

# **Investigation in HEAT of the Effects of Aerosols on Cloud Microphysical Properties, Dynamical Feedbacks and Lightning Activity: Revised Input for the HEAT SOD**

**William L. Woodley  
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## **1.0 INTRODUCTION**

The primary goal of the Houston Environmental Aerosol Thunderstorm (HEAT) project is to examine anthropogenic impacts on the vigor of convection, lightning and precipitation, using substantial apparent effects of Houston as the case study. A 50% enhancement of cloud-to-ground lightning discharges was observed over Houston, Texas, accompanied with a significant enhancement of precipitation amount downwind of the city. Comparable lightning enhancement apparently has been observed also over Lake Charles, Louisiana. Reaching this goal will involve quantification of the effects of pollution, the urban heat island, and the complex coastline on storms and lightning characteristics in the Houston area. Invigoration of convection means conversion from warm rain to ice precipitation forming processes, and disposition of the released latent heat higher in the troposphere. This has large impact on energizing the weather systems at all scales (Andreae et al., 2004) A second goal of HEAT is the study of thunderstorm processing and transport of air pollutants and nitrogen oxides (via lightning).

During the March 2004 HEAT planning meeting in Boulder, Colorado, Dr. John Latham of UCAR made the following points with respect to cloud electrification and lightning (Personal communication, 2004):

- The electrification of thunderstorms and concomitant lightning activity is intimately related to cloud glaciation.
- The dominant charging mechanism is the non-inductive process involving rebounding collisions between ice crystals and graupel pellets growing by the accretion of supercooled droplets.
- Thus, ICE is utterly central to lightning production and rates, and significant charging will occur only in regions where graupel, supercooled droplets and ice crystals coexist, i.e. in the so-called charging zone.
- Charging increases rapidly with decreasing temperature within the zone – largely because of the high sensitivity of the charge transfer per collision to crystal size.
- Thus, the updraft velocity  $W$  becomes an important factor, because the height of the lid of the charging zone is usually dictated by the height to which the precipitation (graupel) can rise before its terminal fall-speed  $V$  exceeds  $W$ .
- Evidence shows that two glaciation mechanisms are important in thunderstorms – primary nucleation and ice multiplication (IM)
- The glaciation and electrical development are very sensitive to the glaciation mechanism predominating in a particular situation.

- IM requires a broad droplet spectrum for its effective operation, so if the number concentration  $N$  is increased by pollution beyond a certain value it seems possible that lightning activity may be inhibited because IM would be suppressed.
- Thus lightning production and activity is determined by a number of highly interactive microphysical, dynamical and electrical processes in which ice plays a central role.
- The specific goal of establishing whether pollution causes enhanced lightning activity cannot be addressed properly unless a comprehensive study is conducted within HEAT of the influence of pollution on the glaciation of the thunderclouds and the production of solid precipitation within them. The same comments apply to any other proposed mechanism of enhanced lightning activity.

Put simply and succinctly, a deep, vigorous, mixed-phase zone in clouds is essential to the generation and separation of electric charge and to subsequent in-cloud and cloud-to-ground lightning. Thus, clouds with strong direct forcing (e.g., UHI convergence) or with indirect forcing through feedbacks from cloud microphysics are those most likely to have strong drafts and a deep mixed-phase zone in which ice hydrometeors in many sizes and habits coexist with deep supercooled cloud water. Such clouds, which exist primarily over land and not over water due to the disparity in updraft intensities, are normally highly electrified.

Many mechanisms can be invoked for the direct vigorous forcing of convective clouds and their subsequent electrification. In the context of HEAT the urban heat island (UHI), the effects of an irregular coastline and pollution may contribute individually or collectively to the increased cloud vigor and lightning activity in the Houston area. The first two contribute directly by the generation of updrafts in regions of increased convergence while the third may contribute indirectly by delaying coalescence and rainfall and the disruptive effects of premature downdrafts on the cloud updrafts. All three mechanisms will be investigated thoroughly in HEAT. The focus here is on the potential effects of aerosols on cloud electrification and lightning, both directly and through the feedbacks of the aerosol effects on the cloud dynamics through their impacts on the precipitation processes. The other two are addressed elsewhere in the HEAT SOD.

