Potential of cloud-resolving model parameters to be used as proxies for the total flash rate

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ABSTRACT: Forecasting the electrical activity of a storm is a difficult task due to the complexity of the cloud electrification and lightning propagation processes. Today, only few models are able to explicitly simulate the complete life cycle of electric charges in the clouds. But, mainly due to their computational cost, these schemes can not be used in operational models. Then, it is tempting to rely on correlations between the flash rate and some dynamical and microphysical parameters.

The objective of our study is to investigate if one elaborated dynamical/microphysical parameter but easily available in the models, can serve as a proxy to diagnose for the total lightning activity. To this aim, simulations of several thunderstorms are then performed with Meso-NH and its electrical scheme CELLS. Some parameters and the total flash rate predicted by the model are recorded and the potential of each parameter to serve as a marker of the lightning activity is investigated. The importance of analyzing the lightning activity in individual convective cells is shown, in particular when performing simulation initialized with meteorological analysis and/or over large domains. A potential application of lightning proxies is presented throught maps of lightning flash density.

INTRODUCTION

Currently, few mesoscale models include an explicit electrical scheme [*Mansell et al.*, 2002; *Barthe et al.*, 2012]. However, the complexity and huge numerical cost of these schemes prevent them from being used in numerical weather prediction (NWP) models. The flash rate is essential to model the nitrogen oxides produced by lightning flashes in mesoscale and climate models. Moreover, such relationships could be used to estimate the ice content in deep convective clouds or to determine the stage or severity of a storm for nowcasting purposes. There is also an increasing interest for lightning data assimilation [*Mansell et al.*, 2007; *Pessi and Businger*, 2009; *Fierro et al.*, 2013]. In most cases, deep convection is simply triggered or inhibited while modifying the humidity profile. If reliable proxies are highlighted, it may be more relevant to adjust these parameters depending on the detection or not of flashes in the region.

An alternative to explicit electrical schemes consists in determining dynamical and/or microphysical proxies of the electrical activity. Numerous studies based on observation data have already attempted to link the flash rate to storm parameters such as the maximum vertical velocity [*Price and Rind*, 1992], the updraft volume [*Deierling et al.*, 2008], the precipitation ice mass [*Wiens et al.*, 2005; *Deierling et al.*, 2005; *Latham et al.*, 2007] or the convective precipitation rate [*Petersen and Rutledge*, 1998; *Soula and Chauzy*, 2001]. Recently, *Deierling et al.* [2008] have studied the relationships between electrical activity and ice mass fluxes in eleven storms in North Alabama and the Great Plains of Colorado/Kansas using polarimetric ground radars and lightning detection networks. A linear regression best fitted the total flash rate and the precipitation ice mass, the non-precipitation ice mass and the product of the precipitation and non-precipitation ice mass fluxes. This confirmed the hypothesis from *Blyth et al.* [2001], *Petersen and Rutledge* [2001] and *Latham et al.* [2007] who theoretically showed the existence of a linear relationship between

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electrical activity and precipitation ice mass. *Barthe et al.* [2010] used the WRF model to investigate these relationships. They attempted to compute the flash rate from model parameters and the various relationships in the litterature. Six parameters have been analyzed and they showed that the best parameters varied from a storm to another with significant differences in trend and amplitude. These differences could be due both to errors in the model and in the observations.

The objective of our study is to investigate if one dynamical/microphysical parameter but easily available in the models, can serve as a proxy to diagnose for the total lightning activity. The present study frees from part of the constraints limiting the previous studies. In particular, the consistency betweeen dynamical, microphysical and electrical fields is ensured by the use of a cloud-resolving model coupled to an explicit electrical scheme. Due to increasing supercomputer capabilities, horizontal domains becomes larger, and several convective cells can be simultaneously present in the model domain. Two different approaches are compared in the following: a global approach and a per-cell approach for which an algorithm to detect convective cells has been developed. Then, the regression equations obtained in this study are used to produce flash density maps based on parameters easily computed from high resolution models outputs.

METHODOLOGY

The Meso-NH model

The Meso-NH model [*Lafore et al.*, 1998] (`http://mesonh.aero.obs-mip.fr/`) is able to simulate idealized precipitating systems at high resolution and real meteorological events on large domains with complex terrain. In the later case, Meso-NH needs meteorological analyses for the initialization and the open boundary conditions while high resolution, typically the kilometer scale, is achieved automatically via the grid nesting facility. Since the code is fully vectorized and efficiently parallelized [*Jabouille et al.*, 1999], the 3-D evolution of any cloud system is currently simulated on large grids with hundreds of points in each horizontal direction.

