ANTHROPOGENIC AEROSOLS INVIGORATING HAIL

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1. PROJECT ANTISTORM

1.1 The ANTISTORM project summary

Here we report the main results of the ANTISTORM (Anthropogenic Aerosols Triggering and Invigorating Severe Storms) FP6 project that took place for the two years of 2006 and 2007.

According to the ANTISTORM conceptual model, illustrated in Fig. 1, a main cause for the lack of hail in pristine warm base clouds is the depletion of cloud water to rain before reaching the freezing level. The water that does ascend to the supercooled produce many ice precipitation embryos that compete on the remaining cloud water, and hence cannot grow to large hailstones. Suppressing the warm rain up to the supercooled levels requires large amounts of aerosols, which, according to the explicit microphysics model simulation, produce more than 1500 drops cm^{-3} at cloud base. Higher amounts of aerosols can suppress the warm rain to the extent of creating too few ice hydrometeors that would therefore produce less hail, unless significant recirculation of precipitation occurs. Recirculation should produce the largest hailstones, especially in the case of very high aerosol amounts that suppress much of the precipitation in the intense updrafts except when containing re-circulated precipitation particles. In such case all the cloud water would be available for the efficiently growing large hailstones. Therefore, the "optimum" amount of aerosols for warm base clouds should be very high, or even non-existent in certain dynamic circumstances that are prone to significant recirculation.

A shorter distance between cloud base and the freezing level exists in convective clouds with cooler bases, as was observed and simulated. Therefore smaller concentration of aerosols is required for suppressing the early warm rain that would prevent the formation of large hail. On the other hand, large concentrations of aerosols would more easily suppress the warm rain to the extent of scarcity in hail embryos.

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Clouds with very cold base, near 0°C, already form as supercooled clouds with little room for rainout. In such clouds only quite pristine conditions would produce excess of precipitation embryos that would compete on the available cloud water and prevent the formation of hail. Already moderate concentrations of aerosols can suppress the formation of ice precipitation embryos to the extent that hail is substantially reduced.

1.2 The objectives of ANTISTORM project

1. Testing the hypothesis that added pollution aerosols can invigorate convective storms and induce them to produce more hail.
2. Testing the whether this phenomenon can occur within the European region.
3. Providing the basis for improving the numerical weather forecasting of severe convective storms in Europe by merging pollution aerosol prediction with convective storm prediction in a model that contain the physical processes by which these aerosols affect the convective storms.

Much of the effort in the project was concentrated on building 2 moment bulk microphysical model that would provide similar results as the bin microphysics, when run on the same dynamical framework. This objective was not fully achieved. Therefore we report here only on the bin microphysics component of the simulations, without necessarily claiming that it is more correct than the bulk simulations.

1.3 The ANTISTORM consortium

The project was a NEST FP6 consortium, composed of:

1. Daniel Rosenfeld and Alexander Khain, The Hebrew University of Jerusalem, Israel. This partner was responsible for the overall coordination of the project, and for simulations with the Hebrew University Cloud Model with explicit bin microphysics.
2. Meinrat O. Andreae and Jos Lelieveld, Max Planck Institute for Chemistry, Mainz, Germany. This partner was responsible for simulations and observations of CCN aerosols.
3. Klaus Beheng, University of Karlsruhe, Germany. This partner was responsible for simulations with bulk microphysics over domains that are two large for the HUCM simulations.