A conceptual model for the enhancement of lightning due to pollutants has been advanced by Dr. Daniel Rosenfeld (Rosenfeld and Lensky, 1998; Williams et al., 1999, 2002; Andreae et al., 2004). The hypothesis is quoted here from Williams et al. (2002):

*"Air drawn from the clean (polluted) boundary layer air will contain a small (large) number of large (small) droplets. Active coalescence and rainout of the cloud prevail in the warm portion of the maritime cloud, leading to the depletion of liquid water from the colder mixed phase region. A dominance of diffusional droplet growth and suppressed coalescence prevail in the continental CCN-rich clouds, preventing rainout and allowing liquid water to ascend to the mixed phase region where it plays a dual role. First, it can contribute to cloud buoyancy and the updraft strength by the latent heat of freezing. Second, it can contribute to the growth of graupel particles and catalyze the process of charge separation by ice particle collisions.*

*In clouds with very large concentrations of small CCN the formation of the ice phase can be delayed to very high altitudes and low temperatures [Rosenfeld and Lensky, 1998; Rosenfeld,*

2000; Rosenfeld and Woodley, 2002; Khain et al., 2001]. The delay in the ice formation to above the  $-20^{\circ}\text{C}$  isotherm is likely to deprive the lower part of the mixed phase region of a key ingredient for charge separation in a temperature range where it is most potent [Takahashi, 1978], and thereby addition of aerosols beyond a certain "optimum" may not enhance any more lightning, and may even decrease it with respect to that "optimum".

It involves the following sequential steps:

- Pollution from urban and industrial sources contains high concentrations of small ( $< 1$  micron diameter) cloud condensation nuclei (CCN).
- When this pollution is ingested into the clouds, condensation takes place on these many particles, resulting in a narrow spectrum of small drops and suppressed coalescence.
- The later onset of precipitation delays the formation of disruptive downdrafts, allowing for more cloud growth.
- In tropical maritime clouds with natural active warm rain that occurs below the freezing level, the suppression of the warm rainout allows more water to ascend to and above the freezing level, where it freezes, releasing greater amounts of latent heat, which act to further invigorate the clouds.
- In such clouds, the slower coalescence and the greater amounts of supercooled water in the stronger updrafts result in a deeper mixed-phase region.
- When the onset of precipitation is delayed from the warm to the lower supercooled portions of the cloud, large quantities of supercooled liquid water and ice hydrometeors of various sizes and habits coexist within the strong updrafts. This results in enhanced charge separation and more lightning.
- Under extremely high concentrations of small CCN the drops may be smaller than the threshold for ice multiplication, thereby suppressing the ice formation at the supercooled levels. This would induce suppression of the cloud electrification, especially at the most vigorous clouds. Therefore, in principle, an aerosol concentration for maximum cloud electrification should exist.

Thus, the key is the initial cloud conditions. In clouds having warm cloud bases, active warm rain below the height of the  $0^{\circ}\text{C}$  isotherm and little subsequent supercooling, the ingestion of numerous small CCN pollutants results in the sharing of the available liquid water in the storm updrafts among larger concentrations of smaller droplets. This reduces the mean droplet size and droplet collision efficiency and suppresses coalescence, leading to a deeper mixed-phase region in the cloud. This allows for more supercooled water in the presence of ice, and, therefore, greater charge separation and potentially more lightning, according to theory. This is the typical situation in the tropics and moist subtropics such as Houston, Texas. In continental high-based convective clouds, however, the ingestion of CCN pollutants will make the clouds even more microphysically inefficient such that the mix of supercooled water, graupel and ice crystals that is necessary for the generation and separation of electric charge might not be achieved. In such clouds, pollutants should lead to the suppression of cloud electrification.

These observations underline our limited understanding of mixed phase processes in clouds, especially those at highly supercooled temperatures, and the eventual freezing of the

cloud droplets. More measurements with state of the art cloud physics instruments as is planned in HEAT are necessary to understand the electrification process.

