MODIFICATION OF PRECIPITATION LOCATION BY NATURAL AND ARTIFICIAL CLOUD SEEDING

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ABSTRACT
The rate of precipitation formation depends on the droplet concentration and the width of droplet spectrum. An increase of the concentration of small aerosols (with radii below 0.1 μm) leads to a delay (sometimes by several tens of minutes) in the precipitation formation and often fosters the formation of low density ice with small fall velocity. In the presence of a background wind, the delay in the precipitation formation means the spatial shift of precipitation. This spatial redistribution can be used for the purposes of rain enhancement. In the study we simulate cloud and precipitation distribution in the Eastearn Mediterranean region during the cold season under different aerosol concentrations.

1. INTRODUCTION
During the rain season in the Eastern Mediterranean (from November to April) the sea surface temperature (SST) is several degrees higher than the land temperature. The typical SST in December is 19-20°C, while the mean surface temperature in Tel Aviv is 13°C. The difference in the temperatures induces the local circulation of the land-breeze type. The interaction of this local circulation with the background westerlies leads to a convergence zone formation over sea 10-20 km off the coastal line (Khain and Sednev, 1996). This convergence results in the formation of new convective clouds or to invigoration of existent clouds (within cyclones approaching the coast). Most of these clouds precipitate rapidly over sea, not reaching the land, or reaching the coastline creating floods in such cities as Tel Aviv, Haifa located at the coastline. An example of the cloud and precipitation propagation in the region is shown in Figure 1, where radar reflectivity fields during the rain event on 20.01.07 at three time instances are presented. This specific feature of the region leads to the climatologic rain distribution, according to which precipitation over the sea ~10-20 km off the coast line exceeds precipitation maximum over the land more than three times.

Figure 1. Radar reflectivity fields during the rain event on 20/01/07 in one hour intervals. One can see that a significant fraction of precipitation falls over the sea not reaching the land.
The rate of precipitation formation depends on droplet concentration and width of droplet size spectrum. An increase in the concentration of small aerosols (with radii below 0.1 \( \mu m \)) leads to a delay of precipitation formation and often fosters the formation of low density ice with small fall velocity. In the presence of a background wind, the acceleration or the delay in precipitation formation means a spatial shift of precipitation. The conceptual scheme of such precipitation shift downwind with an increase in the aerosol concentration is presented in Figure 2.

Simple computations indicate that the time delay of the surface precipitation beginning at 20 min corresponds to a precipitation shift downwind by ~15-20 km. However, this estimate does not take into account the formation of light ice particles in case of high aerosol concentration. These particles have a low sedimentation velocity, which increases the residential time of the particles in clouds and increases a possible spatial shift of precipitation. We hypothesize that the ability of small aerosols to decelerate precipitation formation and to shift precipitation can be used for the purposes of rain enhancement over land at the expense of the decrease precipitation over sea.

In this study we simulate cloud and precipitation distribution in the Eastern Mediterranean region during the cold season under different aerosol concentrations and discuss the possibility to use this effect for purposes of precipitation enhancement.

2. RESULTS OF SIMULATIONS

2.1 THE 2-D SIMULATIONS

The simulations have been performed using a 2D spectral bin microphysics Hebrew University cloud model (HUCM) with 350 m x 125 m horizontal spatial resolution. A detailed description of the model can be found in Khain et al (2004; 2005 and 2008) and other extended abstracts of the authors in this issue. The model microphysics is based on solving the equation system for size distribution functions of water, three types of ice crystals, as well as of snow, graupel and hail. Aerosols are described using a aerosol size distribution function with maximum aerosol radius of 2 \( \mu m \). Aerosols are advected by the air velocity. In case of supersaturation takes place, aerosols with sizes exceeding the critical value are transferred to drops. The corresponding aerosol mass bins become empty. In this model version all size distributions are described using mass grids containing 33 doubled mass bins. Simulations with HUCM have been performed with two concentrations of cloud condensational nuclei (CCN) (at supersaturation of 1%): 100 cm\(^{-3}\) and 2000 cm\(^{-3}\). The first simulation will be referred to as L(ow)-run; the second as to H(igh)-run. In both cases the maximum aerosol radius was 2 \( \mu m \). These aerosols produce cloud droplets of the 8-10 \( \mu m \) radius at cloud base. The existence of aerosols of such size is assumed to take into account a possible effect of sea spray on precipitation.

