Influence of tilting effect on charge structure and lightning flash density in two different convective environments

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Abstract
The influence of the tilting effect on charge density and lightning flash density was investigated using idealized Weather Research and Forecasting explicit charging/discharge module (WRF-ELEC) simulations for two thunderclouds. No shear (NS) and with shear (WS) simulations were conducted based on different values of wind velocity components in input sounding. Results from the NS and WS simulations show that the tilting effect extended the lifetime of the simulated convective clouds in both case studies, while leading to higher maximum vertical velocity only for the environment with intense convection. The ice and graupel in the cloud cell appear almost simultaneously in both the NS and WS simulations for the two case studies, but larger values are obtained for the WS simulations. It is noted that the increase of convection intensity postpones the larger values to the mature stage. The tilting effect results in an increase of total non-inductive charging, especially in a severe thundercloud. Moreover, the tilting effect does not lead to the same results for the polarity and intensity of charge density in the two studied cases. In the real case study, a dipolar charge structure was seen for both NS and WS simulations, but the intensity of charge density decreased with regard to the tilting effect. In contrast, the intensity of the charge increased with the tilting effect and resulted in tripolarity in the idealized case with a high value of convective available potential energy. Finally, considering the tilting effect leads to an increase of the number of lightning occurrences in the two case studies.

KEYWORDS
charge density, lightning flash density, polarity, tilting, WRF-ELEC

1 INTRODUCTION
It is obvious that thunderclouds (cumulonimbus clouds) are the primary sources of lightning. An electrical discharge that most commonly occurs within a cloud (Poelman, 2010) can be produced by the coexistence of graupels and ice crystals. These particles are the essential constraints for highly positively and negatively charged particles (Latham and Stow, 1969) and affect the electrical characteristics (Gunn, 1950; Sartor, 1973; Williams, 1988;
Miller et al., 2001; Uman, 2001). To investigate the mechanism, numerous experimental studies have been carried out, such as those by Takahashi (1978), Jayaratne et al. (1983), Keith and Saunders (1990), Saunders et al. (1991; 2004; 2006), Brooks and Saunders (1994), Takahashi and Miyawaki (2002), Saunders (2008) and others. In addition, much effort has been made to evaluate the laboratory results using numerical models; from using 1D models (Solomon and Baker, 1996; Solomon et al., 2005; Albrecht et al., 2008; Mitzeva et al., 2009; Tsenova and Mitzeva, 2009; 2011) to using 3D models (Heldson et al., 1992; MacGorman et al., 2001; Barthe and Pinty, 2007; Ávila et al., 2011; Barthe et al., 2012; Fierro et al., 2012; Liu et al., 2014; Tsenova et al., 2014; Xu et al., 2014; Wang et al., 2015). Also, many observational studies have been conducted to verify the effect of cloud dynamics (i.e. the updraft strength) on lightning occurrence (Workman and Reynolds, 1949; Williams and Lhermitte, 1983; Baker et al., 1995; 1999; Lang and Rutledge, 2002; Wiens et al., 2005; Deierling and Petersen, 2008; Albrecht et al., 2011). Some researchers examined the effect of cloud dynamics on charge structure focusing on vertical velocity (e.g. Brooks et al., 1997), temperature, cloud water content (e.g. Mansell et al., 2005) and ice crystal size distribution on intra-cloud charge transfer (e.g. Saunders et al., 2006).

As the cloud column develops vertically and passes through layers with wind shear, dynamically it is forced to tilt from its initial vertical state. Thus, the updraft and downdraft occur in separate regions of the cloud and a fraction of the precipitation leaves from the updraft; hence the flux of water loading decreases in the updraft column (e.g. Klemp and Wilhelmson, 1978; Ferrier and Houze, 1989). Therefore, the downdraft will not stop air flowing up into the storm and consequently reinforcing the updraft. Hence, the updraft column is maintained for a longer period of time (e.g. Das, 2017). Also, Gharaylou et al. (2013) in a 1D analysis demonstrate that, as the tilting angle increases, total mass, heat and moisture fluxes decrease. Yet there is less sensitivity to a tilting angle above 20°. The dependence of updraft and downdraft strength on the tilting angle has an influence on the vertical distribution of fluxes (Gharaylou et al., 2013).