## 2.0 RESEARCH STRATEGY

The strategy that one employs in a research effort is crucial to its success. Knight (2004, personal communication) has emphasized the importance of defining a backbone for the HEAT project, which would be a rather inflexible routine of basic measurements that would enable relatively objective comparisons to be made, between "Houston storms" and "non-Houston storms". As he sees it, this would necessarily consist of:

- 1) Lightning network measurements.
- 2) Extensive, routine, background, aerosol measurements.

Routine aerosol measurements outside of cloud in the boundary layer in and around Houston **will require a commitment of a dedicated third aircraft for the needed aerosol measurements, which would be done every day that has storm potential.**

- 3) Satellite coverage.

Data from polar orbiting satellites carrying multi-spectral sensors (NOAA/AVHRR, MODIS Terra and AQUA) will be used to infer cloud microphysical properties over the entire experimental domain using the methodology of Rosenfeld (Rosenfeld and Lensky, 1998).

- 4) Radars

WSR-88D will be used for the full area coverage. Polarimetric radar measurements are necessary for identifying the types and sizes of the precipitation particles in the clouds. S-Pole and/or CHILL radars will be able to do these measurements, by focusing the scanning on the clouds which are measured by the aircraft, and otherwise providing a surveillance scanning of these properties from the storms over Houston and its vicinity.

- 5) Regularly available meteorological data.

Tracking the chain of events in the HEAT hypotheses require tracking the evolution of the convective cloud elements from their start at cloud base, the evolution of cloud drop size distribution with height, the initiation of precipitation in both water and ice phases, the initiation of the ice phase and the proliferation of the ice within the young convective elements, and the eventual total glaciation and disappearance of the cloud water sufficiently high in the cloud (what is that height and how it varies with updraft velocity and aerosols is a major research question). In practical terms it requires to concentrate with the cloud physics aircraft on the growing convective elements, and avoid the operationally messy parts of the mature storms.

Mature thunderstorms are complicated, with complex electric field structures, often complex dynamics and complicated recycling of ice and water hydrometeors. Supercooled water and ice contents vary considerably depending on both location and time. But the first-echo stage, up to the first couple of lightning events, "should" be simpler: at least there is a chance of it being simpler, and it seems to logical to spend some effort looking there for microphysical and electrical responses to pollution: Not only first echo heights, but liquid vs. ice (using ZDR), the early echo growth characteristics, and the early lightning characteristics as related to the radar features. Aircraft can be used more freely in these early stages as well. This too is consistent with the recommendations of Knight (2004).

Thus, the emphasis in HEAT should be on well-documented case studies, especially the early stages of a cloud system, and not on the development of statistical relationships that are unattainable in the limited duration of the field campaign. The most progress will be obtained through the physical insights gained by careful measurements of the relevant environmental and cloud properties, and their interpretation in the framework of a detailed microphysics 3-D cloud model that encompasses the scale of the experimental domain. Aerosol induced changes have strong dynamical feedbacks, which make it very difficult to separate the microphysical from the dynamic factors that affect the evolution of the cloud and the related cloud electrification processes. The separation of the dynamic from the aerosol effects is a major challenge that must be confronted in HEAT. It is proposed to address in the following way:

1. Documentation of the thermodynamic structure and the aerosols in the environment in which the potential thunderstorms will be growing, prior to and during their major growth phases.
2. Documentation of the vertical evolution of the young growing cloud elements, especially the following cloud properties as a function of height:
  - a. Updraft velocity.
  - b. Cloud drop size distribution.
  - c. Rain drop size distribution.
  - d. Ice crystal types and size distribution, and the same for graupel, hail and frozen drops.
  - e. Time evolution of these properties.
  - f. Interactions of individual clouds with each other, their merging and the development of clusters and squall lines.
  - g. Lightning origination in the context of the evolution of these clouds.

Properties a to d, and possibly e, can be done with aircraft measurements.

Properties c to f can be done with radars.

Property g can be measured with the lightning detection networks.

Property b can be documented on the larger scale with satellites.

In addition, the mesoscale flow patterns can be obtained from Doppler winds and from the meteorological observations of surface winds, temperature and moisture.

