SIMULATION OF THE DEVELOPMENT OF ELECTRIC FIELD IN A 3-DIMENSIONAL WINTER THUNDERCLOUDS FIELD USING THE RAMS MODEL

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1. INTRODUCTION

Previous studies made on the electrical activity of thunderstorms over Israel and the adjacent Mediterranean Sea showed that there are larger frequencies of lightning flashes over sea than over land and over the Carmel Mountain than over other parts of the coast (Altaratz et al. 2003). Hence, it is desirable to develop a capability to simulate electrified storms on a regional scale in order to study the influence of different geographical and meteorological factors on the dynamical and microphysical behavior of thunderstorms. Previous numerical studies (e.g. Takahashi, 1984; Helsdon and Farley, 1987; Ziegler et al., 1991; among others) of the electrification of thunderstorms described the development in single thunderclouds without any topography. This work describes the pre-lightning electrification of mid-winter thunderclouds over the coastal area of Israel: around Haifa and the Carmel Mountain (a mountain ridge, 500 m height, see fig. 1) in the northern coast. For brevity the simulations around Tel Aviv in the central coast will not be presented here. The goal was to study the influence of geographical factors on thunderclouds electrical evolution. For this purpose the RAMS, 3D mesoscale model, was modified to include the electrical development in a realistic cloud field. The model calculates charge separation, charge buildup and the development of charge centers, which is subsequently used to calculate the electrical field in the clouds. The results demonstrate the differences between the clouds that develop over the sea and those over land.

2. THE NUMERICAL MODEL

The Regional Atmospheric Modeling System (RAMS) is a 3-D multipurpose, numerical prediction model that simulates atmospheric circulations ranging in scale from an entire hemisphere down to eddies in the planetary boundary layer. A comprehensive review of the RAMS model can be found in Pielke et al., (1992) and Cotton et al., (2003).

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2.1 The microphysical scheme

The RAMS version 4.3 includes a bulk cloud microphysical scheme (with few exceptional processes, which are described by bin microphysics). The water class is divided into eight different categories: vapor, cloud droplets, rain, pristine ice, snow, aggregates, graupel and hail. Cloud droplets and rain are liquid water, pristine ice, snow and aggregates are completely frozen, and graupel and hail are mixed phase particles. A generalized gamma function is assumed for the size spectrum. A two-moment hydrometeor prediction scheme predicts the mixing ratio and the number concentration of all the water species. A full description of the microphysical model can be found in Walko et al. (1995, 2000) and Meyers et al. (1997).

2.2 Electrification scheme

In the present work the noninductive charging mechanism is the only charging process to be simulated. Two parameterizations of this mechanism were implemented into the model; one is based on the experimental studies of Saunders et al. (1991) and the other on the experimental results of Takahashi (1978). The parameterization of the noninductive charge separation mechanism requires the determination of charge transfer per separation event (collision and rebound) and the calculation of the number of these events (out of the collisions events) for the particular hydrometeor class at a grid point during a time step of the model. The charge transferred per separation event was calculated according to the two different schemes.

Saunders et al. (1991):

The charge δq, transferred to a graupel particle via collision and rebound with pristine ice, snow or aggregate is:

$$\delta q(D_i, D_g, T) = \left|\frac{\Delta V}{k}\right|^3 G(D_i) \qquad (1)$$

Where ΔV (m/s) is the difference between the large and small particle fall velocities, k is a constant equal to 3m/s, and $G(D_i)$ is a polynomial fit to the experimental data from Keith and Saunders (1989) in units of fC.

The polarity of the charge, which is transferred to the graupel, is a function of the temperature and of the effective liquid water content. Saunders et al. (1991) determined the effective liquid content as the accreted fraction of liquid water content in the path of the graupel, given by the ambient liquid water content multiplied by the collection efficiency ($EW=LWC*E_{coll}$). They gave the following expression for EW_{crit} (gr/m^3), valid for temperatures between -10.7°C>T>-23.9°C:

$$EW_{crit} = -0.49 - 6.64 \times 10^{-2} T \qquad (2)$$

If the effective liquid water content is above the value calculated in equation (2) the graupel is charged positively, otherwise negatively.