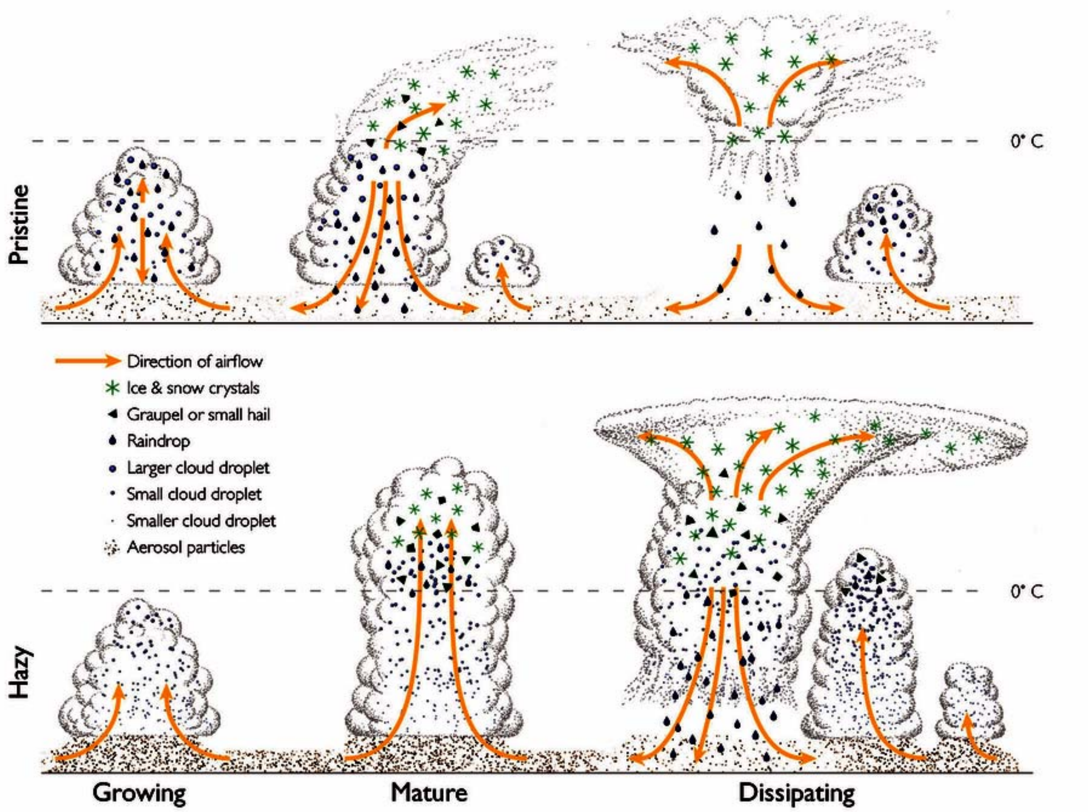

Figure 1: The conceptual model for pollution aerosols invigorating warm-base convective clouds. The early rain formation in the pristine case invokes early downdraft and prevents the lifting of much water to the supercooled levels, so that the cloud dies early with a moderate amount of rainfall. In the hazy case the rain is delayed, so that much supercooled water is accumulated in the mature stage that produces hail, strong precipitation and downdraft in the dissipating stage. The gust front can be sufficiently strong to trigger the next generation of convective clouds and so on, leading to the formation and propagation of a squall line (from Rosenfeld, 2006).

4. Vincenzo Levizzani, Institute of Atmospheric Science and Climate -- CNR, Bologna, Italy. This partner was responsible for satellite remote sensing of the cloud microstructure.

2. THE ANTISTORM CONCEPTUAL MODEL

Impact of manmade pollution aerosols have been widely recognized as affecting the climate system by suppressing drizzle from shallow marine clouds and so extending the cloud cover by preventing their dissipation by raining out, in a mechanism that was recognized only very recently (*Rosenfeld*, 2006). The impact of pollution aerosols on deep cloud has been less obvious, although as important. The suggested climate impact of the aerosols has been summarized by the coordinator of ANTISTORM into a white page paper, which also proposes a way forward. This white page paper was endorsed and announced as a joint IGBP (International Geosphere-Biosphere Programme) – WCRP (World Climate Research Programme) initiative (*Rosenfeld and Silva Dias*, 2008).

The ANTISTORM hypothesis is formulated there in the following language: "In deep convective clouds with warm bases, such as prevail in the tropics and during summer in the midlatitudes, the delayed precipitation due to more and smaller droplets may cause the condensates to ascend to the supercooled levels instead of raining out earlier by processes that do not involve the ice phase. By not raining early, the condensate would then form ice hydrometeors that release the latent heat of freezing aloft and reabsorbing heat at lower levels where they melt. The result would be more upward heat transport for the same amount of surface precipitation. The consumption of more static energy for the same precipitation amount would then be converted to equally greater amount of released kinetic energy that could invigorate the convection and lead to a greater convective overturning, more precipitation and deeper depletion of the static instability. Furthermore atmospheric moisture that is not rained out due to suppression of rainfall by aerosol, may eventually increase the rainfall elsewhere. The enhanced and delayed aerosol-induced release of latent heat may lead to regional scale enhancement and re-distribution of convection, low level moisture convergence and precipitation." The conceptual model is illustrated in Figure 1 (*Rosenfeld*, 2007), and further elaborated on in (*Rosenfeld*, 2006).