The CELLS scheme is integrated in Meso-NH and allows to simulate explicitly the electrical activity of thunderstorms. The mass charge density (Q_x in C kg^{-1}) is the prognostic electrical state variable related to the mixing ratio r_x of species x (cloud droplets, rain, ice crystals, snow/aggregates, graupel). A set of prognostic equations for Q_x is included. Details about the electrification scheme and the electric field computation can be found in *Barthe and Pinty* [2007a]. In addition, conservation equations for both positive and negative ions concentrations [*Helsdon and Farley*, 1987] are added. In particular, each electrified cell in the domain of simulation is delineated to enable a parallel treatment of the lightning [*Barthe et al.*, 2012]. The flashes propagate first vertically as bidirectional leaders, and branches are generated in regions of high charge density. The number of branches is limited by a fractal law. The total charge in excess of a threshold and neutralized in the lightning flash, is first redistributed to the ions of opposite sign and to the hydrometeor category but in proportion of their surface area.

Case studies

Eight different kind of storms (supercells, multicells, single cells) from different regions have been investigated to obtain a generalized relationship fitted for any storm.

The supercellular storm (KW78) is initialized in an homogeneous environment using the sounding from *Klemp and Wilhelmson* [1978]. It is characterized by a strong instability, a rotating wind shear and a very dry atmosphere aloft and that leads to the splitting of the storm [*Klemp and Wilhelmson*, 1978].

The initial sounding of the multicellular storm (WK84) comes from *Weisman and Klemp* [1984]. The environment is characterized by favorable dynamical conditions for the development of multicells.

The 19 July 1981 CCOPE (Cooperative Convective Precipitation Experiment) storm developed in a moderate unstable environment characterized by weak wind shear. The simulated cloud system is a short-lived single-cell thunderstorm [*Dye et al.*, 1986]. The sounding used to initialize the model run comes from *Helsdon and Farley* [1987]. The microphysical, dynamical and electrical features of this storm have been investigated by *Helsdon and Farley* [1987] and *Miller et al.* [2001] from numerical simulations.

The 18 July 2002 storm occurred in the southern Florida during the CRYSTAL-FACE (Cirrus Regional Study of Tropical Anvils and Cirrus Layers-Florida Area Cirrus Experiment) field campaign. The environment is initialized by the sounding from Miami airport at 15 UTC [*Leroy et al.*, 2009]. The cloud top reached 14 km-altitude and a large anvil developed southwest, downwind from the convective core [*Heymsfield et al.*, 2005].

The 21 July 1998 EULINOX (European Lightning Nitrogen Oxides project) storm was a thunderstorm which occurred in the Munich region, Germany. The storm splitted after a period of intensification: the northern cell turned into a multicellular storm and the southern cell became a supercell [*Höller et al.*, 2000]. The lightning activity of this storm has been subject to observational [*Dotzek et al.*, 2001] and modeling [*Fehr et al.*, 2004; *Ott et al.*, 2007] works.

The 10 July 1996 STERAO (Stratospheric-Tropospheric Experiment: Radiation, Aerosols and Ozone) storm was initially a multicellular storm but turned into a supercell after 2 hours [*Dye et al.*, 2000]. The thermodynamic conditions are given by the sounding from *Skamarock et al.* [2000]. As for the EULINOX storm case, the lightning activity of the storm has been widely studied [*Defer et al.*, 2001; *Deierling et al.*, 2008; *Barthe et al.*, 2007c, 2010].

The 29 June 2000 STEPS (Severe Thunderstorm Electrification and Precipitation Study) storm is a supercell that occurred near the borders of Colorado, Nebraska and Kansas. The sounding used herein comes from *Kuhlman et al.* [2006]. The kinematic, microphysical and electrical aspects of this storm have been studied by *Tessendorf et al.* [2005] and *Wiens et al.* [2005]. The modeling part was performed by *Kuhlman et al.* [2006] who focused on the sensitivity of the charge structure to the non-inductive charging schemes.

The 30 November 2001 Hector storm is the only storm initialized with meteorological analysis. This kind of thunderstorm uses to form at the beginning of the afternoon over the Tiwi islands (north-west of Darwin, Australia) during the pre-monsoon period. This storm is characterized by a multicellular structure with a lot of small convective cells.

Microphysical and dynamical parameters

Several microphysical and dynamical parameters easily deduced from model output have been tested in this study: the cloud top height, the maximum vertical velocity, the updraft volume with vertical velocity (w) higher than 10 m s^{-1}, the non-precipitation and precipitation ice mass fluxes product, the graupel mass, the ice water path, the 40-dBZ radar echo volume, and the mean updraft at the base of the charging zone. These eight parameters have been chosen because they have already been widely used in the literature or because they seem to be representative of the electrification process.