Figure 3 shows fields of droplet concentration (t=1800s), and fields of cloud water content (CWC) at t=1800s, 3600s and 7200s obtained in the H-run and L-run simulations. One can see that CWC in the H-run is larger than in the L-run. The physical reason...
of this result is clear: in the H-run droplets are smaller and their
Figure 3. Fields of droplet concentration \((t=1800s)\), as well as fields of CWC (units indicated by the color bars) at \(t=1800s, 3600s\) and \(7200s\) in sea breeze simulations with high (left panels) and low (right panels) aerosol concentrations. The dashed line indicates the coastal line.

Collisions are much less intense as compared to those in the L-run. As a result, in the L-run raindrops form faster and fall out. At the same time, smaller droplets in the H-run continue ascending growing by diffusion growth (condensation). This feature was observed and simulated in many studies (see references in Khain et al 2008).

The clouds forming under the effect of sea-land temperature difference arise in the convergence zone about 10 km off the coastal line. Having their roots in the boundary layer, these clouds within the sheared background flow break up into several clouds as it is seen in the lower panel in Fig. 3. These secondary clouds have higher cloud base, lower cloud base velocity and respectively, lower droplet concentration. The high humidity in the boundary layer diminishes the height of the cloud base over the sea to 700 m (lower panel of Figure 3). As a result, warm rain dominates in the vicinity of the coastal line (Figure 6).

Farther inland precipitation is determined by rain formed by melting of graupel and snow. Fields of graupel mass contents at \(3600s\) and \(7200s\) in the sea breeze simulations with high (left panel) and low (middle panel) aerosol concentrations are shown in Figure 4. The H-L-run difference of these fields is shown on the right panels.

From the difference of the fields it can be seen that in the H-run graupel is transported farther inland because their size is smaller than in the L-run, i.e. they have smaller fall velocity.

Figure 4. Fields of graupel mass contents at \(3600s\) and \(7200s\) in simulations with high (left panel) and low (middle panel) aerosol concentrations. The difference of these fields is shown on right panels.

An even larger difference between cloud microphysical structures in the H-run and the L-run is seen in the snow mass content (Figure 5). The amount of snow is substantially larger in the H-run, which agrees well with results of single clouds, discussed above. The higher production of snow in the H-run can be attributed to the fact that small droplets reach higher levels in this case and freeze producing small ice particles which are assigned to ice crystals. Their collisions produce snow. Since snow particles
have a low sedimentation velocity and form in zones of strong background wind snow can be advected inland by several tens of kilometers. At such distances from the coast line snow is the major contributor to the precipitation. As a result, an increase in aerosol concentration leads to a significant shift in precipitation from the sea to the land as it is seen in Figure 6. While the rainwater content (RWC) over sea is larger in the low aerosol concentration case, the RWC over land is larger in the large AP concentration case. The same conclusion can be derived from Figure 7 showing the radar reflectivity fields in the H-

Figure 5. Fields of snow mass contents at 3600s and 7200 in simulations with high (left panel) and low (middle panel) aerosol concentrations. The difference of these fields is shown on right panels.

Figure 6. Fields of rain water content at 3600 and 7200 s in simulations with high (left panels)
and low (middle panels) aerosol concentrations. The differences between these fields are shown in the right panels. While RWC over the sea is larger in low aerosol concentration case, the RWC over the land is significantly larger in the large AP concentration case.

Figure 7. Fields of radar reflectivity at 3600 and 7200 s in simulations with high (left panels) and low (middle panels) aerosol concentrations. The differences between these fields are shown in the right panels. While radar reflectivity over the sea is larger in the low aerosol concentration case, the radar reflectivity over the land is significantly larger in the high AP concentration case.

Accumulated rain amount as a function of time in the simulations with high and low aerosol concentrations are shown in Figure 8 (left panel). Figure 8 (right panel) shows accumulated rain over the land only. One can see that precipitation starts earlier (i.e., more westward) in the low AP concentration case.

Over the whole computational area precipitation in the low aerosol concentration case dominates. At the same time, the increase in the aerosol concentration redistributes precipitation in such a way that precipitation over the land increases and exceeds that in the low aerosol concentration case.