The Takahashi's scheme

The results of Takahashi's experiments, for the charge transferred per collision, have been stored in a lookup table in the model code (Takahashi, personal communication). A value of the charge transfer per collision event is retrieved from the lookup table, depending on the temperature and liquid water content in the interaction location. It should be pointed out that in contrast to Saunders who used charge per separation event, Takahashi describes his results in terms of charge per collision. Therefore, the charge per collision has to be multiplied by an efficiency factor α (Marshall et al., 1978, Takahashi 1984) that converts it to charge per separation event to yield:

$$\alpha = 5\left(\frac{D_i}{D_0}\right)^2 \left|V_g - V_i\right| / V_0 \qquad (3)$$

Where D_i is the ice (or snow or aggregates) diameter (m) and V_g and V_i are the terminal fall velocities of the graupel and ice (m s^{-1}). The values of D_0 and V_0 are 100 μm and 8 m s^{-1} respectively (Takahashi, 1978). α is restricted to a value of 10, which is the apparent saturation value for large snow crystals (Marshall et al., 1978). This factor determines the dependence of the riming charge magnitude on the ice crystal size and terminal velocities.

After the calculation of the charge transfer per separation event, the determination of the total charge transferred per time interval, is done by multiplying the calculated charge transferred per separation event by the number of these events.

The rate of change of the charge density ρ on the graupel category is given by:

$$\frac{\partial \rho}{\partial t} = \frac{\pi}{4} \int\int (D_g + D_i)^2 \left|V_g - V_i\right| E_{gi} n_i(D_i) n_g(D_g) \, \delta q \, dD_i \, dD_g \qquad (4)$$

Where D_g and D_i are the graupel and the ice diameters, respectively; V_g and V_i are the terminal fall velocities of the graupel and the ice, respectively; n(D) is the size distribution of the particular type of hydrometeor and E_{gi} is the collision-separation efficiency for graupel and ice.

The electric field is calculated offline after the RAMS model simulation is completed. It is done by the use of a standard numerical algorithm to solve for the electrical potential φ at all grid points by inverting the Poisson's equation. Finally, the electric field is computed from the value of this electrical potential. The electric field is computed until its value reaches a pre-assigned threshold value for the electric breakdown.

In order to use the numerical Poisson solver, boundary conditions for φ were specified. Since, the ground is an equipotential plane, the potential of the bottom layer of the grid was set to a constant. The lateral boundary conditions were set according to the fair weather potential (Gish, 1944) since they are far enough from the charge distribution in the clouds.

The upper boundary condition of the potential is set to the fair weather potential at the corresponding height.

3. RESULTS

The 5-6 January 2000 storm was a "Cyprus Low" event, which caused heavy rain and intense electrical activity along the coast of Israel. We chose to study the postfrontal electrical activity in order to be able to track the electrical evolution of a field of single clouds. Two different kinds of simulations will be presented, both of them focused on the Haifa region, the first one with real topography and the second one with a flat topography. The model was run for 8 hours, starting at 18:00 UTC (20:00 local time) on January 5th 2000. Initial and boundary data for the simulations were obtained from the European Center for Medium Range Weather Forecast (ECMWF) objective analysis for 18:00, 24:00 UTC of January 5th 2000. The resolution of these three-dimensional data sets was 50 km. The simulation utilized a two-way interacting nested grid configuration. Five grids were used to zoom down to the region of interest. The two finest grids had dimensions of 94X94X27 points, with 312 m horizontal resolution and 100 m grid spacing in the lowest layer and grid stretching of 1.11 times of this value in the upper levels. The two finest grids were centered at the latitude of Haifa, with one centered over the sea and the second over the land (both of them contained land and sea regions). The time steps for finest grids were 3 sec.

3.1 The Haifa real topography simulation

Eight clouds were analyzed (until their first lightning event), four of them over the sea west or northwest of the Carmel Mountain, and the other four over the mountain and its surroundings. The clouds moved with southwesterly to westerly winds. The cells are marked in figure 1, which shows the liquid water content in the clouds at 2266 m, at 19:22 UTC at the sea grid and 19:24 and 20:24 UTC at the land grid. The locations of the formation of the clouds over the land were not identical for all four cells. One of them formed over the slopes of the Carmel Mountain and it was followed until its first lightning occurrence over the top of the mountain (land1). Two other clouds were formed over the Carmel Mountain and their first electrical breakdown took place east of the northeastern slopes of the Carmel Mountain, over the plane (land2, 3). The last one formed over the sea in the Haifa bay and shortly afterwards moved over land (north of the Carmel) and its first lightning occurred over the slopes of the Galilee Mountains (land 4).