The cloud top height [*Price and Rind*, 1992; *Williams et al.*, 1985] and the maximum updraft speed [*Price and Rind*, 1992] have been widely used to estimate the amount of nitrogen oxides produced by lightning flashes [*Pickering et al.*, 1998; *Fehr et al.*, 2004; *Salzmann et al.*, 2008; *Barthe and Barth*, 2008]. The updraft volumes have been shown to be well correlated to the total flash rate by *Wiens et al.* [2005] and *Deierling et al.* [2005]. Hypothesizing that the non-inductive mecanism is the only process responsible for charge separation, *Blyth et al.* [2001]; *Latham et al.* [2004] proposed an analytical relationship linking the total flash rate to the non-precipitating and precipitating ice mass flux product. Combining total lightning observations and polarimetric radar data for 11 continental storms, *Deierling et al.* [2008] have concluded that the precipitation and non-precipitation ice mass flux product is highly correlated to the total flash rate.

They also showed that the graupel mass is also linearly correlated to the total flash rate. Combining data from PR and LIS onboard TRMM, *Petersen et al.* [2005] deduced a linear relationship between the flash density and the ice water path (IWP, in g m^{-2}). Usually, the 40 dBZ radar echo volume is shown to be linked to the cloud-to-ground activity [*Yang and King*, 2010; *Lang and Rutledge*, 2011; *Buguet*, 2002]. Recently, using a 1-D model with explicit microphysical and electrical processes, *Formenton et al.* [2013] determined a minimum threshold of the mean updraft at the base of the charging zone for lightning production.

Methodology

To obtain results as consistent as possible, the simulations have been performed with common tuning. The horizontal resolution is fixed to 1 km $\times$ 1 km, the time step is 2.5 s, and the microphysical processes are described following the single-moment bulk scheme of *Pinty and Jabouille* [1998]. Seven storms have been simulated in an idealized framework, while the Hector storm is initialized and coupled to ECMWF analysis. The eight simulated storms are presented in the following section and the numerical configuration associated to each storm is displayed in Table 1.

Table 1: List of the simulated storms and associated characteristics of the model domain.

Storms	Date	Region	Type	Domain (km^2)	Vertical grid
CCOPE	19 July 1981	Montana, USA	isolated cell	64 $\times$ 64	50 points
CRYSTAL-FACE	18 July 2002	Florida, USA	isolated cell	128 $\times$ 128	80 points
EULINOX	21 July 1998	Munich, Germany	multicell	180 $\times$ 180	50 points
HECTOR	30 November 2005	Tiwi islands	multicell	192 $\times$ 96	70 points
KW78	-	-	multicell	64 $\times$ 64	40 points
STEPS	29 June 2000	Colorado, USA	supercell	360 $\times$ 360	55 points
STERAO	10 July 1996	Colorado, USA	multi- and supercell	160 $\times$ 160	50 points
WK84	-	-	multicell	64 $\times$ 64	36 points

First, the eight simulated storms have been evaluated. The KW78, WK84, EULINOX and STERAO storms have been successfully simulated with Meso-NH coupled to CELLS by *Barthe and Pinty* [2007a], *Barthe and Pinty* [2007b], *Barthe et al.* [2007c], *Pinty and Barthe* [2008], *Barth et al.* [2007] and *Barthe et al.* [2012]. The dynamical, microphysical and electrical structure and evolution of the CCOPE, CRYSTAL-FACE, STEPS and HECTOR storms have been evaluated against the available literature (see the references above). All these simulated storms successfully reproduced the main characteristics of the observed storms.

Two approaches have been used in this study. Firstly, the storm was globally considered. This means that the microphysical and dynamical parameters, and the total flash rate were computed every 5 minutes over the whole domain.

Secondly, each storm was divided in individual convective cells. Indeed, a simulated thunderstorm is usually made up of different convective cells at different stages, in particular with the current trend of very large horizontal domains. To isolate the convective cells, an algorithm has been developed. This algorithm is based on *Barthe et al.* [2012] for the detection of electrified cells, but adapted to the situation where an explicit electrical scheme is not present in the model. The maximum radar reflectivity (Z_{max}) is first computed: the maximum radar reflectivity for each column is projected onto the surface level (Fig. 1a). A convective cell is detected if $Z_{max} > 40$ dBZ. Contiguous grid points are added to the convective cell if they meet the condition $Z_{max} > 30$ dBZ. This procedure is repeated along the horizontal until no more grid point can be added to the cell surface (Fig. 1b). Then the algorithm loops to analyse the maximum radar reflectivity out of the detected convective cell to find out if another disjuncted cell exists in the whole domain. The 8 parameters are thus computed over each individual convective cell (Fig. 1c).