3.2 3-D SIMULATIONS

In order to investigate the possible 3-D effects and include effects of topography two 3-D models have been used: a) Weather Research

Figure 8. Accumulated rain amount as the function of time in the simulations with high and low aerosol concentrations over the whole computational area (left panel) and over the land only (right panel).
Forecast model (WRF) (developed in NCAR) (Skamarock et al 2005) with the 1 km-resolution and the COSMO (Weather prediction model of the German Meteorological Service) with 2 km resolution and an advanced two-moment bulk microphysics parameterization.

Two rain events have been simulated: on 5 January 2007 and on 20-21 January 2007. Each rain event was simulated for low (maritime) and high (seeded) concentrations of small aerosol particles.

In the simulations using WRF the microphysics module of Thompson et al (2004) was used. The input of this scheme is the droplet concentration. In the low and high aerosol concentrations the droplet concentrations were set equal to 50 and 500 cm\(^{-3}\), respectively.

Fields of accumulated rain calculated for rain event on 5 January 2007 in cases of low aerosol concentration (left panel) and high aerosol concentration (right panel) are shown in Figure 9.

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Fields of accumulated rain calculated for rain event on 5 January 2007 in cases of low aerosol concentration (left panel) and high aerosol concentration (right panel) are shown in Figure 9.

Figure 9. Fields of accumulated rain calculated for the rain event on 5 January 2007 in cases of low aerosol concentration (left panel) and high aerosol concentration (right panel).

One can see that an increase in the aerosol concentration leads to a significant increase precipitation over land; b) this increase takes place both in Northern Israel, and in the southern part of Israel. Similar results are obtained in simulation of the rain event on 20 January 2007 (Figure 10).

Figure 11 shows the time series of the accumulated rain over the land in simulations with low and high aerosol concentrations (rain event on 20 January).

Figure 11. Time series of the accumulated rain over the land in the simulations with low and high aerosol concentrations (the rain event on 20 January 2007).

One can see that the increase in the aerosol concentration led to the increase in the
accumulated rain by 15%. Similar results were obtained for the rain event on 5 January 2007.

Another set of 3-D simulations was performed using the COSMO model which is an operational weather forecast model of the Germany Weather Service. This model uses an advanced two-moment bulk parameterization scheme developed in the Karlsruhe University (Seifert and Beheng 2006). In this parameterization the size distribution functions of hydrometeors are given in the form of generalized Gama-distributions. The parameters of this distribution allow one to vary the concentrations and widths of drop size distributions. Figure 12 shows the size distributions used in the simulations. The first distribution is characterized by smaller droplet concentration and higher width and is referred to as low AP concentration case. The second distribution has higher drop concentration, but smaller width. This distribution can be assigned to the high AP concentration case but is called here intermediate

Figure 12. Droplet size distributions used in simulations with the model COSMO of the Germany Weather Forecast Service in cases of clean air (blue) and polluted air (green).

In this case idealized initial and boundary conditions were assumed and the simulations performed with a SST-land temperature difference equal to 6°C. Figure 13 shows the fields of accumulated rain in case of low (left) and high (right) aerosol concentrations.

![Figure 12](image1.png)

Figure 12. Droplet size distributions used in simulations with the model COSMO of the Germany Weather Forecast Service in cases of clean air (blue) and polluted air (green).

![Figure 13](image2.png)

Figure 13. Fields of accumulated rain calculated using the COSMO model in case of low (left) and high (right) aerosol concentrations. The numbers denote amount of precipitation over the sea and over the land in these two cases. One can see that increase in the aerosol concentration leads to increase in precipitation over the land

One can see that that the increase in the aerosol concentration led to an increase of the precipitation over land and to decrease in the precipitation over sea in a good agreement with the results obtained using HUCM and WRF models. According to the results of the COSMO model the increase in precipitation caused by the increase in the aerosol concentration is about 18-20%.

The good agreement in the results obtained by different models increases the reliability of the results obtained. We attribute this good agreement to the fact that the effect of aerosols on the shift of precipitation is reproduced well by most models with advanced microphysics.