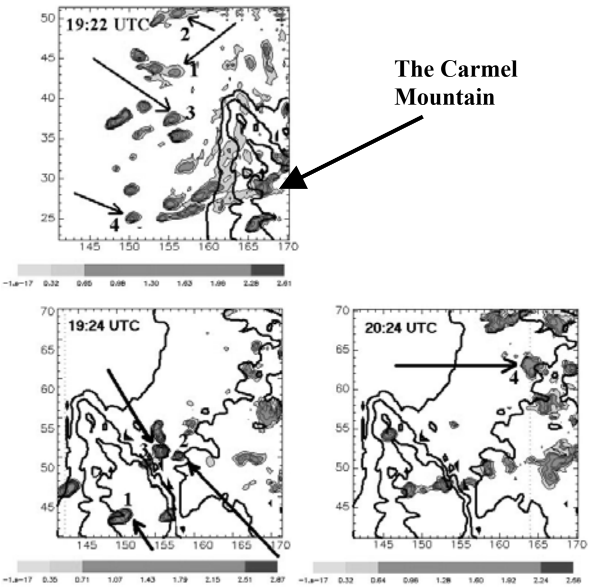

Figure 1: Contours of liquid water content (g Kg^{-1}) at 2266 m, at 19:22 UTC (sea grid), and 19:24, 20:24 UTC (land grid).

Based on Saunders' scheme, the total charge density in the middle of the clouds, shortly before the first lightning, had several possible structures: (a) a dipole (b) an inverted dipole (c) an inverted tripole (d) a tripole with another upper negative charge center. Examples can be seen in figure 2. In contrast to Saunders' scheme, the total charge density based on Takahashi's scheme produced a uniform dipole structure. Table 1 presents the general characteristics of the simulated clouds. The maximal updrafts in the sea clouds were between 15.5 and 18.1 m s^{-1}. The first two clouds (sea1, 2) with the strongest updrafts velocities had the shortest time interval to the first lightning (11 and 10 minutes). The time interval between the appearance of liquid water content of 1 g Kg^{-1} in the cloud and the first lightning was 10-13 minutes for the sea clouds and 12-26 minutes for the land clouds (figure 3). It was similar using both schemes (Saunders and Takahashi).

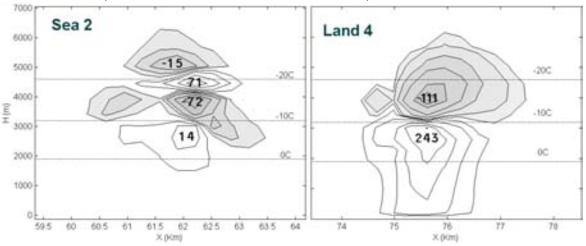

Figure 2: The total charge density for the clouds Sea 2 and Land 4.

The land clouds formed over different sites and as a result, the variance in their characteristics was large. The updraft velocities were between 10 and 18.2 m s^{-1}. Land 4, which was formed over the sea and moved to the land, had the lowest updraft and the longest time to the first lightning. The forcing of the topography didn't influence it.

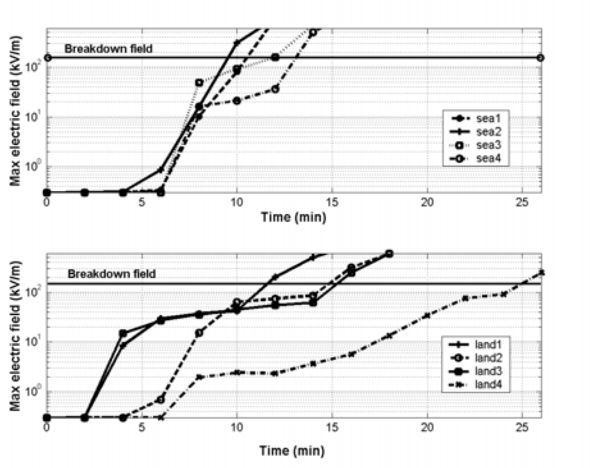

Figure 3: The maximal electric field in the clouds in the real topography simulation as a function of time (kV m^{-1}). The upper panel is for the sea clouds and the lower panel for the land clouds.