3. MODEL SIMULATIONS OF IMPACT OF AEROSOLS ON HAILSTORMS

3.1 The model description

We report here on the results of testing the ANTISTORM hypothesis with a spectral (bin) microphysics (SBM) model. The model is the two-dimensional Hebrew University cloud model (HUCM) with the SBM scheme implemented. The microphysical schemes in the models are described in (*Khain et al.*, 2004; *Khain et al.*, 2005). The model is based on solving a kinetic equations system for size distribution functions for water drops, ice crystals (plate-, columnar- and branch types), aggregates, graupel and hail/frozen drops, as well as atmospheric aerosol particles.

To test the ANTISTORM hypothesis and to simulate mixed-phase microphysics as realistic as possible at the present time, significant activities for model development and update have been carried out. These activities include both further modification of the SBM and other model developments. The modification of the SBM scheme includes:

- The number of mass bins used for the description of all size distribution functions has been increased from 33 to 43. As a result, the maximum diameter of hail stones that can be resolved by the model (as well as melted radii of other hydrometeors) was increased from 1 cm to 6.5 cm. The table of collision efficiencies and kernels has been recalculated accordingly.
- The breakup procedure has been updated (with help of Dr. Seifert) to include larger particles.
- A new approach developed by Dr. Ulrich Blahak for determination of the beginning of wet growth of graupel (which can be interpreted as the formation of hail by graupel riming) has been implemented;
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A more detailed description of the model and additional improvements beyond the ending of the ANTISTORM project is given in the companion extended abstract (Khain et al., 2008).

3.1 The simulations results

Several important conclusions can be derived from the 2D simulations. The main conclusions can be summarized as follows.

1. Hail intensity, hail kinetic energy at the surface and precipitation are very sensitive to aerosol concentrations. The hail kinetic energy is negligible at low aerosol concentrations (lower than 200-300 cm^{-3}).
2. The dependence of hail kinetic energy and precipitation is non-monotonic. There exist aerosol concentrations under which hail kinetic energy and accumulated rain reach their maximum. These values depend on the environmental conditions. They are small (100-300 cm^{-3}) for very dry or clouds with very cold base temperatures, and very high (exceeding 1500-3000 cm^{-3}) for moist tropical conditions with warm cloud base.
3. The results reported earlier about increase in precipitation in maritime tropical conditions and decrease in precipitation in a very continental unstable conditions (*Khain et al.*, 2001; *Khain and Pokrovsky*, 2004; *Khain et al.*, 2004; *Khain et al.*, 2005) (where only two aerosol concentration were tested) agree well with the results.
4. Under intermediate conditions typical, say, of hail storms in Germany, the CCN concentrations under which hail kinetic energy and precipitation reaches their maximum is about 800 cm^{-3}.
5. It was suggested that one of the main parameters determining the response of hail energy (hail size), as well as precipitation amount is the temperature of cloud base.
6. A special set of simulations with idealized temperatures at cloud base, shown in Fig. 2, supported this hypothesis. Clouds with warm cloud base (20°C) correspond to maritime convective clouds, while clouds with very cold cloud base (0°C) correspond to extremely continental clouds developing in dry atmosphere. Hail storms in Germany develop under intermediate conditions (cloud base around 10°C).

Summarizing the results we can conclude that the results of simulation support the ANTISTORM hypothesis concerning the sensitivity of hail production to aerosol concentration. At the same time, the conditions of the hail formation were investigated in more detail, which allowed us to present a classification of conditions of large hail formation.

To our knowledge, for the first time non-monotonic dependence of hail production and precipitation on aerosol concentration was found. So, the question, whether aerosols increase or decrease hail and precipitation cannot be formulated without mentioning particular meteorological conditions of cloud development (one of the major parameters is the cloud base temperature).

It was found that hail increases precipitation efficiency of clouds with high aerosol concentration.

Note that the results obtained within the frame of the 2 years ANTISTORM project are preliminary to some extent. More 3D simulations are required. In 2D simulations the computational area should be increased to prevent the lost of ice hydrometeors through the boundaries during the computations.

More detailed comparison between the results of 2D and 3D simulations is required.

In course of the project it was found the necessity to improve ice representation in SBM models. It is necessary to implement budget of ice nuclei into the model. High sensitivity to breakup indicates that this process has to be simulated as accurately as possible.