4. DISCUSSION AND CONCLUSION

Numerical simulations of sea breeze-affected cloud systems under the conditions
typical of Mediterranean area have been carried out using the spectral bin microphysics model HUCM and two high resolution 3D mesoscale models (WRF and COSMO) with different bulk microphysical schemes. It was found that an increase in the small aerosol particles concentration leads to a delay in the precipitation formation and to a significant increase of the snow amount. Snow has smaller fall velocity and advected downwind for larger distances. Hence, the increase in the aerosol concentration leads to a shift of precipitation from sea to land sometimes up to 100 km, so that precipitation over land increases and exceeds that it was under low aerosol concentration.

According to the results obtained, an increase in the small aerosol production in Europe should lead to an increase in precipitation at the coastal zone of Israel. Such an increase has been indeed reported by Alpert et al (2007), who analyzed precipitation at coastal stations during several past decades.

Note that this result was obtained in case when large aerosols with 4 µm in diameter presented in the initial AP size distribution. The reason of a comparatively low effect of large CCN on precipitation from deep convective clouds in case of high drop concentration is discussed by Khain et al (2008b) in detail. The main reason is that if the droplet concentration is high supersaturation is low and large drops forming on largest CCN grow slowly. One of the reasons is that in course of the diffusional growth, the radii of smaller droplets grow faster than those of large ones (Rogers and Yau, 1989) and the sizes of the initially small droplets tend to those of the largest ones. Besides, in the presence of a comparatively high vertical velocity and comparatively low freezing level, all droplets ascend above the freezing level being of nearly the same size and participate in cold processes. Thus, large aerosols that potentially can exist at strong winds, do not affect significantly the spatial shift of precipitation downwind in case the concentration of small aerosols is significant and the concentration of droplets exceeds about 600-700 cm⁻³.

The fact that all models indicate comparable results shows that the effect can be attributed to quite strong mechanism, clear from the physical point of view and relatively simple for simulations. To get an increase in the precipitation over land, it is not necessary to get total precipitation enhancement (which simulation requires very fine description of all microphysical processes).

We consider our results as potentially important for the rain enhancement activities in the regions when such synergetic interaction of local (sea breeze) and synoptic circulation can take place. In addition to Israel, such conditions supposedly take place in Italy, Egypt, Lebanon, Bulgaria, Portugal and some other countries.

We propose to seed clouds arising over the sea in the vicinity of the coastal zone by small aerosol particles near cloud base. Such seeding would affect the entire cloud, but not only its upper cold part (as it takes place by glaciogenic seeding). The seeding with small aerosols will lead to the formation of larger amount of ice crystals and snow via effects crystal-water and crystal-crystal collisions at the expense of large graupel falling over the sea of over the coastal line (and melted within the boundary layer).

The size of seed aerosol particles may be around 0.1 µm. The mass of such particle is ~10⁷ times smaller than the size of “optimum” size of soluble particle in hygroscopic seeding (Segal et al 2004). Thus, the mass of a seed material to provide a significant increase in the droplet concentration may be of the same order as the mass usually used for the hygroscopic seeding.

It is possible to combine this method of hygroscopic seeding with that of glaciogenic seeding. In this case seeding particles should represent small soluble aerosol particles with some insoluble fraction (which replaces the role of ice nuclei). Small aerosols will increase the mass of supercooled water which can be transferred into snow by glaciogenic component of the seed particles. This can lead to an increase of the formation of larger mass
of snow and to shift precipitation downwind because of lower sedimentation velocity of snow as compared to that of graupel.

The advantages of the method proposed are: a) the cloud development can be predicted with a high precision by the high resolution weather forecast models, so that the zones of the potential seeding will be known well before the seeding operation. b) The radar observations allow us to choose clouds for the seeding; c) the radar will also be used to follow both seeded and non seeded clouds. It will allow one to distinguish between seeded and non-seeded clouds. The effects of seeding must be seen by a longer penetration of seeded clouds inland. We propose such a seeding experiment which will be the first one, where seeding effects could be evaluated and controlled with high accuracy.

A significant advantage of the method is that it does not require obtaining the total precipitation enhancement. Many uncertainties in cloud microphysics, which are of crucial importance for simulation of precipitation enhancement, are of the secondary importance when the spatial shift of precipitation is simulated.

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