersen WA (2008) Total lightning activity as an indicator of updraft characteristics. J Geophys Res 113:D16210

Drobyshev I, Flannigan MD, Bergeron Y, Girardin MP, Suran B (2010) Variation in local weather explains differences in fire regimes within a Quebec south-eastern boreal forest landscape. Int J Wildland Fire 19:1073–1082

Dudhia J (1989) Numerical study of convection observed during the winter monsoon Experiment using a mesoscale two-dimensional model. J Atmos Sci 46:3077–3107

Fierro AO, Mansell ER, MacGorman DR, Ziegler CL (2013) The implementation of an explicit charging and discharge lightning scheme with the WRF-ARW model: benchmark simulations of a continental squall line, a tropical cyclone, and a winter storm. Mon Weather Rev 141:2390–2415

Galanaki E, Kotroni V, Lagouvardos K, Argiriou A (2015) A 10-year analysis of cloud-to-ground lightning activity over the eastern mediterranean region. Atmos Res 166:213–222

Giannaros TM, Kotroni V, Lagouvardos K (2015) Predicting lightning activity in Greece with the weather research and forecasting (WRF) model. Atmos Res 156:1–13

Giannaros TM, Kotroni V, Lagouvardos K (2016) WRF-LTNGDA: a lightning data assimilation technique implemented in the WRF model for improving precipitation forecasts. Env Mod Soft 76:54–68

Grell GA (1993) Prognostic evaluation of assumptions used by cumulus parameterizations. Mon Weather Rev 121:764–787

Grell GA, Devenyi D (2002) A generalized approach to parameterizing convection combining ensemble and data assimilation techniques. Geophys Res Lett 29:L015311

Grell GA, Freitas SR (2014) A scale and aerosol aware stochastic convective parameterization for weather and air quality modeling. Atmos Chem Phys 14:5233–5250

Hamill TM (1999) Hypothesis tests for evaluation numerical precipitation forecasts. Weather Forecast 14:155–167

Holle RL (2008) Annual rates of lightning fatalities by country. 2nd International Lightning Meteorology Conference, Tucson, AZ, Vaisala

Hudman RC, Jacob DJ, Turquety S et al (2007) Surface and lightning sources of nitrogen oxides over the United States: magnitudes, chemical evolution and outflow. J Geophys Res. doi:10.1029/2006JD007912

Janjic ZI (1994) The step-mountain Eta coordinate model: further developments of the convection, viscous sublayer and turbulence closure schemes. Mon Weather Rev 122:927–945

Janjic ZI (1996) The surface layer in the NCEP Eta model. 11th Conference on Numerical Weather Prediction, Norfolk, VA, USA

Janjic ZI (2002) Nonsingular implementation of the Mellor-Yamada level 2.5 scheme in the NCEP Meso model. NCEP Office Note, No 437

Kain JS (2004) The Kain–Fritsch convective parameterization: an update. J Appl Meteorol 43:170–181

Kotroni V, Lagouvardos K (2001) Precipitation forecast skill of different convective parameterization and microphysical schemes: application for the cold season over Greece. Geophys Res Lett 28:1977–1980

Kotroni V, Lagouvardos K (2008) Lightning occurrence in relation with elevation, terrain slope and vegetation cover in the mediterranean. J Geophys Res Atmos 113:D21118

Kotroni V, Lagouvardos K (2016) Lightning in the mediterranean and its relation with sea-surface temperature. Environ Res Lett 11:L034006

Lagouvardos K, Kotroni V, Betz HD, Schmidt K (2009) A comparison of lightning data provided by ZEUS and LINET networks over Western Europe. Nat Hazards Earth Syst Sci 9:1713–1717

Leutbecher M, Palmer TN (2008) Ensemble forecasting. J Comput Phys 227:3515–3539

Liang X-Z, Li L, Dai A, Kunkel KE (2004) Regional climate model simulation of summer precipitation diurnal cycle over the United States. Geophys Res Lett 31:L24208

Liu C, Zipser EJ, Nesbitt SW (2007) Global distribution of tropical deep convection: different percpectives from TRMM infrared and radar data. J Climate 20:489–503

Liu W, Wang S, Zhou Y, Wang L, Zhu J, Wang F (2016) Lightning-caused forest fire risk rating assessment based on case-based reasoning: a case study in DaXingAn Mountains of China. Nat Hazards 81:347–363

Lynn B, Kelman G, Ellrod G (2015) An evaluation of the efficiency of using observed lightning to improve convective lightning forecasts. Weather Forecast 30:405–423

Mansell ER, Ziegler CL (2013) Aerosol effects on simulated storm electrification and precipitation in a two-moment bulk microphysics scheme. J Atmos Sci 70:2032–2050

Mazarakis N, Kotroni V, Lagouvardos K, Argiriou AA (2009) The sensitivity of numerical forecasts to convective parameterization during the warm period and the use of lightning data as an indicator for convective occurrence. Atmos Res 94:704–714