The tilting effect in a developing cloud and its interaction with the ambient wind field were first investigated by Newton and Rodebush Newton (1959). They hypothesized that the tilting effect has a large role on buoyancy forces. The effect of a tilted updraft on cloud growth has been investigated through change of the lifetime, the intra-cloud maximum vertical velocity, mass flux and precipitation (Weisman and Klemp, 1984; Ferrier and Houze, 1989; Chen and Sun, 2004; Chen and Siao, 2010; Gharaylou et al., 2013; Price, 2013).

Some researchers (e.g. Falade and Adesanya, 2014) explored the effect of wind shear on charge structure and the electric field of simulated storms and showed that the wind shear affected the cloud charge dynamics. This issue motivated us to show how much the cloud dynamics and also its microphysics (through the tilting process) can affect charge separation and electrical characteristics, qualitatively and quantitatively, especially using the new Weather Research and Forecasting (WRF) explicit charging/discharging module (WRF-ELEC). Therefore, the main aim of this paper is to examine the effect of tilting on the amount of predicted hydrometeors and the charge density and lightning characteristics. For this aim, the WRF model was used and initialized with a measured sounding over the Tehran area and an idealized sounding. Since strong thunderstorms with high convective available potential energy (CAPE) values occur rarely in our area and thunderstorms which occur in our region do not show very favorable environments for deep moist convection, an idealized sounding was used. However, for both cases, the simulation type is the idealized simulation. Two types of idealized simulations, without and with shear, were conducted based on different values of wind velocity components in two input soundings. To simulate the net charge density, the WRF-ELEC developed by Fierro et al. (2013) was used. This module includes both non-inductive and inductive charging parameterizations.

The description of the 3D WRF mesoscale model together with the electrification parameterization and discharge model are presented in Section 2. Then, the design of the numerical simulations and the validation of the model outputs are presented in Section 3. The results of the simulations are discussed in Section 4. Finally, conclusions are provided in Section 5.

2 | MODEL

2.1 | The WRF model

In the current research, the WRF model (version 3.8.1, which was released on April 18, 2017) was applied. The WRF model uses terrain-following hydrostatic vertical pressure coordinates (Skamarock et al., 2008). Since there is good consistency between idealized and real simulations to produce convective dynamics (Costantino and Heinrich, 2014), an idealized simulation was used to promote our purpose in the current research. It should be noted that idealized simulation provides simplified experiments for analyzing cloud dynamics with better control of the external parameters such as wind
shear, temperature and humidity (Costantino and Heinrich, 2014).

2.2 | The WRF-ELEC model

The new WRF-ELEC was used to parameterize the non-inductive and inductive charging rates. Interested readers are encouraged to see the WRF-ELEC description in Mansell et al. (2005), Fierro et al. (2013) and Gharaylou et al. (2019). In this module, the non-inductive charging rate, which varies with the amount of separated charge density through the collision of hydrometeors, is calculated based on the Mansell et al. (2005) formulation. To calculate the amount of charge separation, the formulation of Saunders et al. (1991) is applied. The inductive electrification resulting from rebounding particle collisions between the cloud water and the ice–graupel–hail in the presence of an external electric field is calculated based on Ziegler et al. (1991). The sedimentation and advection of charge density is treated in an identical mode to the predicted scalars (Fierro et al., 2013). The electric field is obtained by solving the Poisson equation for the electric potential (e.g., MacGorman et al., 1998) using a message-passing-interface black box multigrid iterative solver or BoxMG (Dendy, 1987; extended by Dendy and Moulton, 2010) for the 3D non-symmetric convection–diffusion solution used by the WRF-ELEC model. The discharge model in this module is based on Ziegler and MacGorman (1994) and MacGorman et al. (2001). The discharge initiation threshold ($E_{\text{break/crit}}$) is used according to a simple threshold (Fierro et al., 2013) and the radius of the discharge cylinder is typically considered as 6 km (Fierro et al., 2013).
non-inductive and inductive charging module (WRF-ELEC) only coupled with NSSL two-moment microphysics, the NSSL two-moment microphysical scheme (Mansell et al., 2010) was used to parameterize microphysical processes. In this study, both the inductive and non-inductive electrification mechanisms are considered in the model simulations. There are eight options available as a non-inductive charging scheme, which are all based on the Saunders et al. (1991) scheme with some modification; the default option in the WRF-ELEC was used as the non-inductive scheme in this study. The inductive charge separation has been ignored in some studies due to the small contribution of inductive charging compared with that of non-inductive charging (e.g. Mansell et al., 2005; 2010). However, since the inductive charging process plays a main role in the early stage of the electrification of thunderstorms when the electric field reaches a large value (MacGorman et al., 1998; Liu et al., 2014), it has been considered in this study.