3.2 The Haifa flat topography simulation

In order to evaluate the role of the topography in the clouds' microphysical and electrical evolution, a simulation of the Haifa region with a flat topography was conducted, using only the Saunders' scheme. The electrical development of the clouds was compared with the development of similar clouds in the simulation of the Haifa region with real topography.

The model was run for 2 hours, starting at 18:00 UTC (20:00 local time) on January 5th 2000. The electrical evolution of four clouds were tracked, three of them while moving over the sea (marked as Notopo_sea1, 2, 3) north west or west of the Carmel Mountain and one while moving over the land (Notopo_land1). The cloud that was tracked over the land was formed over the location of the Carmel Mountain (which was a plane in this simulation) and its first electrical breakdown took place east of the location of the northeastern slopes of the Carmel Mountain. A comparison between the characteristics of these clouds and the ones formed over the sea in the Haifa real topography simulation reveals that the microphysical and electrical characteristics of the clouds that developed in similar locations in both simulations were similar (table 1). However, the electrification rate of the cloud, which developed over the land in this simulation, was slower than of the similar clouds in the real topography simulation.

	W_{max} (ms^{-1})	RGP_{max} (gKg^{-1})	Time to the first light (min)	Charge structure (before the 1st lightning)	The charge centers levels
Sea1	18.1	0.59	11	Inverted tripole	-23ºC, -19ºC, -16ºC
Sea2	19.7	0.25	10	Tripole+upper negative	-23ºC,-19ºC, -16ºC, -5ºC
Sea3	15.5	0.65	12	Tripole+upper negative	-27ºC, -19ºC, -12ºC, -5ºC
Sea4	16.0	0.34	13	Inverted tripole	-23ºC, -19ºC, -16ºC
Average	**17.3**	**0.45**	**11.5**		
Land1	18.2	0.16	12	Tripole+upper negative	-22ºC,-19ºC, -16ºC,-3ºC
Land2	15.7	0.43	13	Tripole+upper negative	-27ºC, -19ºC, -8ºC, 2ºC
Land3	12.5	0.7	16	Inverted dipole	-16ºC, -8ºC
Land4	10	0.12	26	Dipole	-16ºC, -8ºC
Average	**14.1**	**0.35**	**16.7**		
Notopo sea1	17.9	0.21	11	Tripole+upper negative	-23ºC, -19ºC, -16ºC, 0ºC
Notopo sea2	17.5	0.2	11	Tripole+upper negative	-23ºC, -19ºC, -8ºC, 2ºC
Notopo sea3	17.5	0.17	11	Tripole+upper negative	-23ºC, -19ºC, -16ºC, 1ºC
Average	**17.6**	**0.19**	**11**		
Notopo land1	14	0.58	20	Tripole	-19ºC, -16ºC, -8ºC

Table 1: Results for the clouds in the two simulations. W=maximal updraft velocity, RGP=graupel mass content.

To summarize these simulations, the results showed that most of the clouds that developed over the sea had higher tops and larger graupel mass contents (in the time prior to the first lighting) than the ones over land. The relative part of thunderclouds that can produce lightning (clouds with electric field high enough to generate lightning) that were found over the sea was larger than over the land. This can be explained by the heat and humidity fluxes from the sea surface. Comparison of the two charge separation schemes showed that in spite of the fact that both parameterizations produced similar charging rate, the charge build up using Takahashi's parameterization led to a simple dipole charge distribution while the parameterization of Saunders' produced more complicated charge distributions composed of multi charge centers. The flat topography simulation demonstrated that the effect of the topography on the electrical development of clouds was dominant for the clouds which formed over the topographic element itself, but it was not significant for clouds which formed over the sea less than 5 kilometers from the topographical obstacle.

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