McCaul Jr EW, Goodman SJ, LaCasse KM, Cecil DJ (2009) Forecasting lightning threat using cloud-resolving model simulations. Weather Forecast 24:709–729

Mills B, Unrau D, Parkinson C, Jones B, Yessis J, Spring K, Pentelow L (2008) Assessment of lightning-related fatality and injury risk Canada. Nat Hazards 47:157–183
Mlawer EJ, Taubman SJ, Brown PD, Iacono MJ, Clough SA (1997) Radiative transfer for inhomogeneous atmospheres: RRTM, a validated correlated-k model for the longwave. J Geophys Res 102:166663–166682
Navarrete-Aldana N, Cooper MA (2014) Lightning fatalities in Colombia from 2000 to 2009. Nat Hazards 74:1349–1362
Papagiannaki K, Lagouvardos K, Kotroni V (2013) A database of high-impact weather in Greece: a descriptive impact analysis for the period 2001-2011. Nat Hazards Earth Syst Sci 13:727–736
Pei L, Moor N, Zhong S, Luo L, Hyndman DW, Heilman WE, Gao Z (2014) WRF model sensitivity to land surface model and cumulus parameterization under short-term climate extremes over the Southern Great Plains of the United States. J Clim 27:7703–7724
Petersen WA, Christian HJ, Rutledge SA (2005) TRMM observations of the global relationship between ice water content and lightning. Geophys Res Lett 32:L14819
Peterson D, Wang J, Ichoku C, Remer LA (2010) Effects of lightning and other meteorological factors on fire activity in the North American boreal forest: implications for fire weather forecasting. Atmos Chem Phys 10:6873–6888
Prentice SA, Mackerras D (1977) The ratio of cloud to cloud-ground lightning flashes in thunderstorms. J Appl Meteorol 16:545–549
Price C, Rind D (1992) A simple lightning parameterization for calculating global lightning distributions. J Geophys Res 97:9919–9933
Price C, Rind D (1993) What determines the cloud-to-ground lightning fraction in thunderstorms? Geophys Res Lett 20:463–466
Price C, Rind D (1994) Modeling global lightning distributions in a general circulation model. Mon Weather Rev 122:1930–1939
Price C, Federmesser B (2006) Lightning-rainfall relationships in Mediterranean winter thunderstorms. Geophy Res Lett 33:L07813
Rodger CJ, Brundell JB, Dowden RL, Thomson NR (2004) Location accuracy of long distance VLF lightning location network. Ann Geophys 22:747–758
Ryu JH, Jenkins GS (2005) Lightning-tropospheric ozone connections: EOF analysis of TCO and lightning data. Atmos Environ 39:5799–5805
Salerno J, Msalu L, Caro T, Mulder MB (2012) Risk of injury and death from lightning in Northern Malawi. Nat Hazards 62:853–862
Skamarock WC, Klemp JB, Dudhia J, Gill DO, Barker DM, Duda MG, Huang XY, Wang W, Powers JG (2008) A description of the Advanced Research WRF version 3. NCAR Technical Note:NCAR/TN-475 + STR, Mesoscale and Microscale Meteorology Division, National Centre for Atmospheric Research, Boulder, CO, USA
Tewari M, Chen F, Wang W, Dudhia J, LeMone MA, Mitchell K, Ek M, Gayno G, Wegiel J, Cuenca RH (2004) Implementation and verification of the Unified NOAH land surface model in the WRF model. 20th Conference on Weather Analysis and Forecasting/16th Conference on Numerical Weather Prediction
Thompson G, Field PR, Rasmussen RM, Hall WD (2008) Explicit forecasts of winter precipitation using an improved bulk microphysics scheme-Part II: implementation of a new snow parameterization. Mon Weather Rev 136:5095–5115
Tinnmaker MIR, Aslam MY, Chate DM (2015) Lightning activity and its association with rainfall and convective available potential energy over Maharashtra, India. Nat Hazards 77:293–304
Wong J, Barth M, Noone D (2013) Evaluating a lightning parameterization based on cloud-top height for mesoscale numerical model simulations. Geosci Model Dev 6:429–443
Yair Y, Lynn B, Price C, Kotroni V, Lagouvardos K, Morin E, Mugnai A, Llasat MC (2010) Predicting the potential for lightning activity in mediterranean storms based on the weather research and forecasting (WRF) model dynamic and microphysical fields. J Geophys Res Atmos 115:D04205
Zepka GS, Pinto O Jr, Saraiva ACV (2014) Lightning forecasting in southeastern Brazil using the WRF model. Atmos Res 135–136:344–362
Zhang Y, Meng Q, Ma M, Zhang Y (2011) Lightning casualties and damages in China from 1997 to 2009. Nat Hazards 57:465–476