Convection was initiated using an ellipsoidal thermal bubble placed at the center of the domain, according to the following relationship:

\[
\Delta \theta = \Delta \theta_0 \cos^2 \frac{\pi}{\beta}, \quad \beta < 1
\]

\[
\beta = \left[ \frac{(x-x_c)^2}{x_r} + \frac{(y-y_c)^2}{y_r} + \frac{(z-z_c)^2}{z_r} \right]^{1/2}
\]

where \(\Delta \theta\) is the potential temperature perturbation, the subscript \(c\) refers to the location of the center of the perturbation and \(r\) denotes its radial dimension in each direction. In the current research, we specify \(x_c = y_c = 14\) km, \(x_r = y_r = 10\) km, \(z_r = 1,500\) m and the maximum potential temperature perturbation of \(\Delta \theta_0 = 3\) K at the center of the bubble. The potential temperature perturbation decreased to 0.0 at 10 km from the center of the bubble in the west-east direction and 1.5 km in the vertical direction.

### 3.2 Validating the model outputs

The lightning flash density from the real simulation was validated using the observed total flash number from the World Wide Lightning Location Network (WWLLN) (Lay et al., 2004; Rodger et al., 2004; 2005). In this regard, a simulation was conducted using the WRF-ELEC initiated by the Global Forecast System (GFS) data, provided in 0.5° (about 50 km) spatial resolution and 6 hr time resolution for the real case study (May 21, 2013). The same

| Parameter | Property |
|-----------|----------|
| Horizontal resolution (m) | 27, 9 and 3 km |
| Number of vertical levels | 35 |
| NX × NY | 110 × 100 (d01) 91 × 61 (d02) 94 × 70 (d03) |
| Boundary layer scheme | MYJ (Mellor and Yamada, 1982; Janjić, 1990; 1994; 1996) |
| Radiation scheme | RRTM (Dudhia, 1989; Mlawer et al., 1997) |
| Microphysics scheme | NSSL two moment (Mansell et al., 2010) |
| Cumulus parameterization scheme | Kain–Fritsch (Kain and Fritsch, 1993) for two outer domains |
| Surface layer scheme | NOAH (Chen and Dudhia, 2001, modified by Liu et al., 2006) |
| Boundary conditions | GFS data with a 0.5° horizontal resolution |

set-up of Gharaylou et al. (2019) was used (Table 1) for the physical parameterization and model set-up.

For validation, only the results of domain 3 were considered. The simulated sum of lightning initiations in the column from the WRF-ELEC was evaluated against the observed total flash number from WWLLN data. The observed lightning data were taken from an area with 50 km radius and the Mehrabad Airport station in the region of Tehran as a center by WWLLN. Both data from the WRF-ELEC and from WWLLN were aggregated in 1 hr intervals for compatibility with each other. Figure 2 shows the observed total flash number from 1900 UTC, May 21, 2013, to 0000 UTC, May 22, 2013 (during the lightning activity hours). Pearson’s correlation coefficient \((r)\) was used to evaluate the similarity between the time series of total flash number estimated by the simulation and those from observations. In this case study, the \(r\) of total flash number from model simulation and observations has a value of 0.45. Therefore, there is an almost moderate correlation between the model results and observation during the lightning activity hours. Since there is no established station in the lightning network (WWLLN) in Iran and the method of measurement requires an interpolation method to extract data for the region of interest, the obtained correlation coefficient seems reasonable.
RESULTS AND DISCUSSION