All of these measurements should be integrated into the framework of a cloud model that simulates microphysical processes explicitly as well as the surface effects on the scale of the whole cloud cluster throughout its life cycle over the greater Houston area and its vicinity. The best way to separate the various factors is to simulate several well-documented case studies using the cloud model with explicit microphysics (i.e., no "tuning" is applicable to such model). The validity of the model will be tested by its ability to reproduce the detail of the observations where they can be done, which is mainly in the growing stages of the clouds (measurements a to d, and when possible e). If the cloud model reproduces the measurable observations under several substantially different conditions, this validated model can be used to simulate the effect of changing the measured parameters, one at a time. Such an interactive process between modeling and observations will probably prove to be the best way of understanding the lightning anomalies in the Houston area.

One potential approach would involve the use of the RAMS model, which will be well suited for its proposed use in HEAT after incorporation of the explicit microphysical scheme of A. Khain. This process is already underway as a cooperative effort between the "fathers" of RAMS: Ronni Avissar, Roger Pielke, Isacc Mahrer, and the creators of the explicit microphysical scheme of the Hebrew University Cloud Model: Alexander Khain and Daniel Rosenfeld.

This microphysical model has the full description of the size distribution and fall velocities of the water and ice hydrometeors and the full interactions (collisions) between all of them. It should be relatively straight-forward effort to combine these simulations with a cloud electrification scheme, and collaborators in accomplishing this end are being sought. This is addressed further later in this document.

### **3.0 SCIENTIFIC OBJECTIVES FOR THE DOCUMENTATION OF THE EFFECTS OF ATMOSPHERIC AEROSOLS**

#### **OBJECTIVE P1: Ambient Pollution**

The documentation of aerosol properties is an integral and unique component of the HEAT effort. As pointed out by Carey, 2004; personal communication), there are several important areas of cloud physics modeling and integrated convective studies that could be pushed forward with such measurements. The goal of this component of HEAT, therefore, is the measurement of CN, CCN and IN (ice nuclei) concentrations and the resultant cloud base drop size distributions over the entire domain of interest on days when thunderstorms are expected, including the Houston metropolitan area, surrounding rural areas, coastal regions and possibly additional areas of known pollution farther to the east of Houston. This activity is consistent with the recommendations of Knight and other HEAT colleagues. Carrying it out properly, however, is going to require a dedicated aircraft for this purpose, because the U. of Wyoming King Air will be committed to the detailed case studies. Further, space will be limited on this aircraft for additional instrumentation. The existing CCN counter of the King Air will be used, however, to provide input CCN data for the case studies.

One possibility for an aircraft to be dedicated to HEAT aerosol measurements is the Piper Cheyenne turbo-prop, cloud physics aircraft, which has been newly put into service by the Texas SOAR program. It comes with a complete cloud physics package, experienced pilot (Gary Walker) and a dedicated flight scientist (Duncan Axisa), and the rates for its use appear to be less than other suppliers for such an aircraft. Regardless of which aircraft is dedicated ultimately to this task, it is emphasized that the continuous measurement of CCN and the associated droplet spectra at cloud base is vital to the success of the overall HEAT program. During the course of its use, the FSSP readings from this aircraft should be intercompared with the FSSP readings from the other cloud physics aircraft to be involved in HEAT, specifically the King Air and the jet cloud physics aircraft.

Dr. Don Collins of TAMU will play a major role in the assessment of possible sources of elevated CCN concentrations and in the determination of the concentration and composition of CN, CCN and IN in urban and non-urban environments, particularly in the vicinity of

thunderstorm updrafts. He envisions operating one TDMA/CCN counter on the ground, perhaps on a high-rise building, and one of the SOAR Cheyenne

A possible collaborator with Dr. Collins is Dr. Jim Hudson of the Desert Research Institute, who also has expressed a strong interest in being involved in HEAT. Two DRI CCN spectrometers would come with his participation. Preferably one of spectrometers would be on an airplane and another would be on the ground, perhaps mobile. These instruments would measure the complete CCN spectrum from 1 to 0.02% supersaturation (S). They have several advantages over other CCN devices especially those that have been mentioned in the HEAT documents to date.