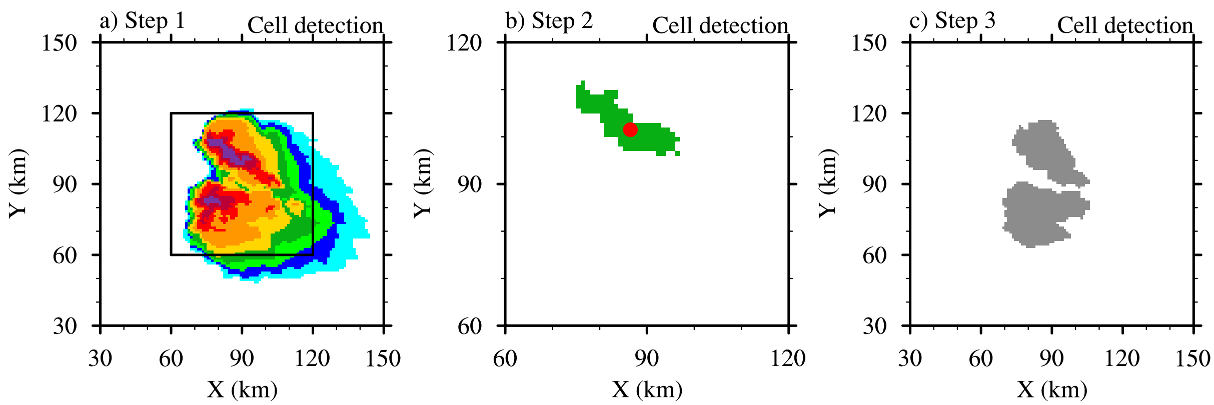

Figure 1: Schematic representation of the cell detection algorithm: (a) maximum radar reflectivity (Z_{max} in dBZ), (b) footprint of a contiguous field of reflectivity values higher than 30 dBZ (green pixels) including at least one value reaching 40 dBZ (red dot), and (c) footprint of identified convective cells (grey).

WHAT INFORMATION A PER-CELL ANALYSIS BRINGS

Table 2 displays the correlation coefficient and regression equation for each parameter and for the global and per cell analysis. If we first focus on the global analysis, three parameters exhibit correlation coefficients around 0.8: the ice mass flux product (r = 0.83), the updraft volume (r = 0.81) and the graupel mass (r = 0.79). The other parameters have correlation coefficient less than 0.5. At the domain scale, these parameters are thus poor proxies of the total flash rate. It is also important to note that the Y-intercept is positive and rather high which would mean that lightning flashes could occur while the dynamical/microphysical parameter is null. On the contrary, for w_{max} for example, the Y-intercept is negative, meaning a vertical velocity threshold is expected before lightning flashes to be triggered. However, the value of the Y-intercept would mean a maximum vertical velocity of $\sim$ 17.5 and 11 m s^{-1} for the global and per-cell analysis, respectively, is necessary to produce lightning flashes, the latter being consistent with the literature [*Zipser and Lutz*, 1994].

The per-cell analysis generally increases the correlation coefficient compared to the global analysis (Table 2). For the cloud top height and the ice water path, the correlation coefficient is dramatically increased but remains less than 0.5 when the per cell analysis is applied. The parameters with high correlation coefficient in the global analysis remains the best estimated proxies. However, the correlation coefficient associated to these parameters does not exhibit a significant increase. It even decreases for the ice mass flux product (0.83 *vs.* 0.77). For most parameters, it is important to note the decrease of the Y-intercept in the regression equation compared to the global analysis. This is consistent with the production of lightning flashes since cloud electrification needs the presence of updrafts and ice particles.

Figure 2 shows the total flash rate vs. 4 selected parameters both for the global and per-cell analysis for the 8 storms. The main difference between the two approaches is obvious for the STERAO, EULINOX and HECTOR storms. Since they are made up of several convective cells at different evolution stage, the per-cell analysis tends to reduce both the flash rate and the parameter value, adding a significant number of points to the bottom-left corner of the plots. This is particularly true for the STERAO storm (blue

Table 2: Correlation coefficients and expressions for the linear fits of total flash rate and the 8 model parameters for the global and per-cell analysis.