The longitude–latitude pattern of the averaged values of vertical velocity \( w (\text{m} \cdot \text{s}^{-1}) \) (calculated for all times and all levels) is illustrated in Figure 3 for both NS and WS simulations for the two case studies. Without ambient wind shear (NS simulations), the WRF model produces a cylindrical axisymmetric cloud (Figure 3a,c) and with ambient wind shear (WS simulations), the updraft is surrounded by a weak downdraft almost near the center of the domain for the two case studies (Figure 3b,d). When the updraft reaches its maximum value in the two cases, the maximum radius of the updraft is about 5 km (2 grid points in Figure 3).

The vertical wind shear at the same time verifies the shape of the cloud and the convection type. The main variable with a critical role in both the dynamics and microphysics of the cloud is wind, specifically the vertical component of the wind. Dynamic and microphysical processes verify the characteristics of thunderstorms, vertical or tilted. The updrafts, downdrafts and wind shear describe the dynamic processes. Microphysical processes consist of all types of particle growth and phase changes in the thunderstorm. Therefore, every change in the dynamics of the environment (inside and outside of convective cells) will influence the microphysical process and vice versa. The updraft flow (a dynamical property) forms a supersaturation condition due to adiabatic cooling during upward flow.

In contrast to the previous discussion which shows the influence of dynamics on the microphysics of the cloud, there are processes which indicate the influence of microphysics on the dynamics of cloud particles. Water vapor condenses onto the cloud condensation nuclei or deposits onto ice nuclei. In this way cloud condensation nuclei or ice nuclei act as a sink of supersaturation. The balance between supersaturation production and consumption determines the number of hydrometeors in the thunderstorm (Rogers and Yau, 1989). The evolution of the size spectrum of hydrometeors is the result of several processes such as collision and coalescence, accretion and aggregation and others, but these processes are sequentially affected by the strength and length of the updraft and the amount of mixing between the cloud and its environment.

The purpose of considering the tilting (produced due to wind shear) is that some produced precipitation leaves the cloud column and so the lifetime of the cloud is extended, because precipitation that remains in the updraft tends to oppose the positive buoyancy. The lifetime of the convective cell is measured from the starting point at which the vertical velocity reaches 2 m·s\(^{-1}\) to the end point when upward or downward motion reaches 2 m·s\(^{-1}\) (Chen and Sun, 2002). Hence, the derived values for the lifetime of a cloud cell and the maximum values of \( w (\text{m} \cdot \text{s}^{-1}) \) are very different in NS and WS simulations (Figures 4a,b and 5a,b). This difference between the maximum values of \( w \) and the lifetime of the cloud cell is significant for case study 2 which has a high value of CAPE (Figure 5a,b).

In the NS1 simulation, the maximum value of \( w (\text{m} \cdot \text{s}^{-1}) \) occurred at around 20 min with a value of 80 m·s\(^{-1}\) and had a decreasing trend; it then switched to increasing behavior due to growth of a new cell (Figure 4a,b). The NS1 cells developed in an environment without shear, but the new cell may not develop in an NS environment and in fact the new NS1 cell is a cell developing in a WS1 environment. So, the comparison between the NS1 and the WS1 cells will be done only for the first developed cell in this case. As Figure 4a,b shows, the tilting effect increases the lifetime of the convective cells (comparison between the NS1 and WS1 simulations). Also, the maximum values of \( w \) were obtained at approximately the same time in the WS1 simulation compared with the NS1 simulation (Figure 4a,b). It is worth noting that the maximum values of vertical velocity decrease in the WS1 simulation. However, the studies show that a tilted updraft can affect the intra-cloud maximum vertical velocity (e.g. Weisman and Klemp, 1984), so that strongly sheared environments present higher values of vertical velocities. This is very clear from the simulation results for case study 2 with a high CAPE. As Figure 5a shows, in NS2 simulation the maximum value of \( w (\text{m} \cdot \text{s}^{-1}) \) occurred at 17 min (about 45 m·s\(^{-1}\)), had a
decreasing trend until a time of 50 min and then switched to increasing behavior due to growth of a new cell. However, in the WS2 simulation, the maximum value of $w$ was obtained approximately 20 min later (compared with that for the NS2 simulation) and was maintained for an hour and then decreased (Figure 5b). The achieved discrepancy confirmed that the tilting effect extends the lifetime of the simulated convective cloud and results in higher vertical velocity values only in a strongly sheared environment. These results show how the results of simulations can be different in environments with different intensity of convection (comparison between Figures 4a,b and 5a,b).