1. They are not limited to concentrations of only  $1000 \text{ cm}^{-3}$ . CCN concentrations in Houston will generally be well above this level.
2. They operate continuously with time resolution as high as 1 per second, which is important for mobile (esp. aircraft) operation.
3. They simultaneously cover a much larger range of S compared to most CCN instruments that cover only 1-0.1% S. This is important for several reasons not the least of which is the fact that giant CCN are of great importance to precipitation initiation, especially in polluted environments, and they have  $S_c$  well below 0.1%.
4. Covering lower S is especially important in polluted environments where cloud S is generally lower due to competition among the large concentrations of CCN/droplets.
5. These instruments can also provide the sizes of CCN, which is an important clue about anthropogenic origins versus natural origins.
6. They can provide particle volatility information that can compliment the size- $S_c$  measurements (5).
7. The instruments can be used to check Kohler theory, which is the basis of CCN measurements and their application to the atmosphere. This could determine whether CCN measurements alone are sufficient to predict aerosol-cloud interactions. A large metropolitan pollution source especially the organic outputs of oil refineries would be likely candidates for perturbations of Kohler theory.

## **OBJECTIVE P2: Cloud droplet spectra**

The available liquid water in a storm updraft is shared among a large number of droplets, when the boundary layer air feeding the storm is 'dirty' or polluted. This reduces the mean droplet size and suppresses coalescence processes (Rosenfeld and Lensky 1998; Williams et al. 1999, 2002). Rosenfeld (2000) has found that aerosols from factories and power plants divide the water in the clouds into droplets too small to precipitate from clouds of modest depth. Similar findings were made for his study of biomass burning (Rosenfeld, 1999). Comparable findings were obtained by Andreae et al., (2004) for a similar study in Brazil. Similar results are expected in HEAT.

The goal of this HEAT component is to collect simultaneous microphysical, thermodynamic and electrical data sets for storms in the vicinity of a polluted urban area. The data sets will be analyzed to determine the relationship of the aerosols, instability and the vertical

evolution of updrafts, cloud droplet spectra, ice crystals and hydrometeors to the observed lightning characteristics. Besides the aircraft measurement of the droplet spectra in individual clouds, the Rosenfeld satellite methodology (Rosenfeld and Lensky, 1998) will be used to infer the droplet effective radius as a function of height (temperature) for clouds over and downwind of Houston and Lake Charles, Louisiana, and over surrounding rural areas. The satellite data will serve as a means to extend the point measurements of the cloud physics aircraft to much greater area in time and space, to be used in conjunction with the areal lightning measurements and the model simulations. These too will be compared to the electrical data sets.

Measurements of the cloud droplet spectra, the water and ice hydrometeors and their evolution with height and time and as a function of updraft velocity in growing convective elements will be made by the University of Wyoming King Air (low to mid-portions of the clouds, up to the 0°C isotherm level) and by the jet cloud physics aircraft (for the upper portions of the cloud) for both high aerosol (urban polluted) and lower aerosol (environmentally clean) storms in order to compare any differences. Such inferences will be made also from AVHRR and MODIS satellite imagery after processing according to the method of Rosenfeld (Rosenfeld and Lensky, 1998). The lightning data set will be obtained by the NLDN and lightning mapping system.

One of the HEAT aircraft research teams, consisting of Drs. D. Rosenfeld (Hebrew University of Jerusalem), W.L. Woodley (Woodley Weather Consultants, and E. Williams (Massachusetts Institute of Technology), hope to play a major role in the measurement campaign with the jet cloud physics aircraft. Their focus will be on the documentation as a function of height of the cloud droplet spectra, the amount of supercooled water, the spectra of the water and the various types of ice precipitation particles and ice crystals, the depth and character of the mixed-phase zone, as well as the updraft velocities. These scientists have many years of flight experience under the challenging conditions that are expected in HEAT, most recently in the powerful hailstorm clouds of northwestern Argentina. This team must coordinate its efforts with all other HEAT scientists who intend to make use of the jet cloud physics data for their scientific purposes.