Parameter	Global analysis		Per cell analysis	
	r	regression equation	r	regression equation
Cloud top height	0.06	1.99 x - 18.01	0.36	3.80 x - 20.99
w_{max}	0.42	2.42 x - 42.30	0.52	1.52 x - 16.30
Updraft volume	0.81	2.07 10^{-10} x + 10.33	0.84	1.94 10^{-10} x + 1.87
Graupel mass	0.79	7.56 10^{-9} x - 12.07	0.80	8.90 10^{-9} x - 2.01
Ice mass flux product	0.83	1.80 10^{-19} x + 13.51	0.77	2.56 10^{-19} x + 7.80
Ice water path	0.28	8.94 x + 4.42	0.50	4.44 x + 4.99
40 dBZ echo volume	0.32	4.86 10^{-11} x + 26.87	0.51	8.17 10^{-11} x + 5.41
Mean updraft	0.24	67.44 x + 23.75	0.34	6.42 x + 2.03

triangles) that exhibits a multicellular structure at the beginning of its lifecycle. This multicell is composed of three aligned convective cells with more or less the same lightning activity. The HECTOR storm (green diamonds) behaves differently. It is made up of a main large convective cells which produces most of the lightning activity. Other smallest convective cells pops up in the domain, but with sporadic and low flash rates.

Several studies have already shown the potential of updraft volume [*Lang and Rutledge*, 2002; *Wiens et al.*, 2005; *Tessendorf et al.*, 2005; *Kuhlman et al.*, 2006; *Deierling and Petersen*, 2008], graupel or precipitation ice mass [*Nesbitt et al.*, 2000; *Petersen and Rutledge*, 2001; *Deierling et al.*, 2005; *Petersen et al.*, 2005; *Wiens et al.*, 2005; *Latham et al.*, 2007; *Deierling et al.*, 2008] and non-precipitation and precipitation ice mass flux product [*Blyth et al.*, 2001; *Latham et al.*, 2007; *Deierling et al.*, 2008; *Barthe and Barth*, 2008] to serve as proxies of the total flash rate. These three parameters are linked to cloud electrification through the non-inductive process which is supposed to be the most efficient mechanism to electrify the cloud [*Reynolds et al.*, 1957; *Takahashi*, 1978; *Saunders et al.*, 1991, among others]. Non-inductive processes need the simultaneous presence of graupel, ice crystals and supercooled water. Only a sustained updraft allows this condition to be realized. In the presence of an intense updraft above the 0°C isotherm, more supercooled water is transported in the charging zone. Thus, there is a large number of ice particles in the charging zone, and a higher collision rate between graupel and ice crystals Moreover, increasing the updraft strength would result in an rising supercooled water content, favoring riming. In addition, the latent heating release associated to condensation/freezing may enhance the updraft strength.

The maximum vertical velocity and the cloud top height have been widely used to parameterize the nitrogen oxides produced from lightning flashes [*Pickering et al.*, 1998; *Fehr et al.*, 2004; *Salzmann et al.*, 2008; *Barthe and Barth*, 2008]. Based on *Vonnegut* [1953] theory, *Williams et al.* [1985] and *Price and Rind* [1992] have shown that the cloud top height could be used to parameterize the flash rate with a power-law relationship. However, *Price and Rind* [1992] separated continental storms from maritime storms, leading to two distinct relationships. For maritime storms, *Boccippio* [2001] has shown that the vertical velocities deduced from the *Price and Rind* [1992] relationship were unrealistic. *Price and Rind* [1992] also proposed a relationship linking the maximum vertical velocity (w_{max}) and the cloud top height. Thus, the flash rate could be parameterized from w_{max}: $f = 5 \times 10^{-6} w_{max}^k$. The value of k is empirical and deduced from satellite data ; following *Price and Rind* [1992], $k = 4.5$ for continental storms. Based on total lightning and radar polarimetric data of 11 continental storms, *Deierling et al.* [2008] analyzed the link between lightning activity and maximum vertical velocity and found that a linear regression best fitted. However, from their