It is well known that one reason for the larger updraft in the WS simulation may be that heat is generated by the larger ice mixing ratio (Takahashi and Shimura, 2004). Hence, for both case studies, the time–height distribution of graupel and ice mixing ratios, $q_g$ (g·kg$^{-1}$) and $q_i$ (g·kg$^{-1}$), are presented for NS and WS simulations in Figures 4c,d and 5c,d.

According to Figure 4c,d, the formation of graupels started at a time of 33 min with a maximum value of 5.38 g·kg$^{-1}$ at a height of 7.5 km in the NS1 simulation, while the appearance of graupels happened a bit earlier in the WS1 simulation and reached a maximum value of 6.33 g·kg$^{-1}$ at a height of 8 km. Also, the maximum value of $q_i$ in the NS1 simulation (11.52 g·kg$^{-1}$ at about 9 km height at a time of 16 min, Figure 4e) is smaller than that in the WS1 simulation (11.75 g·kg at about 10.5 km height at time 15 min, Figure 4f).

**FIGURE 3** Longitude–latitude pattern of the averaged $w$ values (m·s$^{-1}$) for both no shear (NS) and with shear (WS) simulations of (a), (b) the real case study and (c), (d) the idealized case study. (a), (c) NS simulations; (b), (d) WS simulations. The averaged values are calculated for all times and all levels.
In case study 2, graupels were appearing at a time of 18 min with a maximum value of 12.28 g·kg\(^{-1}\) at a height of 10 km in the NS2 simulation (Figure 5c), while graupels were appearing later and reached a maximum value of 10.53 g·kg\(^{-1}\) at a height of 9 km in the WS2 simulation (Figure 5d). The obtained maximum value of \(q_i\) in the NS2 simulation is 5.28 g·kg\(^{-1}\) at about 10.5 km height (Figure 5e), which is greater than that in the WS2 simulation (4.17 g·kg\(^{-1}\) at about 9.5 km height, Figure 5f).

**Figure 4** Comparison of the time–height distribution of (a), (b) \(w\) (m·s\(^{-1}\)), (c), (d) \(q_g\) (g·kg\(^{-1}\)) and (e), (f) \(q_i\) (g·kg\(^{-1}\)) of the real case study. (a), (c), (e) No shear simulations; (b), (d), (f) with shear simulations.
The maximum values of the mixing ratio of graupel, the vertical velocity and the mixing ratio of ice crystals are distributed in that order vertically for the two case studies, but the tilting effect decreases the height of formation of graupel and ice crystals for case study 2 with a high value of CAPE.

The time series of the maximum values of $q_g$ (g kg$^{-1}$) and $q_i$ (g kg$^{-1}$) and extreme (maximum and minimum) values of $\rho_{\text{induc}}$ (pC m$^{-2}$), $\rho_{\text{noninduc}}$ (pC m$^{-2}$) and ice number concentration (kg$^{-1}$) for both the NS and WS simulations of the two case studies are presented in Figures 6a–e and 7a–e. As Figure 6a,b indicates, larger
graupel and ice contents were produced in the WS1 simulation compared with those in the NS1 simulation. However, smaller values of graupel and ice mixing ratios are obtained at 40 min of the WS2 simulation (Figure 7a,b). After that, in the mature stage of the simulated cloud cell, larger graupel and ice mixing ratios were observed in the WS2 simulation compared with those in the NS2 simulation. The ice and graupel in the cloud cell appear almost simultaneously and their time series were increased in both the NS and WS simulations for the two case studies (Figures 6a,b, and 7a,b).