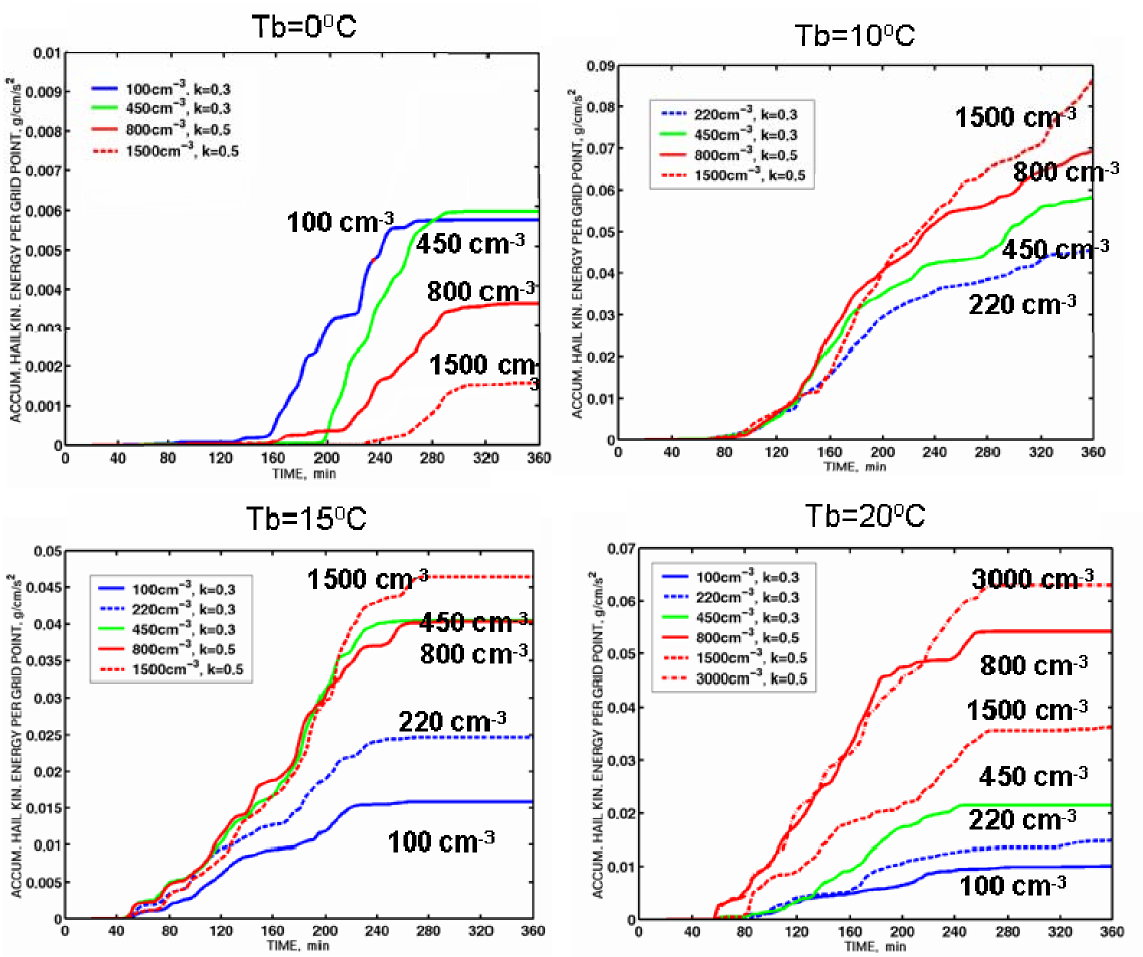

Figure 2: Time dependencies of accumulated hail kinetic energy at the surface in simulations with different cloud base temperatures and aerosol concentrations. The values are exaggerated because shedding of the melting hail is not yet included in these runs.

4. THE REFINED ANTISTORM HYPOTHESIS

According to the conceptual model illustrated in Fig. 1, a main cause for the lack of hail in pristine warm base clouds is the depletion of cloud water to rain before reaching the freezing level. The water that does ascend to the supercooled levels produce many ice precipitation embryos that compete on the remaining cloud water, and hence cannot grow to large hailstones. Suppressing the warm rain up to the supercooled levels requires large amounts of aerosols, which, according to Fig. 3, produce more than 1500 drops cm^{-3} at cloud base. Higher amounts of aerosols can suppress the warm rain to the extent of creating too few ice hydrometeors that would therefore produce less hail, unless significant recirculation of precipitation occurs. Recirculation should produce the largest hailstones, especially in the case of very high aerosol amounts that suppress much of the precipitation in the intense updrafts except when containing re-circulated precipitation particles. In such case all the cloud water would be available for the efficiently growing large hailstones. Therefore, the "optimum" amount of aerosols for warm base clouds should be very high, or even non-existent in certain dynamic circumstances that are prone to significant recirculation.