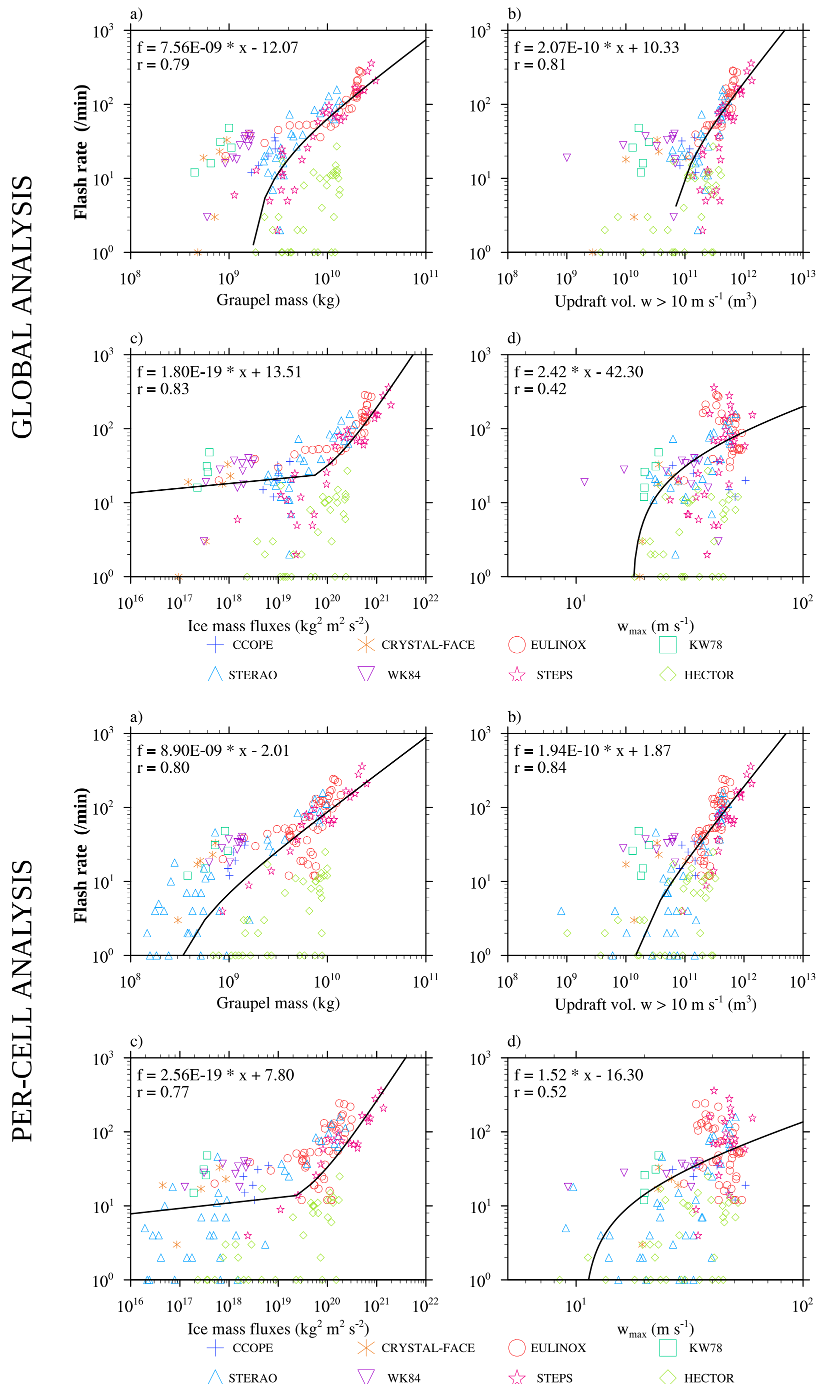

Figure 2: Global (left) and per-cell (right) analysis: total flash rate (fl. min^{-1}) vs. a) the graupel mass (kg), b) the updraft volume for $w > 10$ m s^{-1} (m^3), c) the precipitation and non-precipitation ice mass flux product (kg^2 m^2 s^{-2}), and d) the maximum vertical velocity (w_{max} in m s^{-1}). Each storm is represented by a colored marker (see the legend). For each parameter, the correlation coefficient (r) and the linear regression equation are displayed.

modelling study of the 29 June 2000 STEPS storm, *Kuhlman et al.* [2006] did not find any correlation between the total flash rate and w_{max}. Our results are in agreement with the conclusions of *Kuhlman et al.* [2006].

Using a 1-D numerical cloud electrification model, *Formenton et al.* [2013] suggested that there exists a minimum value of the mean vertical velocity at the base of the charging zone (V_{meanZC}) that allows a given total flash rate. They argue the updraft presence at the bottom of the charging zone supplies moisture and supercooled droplets, and sustains rimed particles within the charging zone. Thus, this would reinforce charge separation. However, they found a quadratic relation between V_{meanZC} and the total flash rate while we only tested linear relationship in our study.