The electrical processes in the thunderstorm consist of the electrification, charge distribution and discharge process. The electrification process of the thundercloud is based on both the non-inductive electrification mechanism of ice crystals and graupel particles and the inductive
electrification mechanism of graupel and cloud droplets (Miller et al., 2001; Tan et al., 2006). Therefore, the time series extreme values of $\rho_{\text{induc}}$ and $\rho_{\text{noninduc}}$ for both the NS and WS simulations of the two case studies are presented in Figures 6c,d and 7c,d respectively. The graupel and ice mixing ratios are the influential factors in the electrification process and the simultaneous presence of graupel and ice crystals provides the charge separation in the cloud (Miller et al., 2001). The reason is that charge separation occurs due to the movement of precipitation particles by gravity according to non-inductive theory. So, there should be a connection between the appearance of graupel and ice crystals, which are involved in charge separation, and the charge density. This emphasizes the role of convective cloud dynamics and microphysical processes in charge separation and electrification (Price, 2013).

For case study 1, as mentioned before, the new cell (which is formed after 50 min) may not develop still in an NS environment and therefore the comparison between the NS1 and WS1 cells will be done only for the first developed cell. For the first cell in this case, both total inductive and non-inductive charging are almost

FIGURE 7  As Figure 6 but for the idealized case study
zero in the NS1 simulation. However, they are gradually enhanced and then decreased in the WS1 simulation (Figure 6c,d). Meanwhile, the values of total inductive charging are smaller than the values of total non-inductive charging. This result verifies the previous research on the electrification mechanism which shows that the non-inductive charging process plays a main role in the electrification process (e.g. Ziegler et al., 1991).

For case study 2 (the severe thundercloud case), higher values of the total non-inductive charging are obtained (Figure 7d) but the total inductive charging is very small for both the NS2 and WS2 simulations.

Helsdon et al. (2001) showed the importance of ice crystal size and concentration in electrification. Therefore, the time series of maximum values of the concentration of ice particles are provided in Figures 6e and 7e. For case study 1, the ice number concentration varied directly with ice crystal mixing ratio up to a maximum which was achieved at 25 min for both NS1 and WS1 simulations and decreased thereafter due to the collection by graupel particles. The ice crystal number concentration of the NS1 simulation is higher than that of the WS1 simulation which leads to an enhanced lightning activity in NS1 during the first 40 min of simulation time (Figure 9a), confirming the results from both observational and numerical studies (e.g. Koren et al., 2005; Khain et al., 2008) which show that increasing the ice crystal concentration results in an enhancement of lightning activity. For case study 2, the smaller ice water content leads to a lower ice concentration in WS2 compared with the NS2 simulation.

In order to investigate the tilting effect on charge density, both the charge intensity and polarity of the charge distribution are considered. The time–height distribution of net charge density $\rho_{\text{tot}}$ (in pC m$^{-3}$) superimposed on the equivalent potential temperature ($K$) contours along with the vertical distribution of the electric field $E_z$ (kV m$^{-1}$) for NS and WS simulations of the two cases are presented in Figure 8. The equivalent potential temperature contours give information about the cloud base and top height so that the height distribution of charge density in the cloud can be easily discussed. The vertical patterns of $\rho_{\text{tot}}$ in the cloud column show the dipolarity (positive charges above negative charges) for both the NS1 and WS1 simulations, but the tilting effect decreases the intensity of the charge density in case study.

**FIGURE 8** The time–height distribution of $\rho_{\text{tot}}$ (pC m$^{-3}$, shading) superimposed on the equivalent potential temperature values of $\theta_e$ (K, thick contours) and the vertical profile of $E_z$ (kV m$^{-1}$, shown on the right side of each plot) for no shear (NS) and with shear (WS) simulations of (a), (b) the real case study and (c), (d) the idealized case. (a), (c) NS simulations; (b), (d) WS simulations.
The vertical profile for $E_z$ corresponds to the vertical distribution of charge variation; two varying regimes of $E_z$ comprise a positive field at altitudes of 2–5 km and a negative field on the upper levels in case study 1 (Figure 8a, b).