A shorter distance between cloud base and the freezing level exists in convective clouds with cooler bases, as was observed (see Fig. 3) and simulated. Therefore smaller concentration of aerosols is required for suppressing the early warm rain that would prevent the formation of large hail. On the other hand, large concentrations of aerosols would more easily suppress the warm rain to the extent of scarcity in hail embryos.

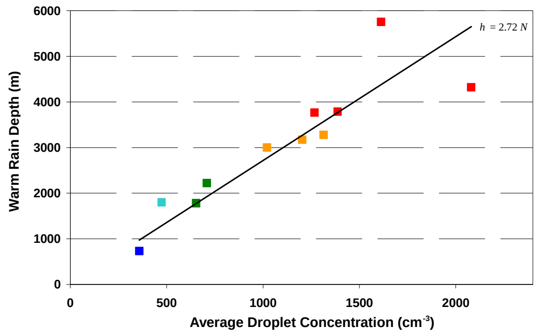

Fig. 3: Relation between cloud base drop concentration and the height for onset of warm rain in young growing convective clouds in the Amazon (*Freud et al.*, 2008). The drop concentration, in turn, depends on the CCN concentrations. Note the increased depth for warm rain with greater number concentration of drops at cloud base and hence of CCN concentration.

According to the refined conceptual model (Fig. 4), clouds with very cold base, near 0°C, already form as supercooled clouds with little room for rainout. In such clouds only quite pristine conditions would produce excess of precipitation embryos that would compete on the available cloud water and prevent the formation of hail. Already moderate concentrations of aerosols can suppress the formation of ice precipitation embryos to the extent that hail is substantially reduced.

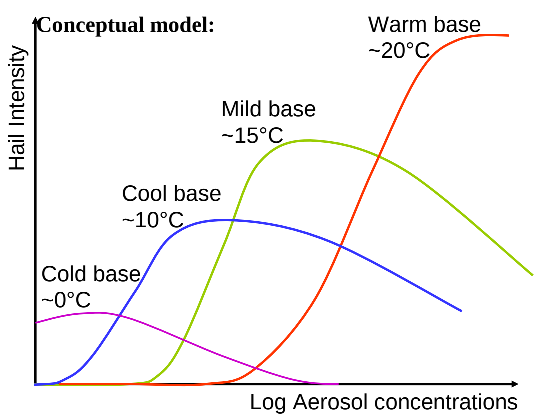

Figure 4: The refined ANTISTORM conceptual model. There is an "optimal" level of amount of aerosols for the most intense hail, which increases with warmer cloud bases. Beyond that optimum the amount of hail and storm intensity starts to decrease, but not to the low level of the pristine storms. The "optimal" storm intensity increases with warmer cloud base, which requires greater amounts of aerosols.

5. CONCLUDING REMARKS

To our knowledge, for the first time non-monotonic dependence of hail production and precipitation on aerosol concentration was recognized. So, the question, whether aerosols increase or decrease hail and precipitation cannot be formulated without mentioning particular meteorological conditions of cloud development (one of the major parameters is the cloud base temperature).

The simulations indicate that hail increases precipitation efficiency of clouds with high aerosol concentration. This feature could not yet unambiguously be captured in the bulk model. Besides different mechanism used in the bin and bulk model to create and grow hail also the different model geometries (2D vs. 3D) may be a source of the differing results (not reported here). Note that the results obtained within the frame of the 2 years ANTISTORM project are preliminary to some extent. More 3D simulations are required. In 2D simulations the computational area should be increased to prevent the lost of ice hydrometeors through the boundaries during the computations.

In course of the project it was found necessary to improve ice representation in SBM models. It is necessary to implement budget of ice nuclei into the model. High sensitivity to breakup indicates that this process has to be simulated as accurately as possible. After the ending of the project additional effort was invested in improvement of the model processes of hailstorms, which are reported in the companion extended abstract (Khain et al., 2008). At the point of conclusion of the project, reported here, we have reached the state where the simulation of hailstorms with a bin model allowed us to gain the insights that led to the refined ANTISTORM conceptual model, shown in Fig. 4.

ANTISTORM did produce a new insight to the way aerosols affect severe convective storms, and opened ways for implementing these insights to a better prediction of severe convective storms. These insights will help in the future also to reduce the risk of these storms if ways will be found to reduce the particulate air pollution during the warm and moist summer days. However, much work remains to foster the results and make them workable in operational forecasting environment.

6. ACKNOWLEDGEMENTS

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