Recent studies have shown the high radar reflectivity volume was correlated to the CG lightning activity. *Yang and King* [2010] obtained their best results using the 40 dBZ volume to estimate the CG flash rate. The presence of a 40 dBZ radar echo above the freezing level could be a sufficient criteria for CG production [*Lang and Rutledge*, 2011]. An increase in the 40-dBZ echo volume would be associated to more graupel and supercooled water content in the charging zone which would favor cloud electrification. Our study does not show a good correlation between the flash rate and the 40 dBZ echo volume, but we studied the total flash rate while *Yang and King* [2010] and *Lang and Rutledge* [2011] focused on the CG activity.

All these results have been obtained using the *Takahashi* [1978] parameterization for the non-inductive process. However, we performed the same simulations and applied the same methodology with the *Saunders et al.* [1991] parameterization. The updraft volume, graupel mass and precipitation and non-precipitation ice mass flux product remain the parameters with the best correlation coefficients (not shown). The regression equations are modified due to different flash rates produced in the two non-inductive parameterizations. Nevertheless, it is important to note that the flash rates simulated with the *Takahashi* [1978] parameterization and the *Saunders et al.* [1991] parameterization are well linearly correlated (r = 0.8, see Fig. 3).

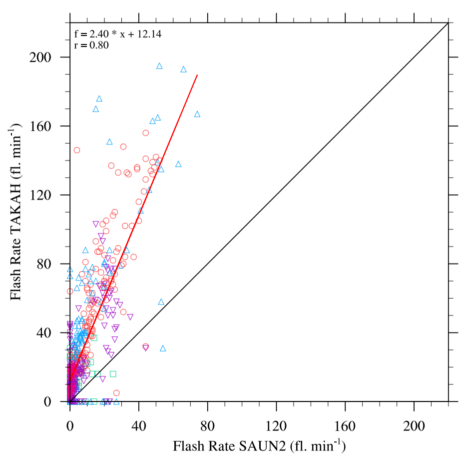

Figure 3: Total flash rate using the parameterization of *Takahashi* [1978] vs. total flash rate using the parameterization of *Saunders et al.* [1991]. See Fig. 2 for the correspondence between the markers and the storms. The red and black lines correspond to the linear regression curve and to the $y = x$ line, respectively.

TOWARD LIGHTNING RISK MAPS IN NWP...

A potential application of these lightning proxies could be found in nowcasting severe storm events. Every 5-min, the best parameters are computed in each detected convective cell. The linear regression equations listed in Table 2 are applied to get an estimated total flash rate for each cell. A flash density (fl. km^{-2}) is spread over the whole surface of the convective cell by dividing the total flash rate per convective cell by the surface of the cell. Then, a flash density map for the whole storm duration is obtained through the sum of the flash density per pixel every 5 min.

Figure 4 shows the flash density from Meso-NH-CELLS, and deduced from the graupel mass and the updraft volume, for the 8 simulated storms. Only the potential of graupel mass and updraft volume to serve as a proxy of total flash density is investigated in this section. For graupel mass, two groups of storms can be distinguished. The first group (CCOPE, KW78) underestimates the flash density. On Fig. 2, these two storms have all their markers above the regression line, meaning this fitting curve will tend to overestimate their flash rate. The second group (CRYSTAL-FACE, EULINOX, STEPS, STERAO and WK84) shows a good agreement between the estimated flash rate from the graupel mass and the flash density computed by CELLS. Both the extension of the convective cells and the amplitude of the flash density are well reproduced.

The updraft volume tends to overestimate the total flash density for all storms except KW78.

CONCLUSIONS

This study analysed the potential of several dynamical and microphysical parameters extracted from high resolution numerical model outputs to serve as proxies of the total flash rate. The eight parameters have been chosen because they have been widely studied in the past or because they are related to the non-inductive mechanism thought to be responsible for cloud electrification. This is the first study that attempt to find proxies of the total flash rate only based on cloud-resolving model simulations. This ensures the consistency between the dynamical and microphysical fields simulated by the Meso-NH model and the electrical activity issued from the CELLS scheme coupled to Meso-NH. Eigth different storms have been simulated and the correlation between the total flash rate and the eight parameters are evaluated both at the global and cell scale.

It is shown that the parameter-flash rate relationship at the convective cell scale increases the correlation coefficient for all parameters except the ice mass flux product. Two parameters exhibit high correlation coefficient: the graupel mass (r = 0.80) and the updraft volume (r = 0.84). They have been used to plot flash density maps for the eight storms. First results show a good agreement for the total flash density computed by CELLS and the one deduced from the graupel mass. The updraft volume tends to produce higher flash density than simulated by Meso-NH-CELLS. However, it must be noted that the regression equation have been applied as it is, and no tuning has been made.