In the NS2 and WS2 simulation, a tripolar structure (negative charges are sandwiched between two positive charges) is produced (Figure 8c, d). A thin negative charge screening layer at the top cloud boundary may have developed due to the flux of negative ions toward the cloud top and their attachment to ice crystals. The significant values of positive or negative net charge density at lower levels can be explained by the charge carried by precipitation below the cloud base. The intensity of the charge is increased in this case on considering the tilting effect (comparison between Figure 8c and d). The situation for $E_z$ corresponds to the vertical distribution of the charge density variation.

Subsequently, the time series of the lightning flash density is presented in Figure 9 for the two case studies. As Figure 9a, b demonstrates, the two cases, especially the WS2 simulation, experienced more lightning flash densities. The larger maxima in the net charge values and the tripolar charge structure of the WS2 simulation can be interpreted as indicative of higher flash rates in case study 2 (Figure 9b).

FIGURE 9 Time series of the simulated lightning flash density of (a) the real case study and (b) an idealized sounding for no shear and with shear simulations

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5 | CONCLUSIONS

In this research, the tilting effect on the charge density and lightning flash density was investigated using the 3D Weather Research and Forecasting (WRF) model with an explicit charge/discharge module (WRF-ELEC) developed by Fierro et al. (2013) initialized with a measured sounding over Tehran City (May 21, 2013) and an idealized case. The idealized case is used because the real selected case study does not show very favorable environments for deep moist convection. In each case study, the WRF model was run using two input soundings: (a) with zero values of wind velocity to produce a no shear (NS) simulation and (b) with the same values of wind velocity as the input sounding to produce a with shear (WS) simulation. The WRF-ELEC was used to calculate the charge density and lightning flash density. For the real case study, the total flash number from the WRF-ELEC simulation was validated using observational data taken from the World Wide Lightning Location Network, which results in a good correlation between them during lightning activity hours ($r = 0.45$).

Results from the outputs of the NS and WS simulations showed that, in the real case study, the tilting effect decreases the maximum values of the vertical velocity. However, the maximum values of the vertical velocity increase in the WS simulation of the idealized case with a high convective available potential energy (CAPE). These results show how the results of the simulations can be different in environments with different intensities of convection. Also, the tilting effect extends the lifetime of the convective cell in both case studies.

The ice and graupel in the cloud cell appear almost simultaneously in both the NS and WS simulations for the two case studies. Also, higher values of total non-inductive charging are obtained for the case study with intense convection, supporting results of a good correlation between non-inductive charging and the intensity of convection (Shi et al., 2019).
Since previous studies showed that the charge structure was influenced by cloud dynamics and microphysics (Houze, 2010; Xu et al., 2014) and more precisely the polarity of the charge structure in the updraft columns of thunderclouds was dependent on a non-inductive mechanism (e.g. Takahashi, 1978; Saunders and Peck, 1998; Stolzenburg et al., 1998), the role of the tilting effect on the charge vertical distribution and the charge polarity was investigated in the current research. Our findings indicated that the tilting effect does not lead to the same results for the polarity and intensity of charge density in the two studied cases. In the real case study, a dipolar charge structure was seen for both NS and WS simulations, but the intensity of the charge density decreased regarding the tilting effect. In contrast, the intensity of the charge increased on considering the tilting effect and resulted in tripolarity in the idealized case with a high value of CAPE. Our results are consistent with other research which shows the complex charge structure in severe thunderclouds (MacGorman et al., 2005).

Finally, considering the tilting effect leads to increases in the number of lightning occurrences. This finding is consistent with the observed feature in which Krehbiel (1983) showed that increased environmental wind shear can change the charge structure of a thunderstorm and results in an increase in the storm’s percentage positive lightning.

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