More case studies are needed to ensure that these relationships be invariant between land and ocean, and between mid-latitude and tropical storms. Ongoing simulations of electrified HyMeX storms and tropical cyclones will be helpful to validate the cell detection algorithm and to find a robust relationship between model parameters and total flash rate.

ACKNOWLEDGMENTS: Computations have been performed on the supercomputer facilities of Université de la Réunion and Météo-France.

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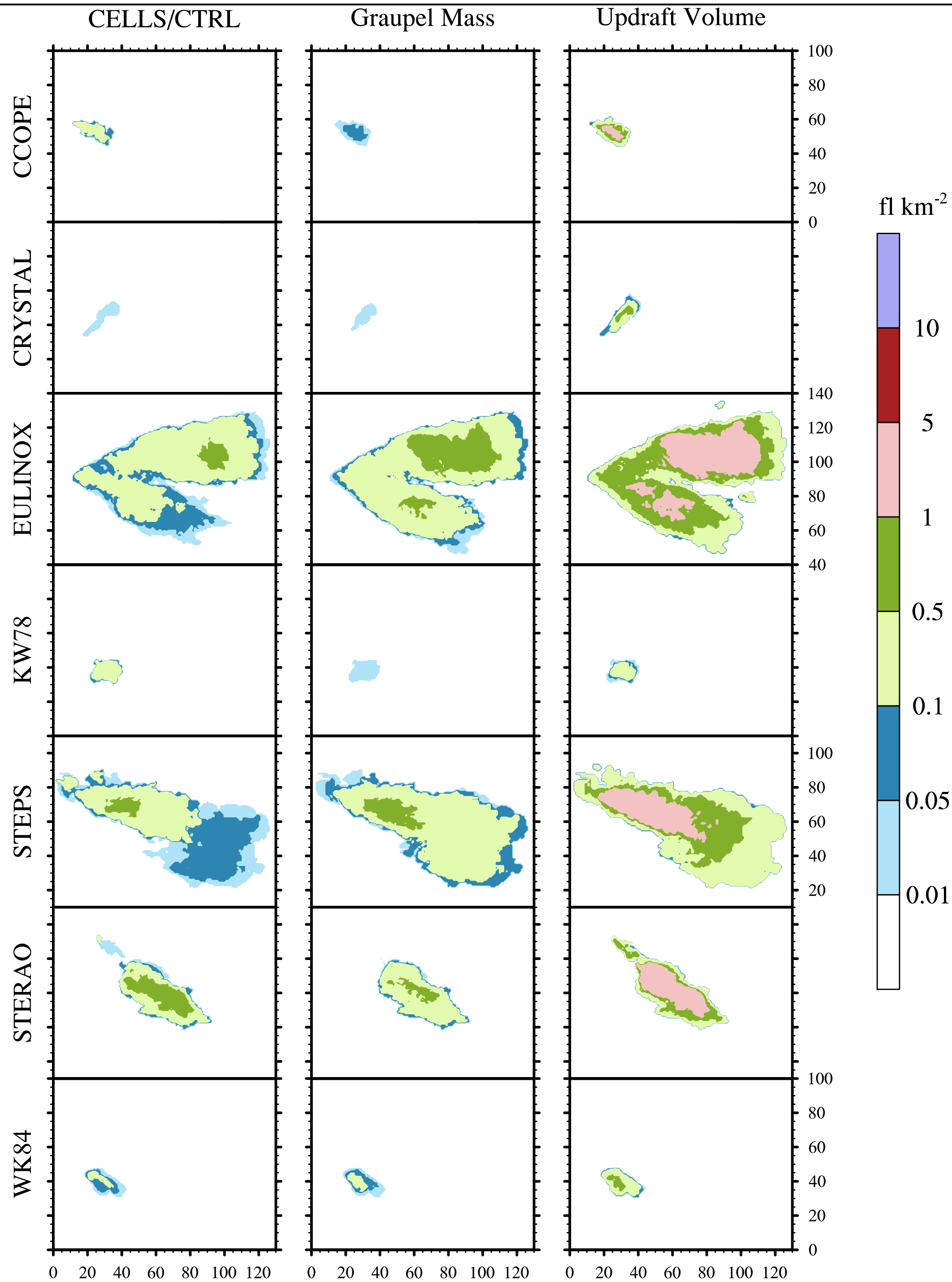

Figure 4: Flash density (fl. km^{-2}) computed from the explicit electrical scheme CELLS (left column), from the graupel mass (middle column) and from the updraft volume (right column) for the 8 simulated storms.

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