The measurement of the droplet spectra will be made by ascending rapidly from cloud base to anvil cloud tops in vertical increments of approximately 2000 feet. The most vigorous convective cloud(s) within immediate range of the aircraft will be penetrated for cloud microstructure during each height increment. The evolution of cloud microstructure with time at a fixed height will also be measured by repeated penetrations in the same cloud element at the same height as it matures and stops ascending. First-look processing and data assessment will be made at the end of each flight before plans are made for the next day. Free and ready exchange of the aircraft data, according to established HEAT procedures, will be made with other scientists desiring access to the aircraft data. The research team intends to submit a proposal to the NSF for the design, conduct and evaluation of the jet cloud physics program after adding Dr. Alexander Khain of the Hebrew University of Jerusalem to the team for the simulation of cloud microphysical processes using the Hebrew University Cloud Models (Khain et al., 2001) that address cloud microphysical processes explicitly. This should be done in HEAT in conjunction with the measurements from the jet cloud physics aircraft if one is to address the effects of aerosols on cloud drop and hydrometeor particles size distributions realistically. A good example

of the interactive use of such cloud models and observations is provided by the documentation (Rosenfeld and Woodley, 2000) and simulation (Khain et al., 2001) of clouds in West Texas in which substantial quantities of liquid water were found by the Lear jet cloud physics aircraft to near the point of homogeneous nucleation ( $-38^{\circ}\text{C}$ ).

In addition to its boundary-layer duties and its CCN measurements, the U. of Wyoming King Air will be used to measure the droplet spectra from cloud base to roughly  $0^{\circ}\text{C}$  to  $-10^{\circ}\text{C}$ , using procedures comparable to those to be employed by the jet cloud physics aircraft. The PI for the use of this aircraft apparently had not been identified as of this writing. If this is indeed the case, a flight scientist from the team of the jet cloud physics aircraft will serve as PI on the U. of Wyoming King Air.

**OBJECTIVE P3: Depth of the supercooled liquid water and characteristics of the mixed-phase zone**

A consensus has developed among HEAT scientists that the electrification of Houston urban and rural clouds will depend in part on the sizes and habits of ice hydrometeors that exist within a deep zone of supercooled cloud water. Most would agree, therefore, on the importance of complete documentation of cloud microphysical and dynamical properties from cloud bases to cloud tops in HEAT. There is no consensus, however, on the mechanisms that might be responsible for the enhancement of this coexistence of ice and water. Some focus on the ingested aerosols while others invoke dynamic factors such as increased convergence and updrafts in the UHI as causal factors. In reality cloud microphysics feeds back into cloud dynamics and vice versa, so the answer is not likely to lie in an either/or proposition. Case studies that are interactive with cloud modeling will be necessary to separate out the factors responsible for the increased cloud electrification.

This provides tremendous motivation to make the needed measurements in the vigorous clouds of HEAT and a willingness on the part of the pilots and the scientists to penetrate the convective cores that drive the cloud processes. Further, the jet aircraft to be employed for this purpose, whether it be the UND Citation or the WMI Lear, must have sufficient performance to carry out the mission as designed.

The goal of this component of HEAT, therefore, is to collect simultaneous polarimetric, microphysical, and electrical data sets of storms within and outside the polluted Houston urban environment. The data sets will be combined to aid in determining the effects of pollution on the microphysics of cloud structure and the electrification processes. The observed data will have a large spatial and temporal resolution, so idealized cloud models will be utilized to provide complete data fields to study. The numerical cloud models from SDSMT and University of Oklahoma/National Severe Storms Laboratory, which have parameterizations for microphysical and electrical processes, will be used for this purpose as is intended by some investigators. An alternative approach discussed earlier would be the use of the RAMS 3-D cloud model after incorporation of an explicit cloud microphysical scheme (underway) and a module that simulates cloud electrification. This is the preferred course of action from this writer's perspective.

Measurement of the supercooled liquid water and ice contents will be made by the CSU-CHILL and the S-Pol polarimetric radars. Electrical data sets will be collected by the NLDN and lightning mapping system. Simultaneous measurement of the cloud microphysical and draft structures will be made by the jet cloud physics aircraft. The mixed phase zone will be measured for its vertical extent (i.e., glaciation temperature) and the development of graupel and ice crystals with height and time in the convective cores. This is a challenging mission, which will require the special skills of the jet pilots and associated scientists, who have had significant experience with such missions in Texas (Rosenfeld and Woodley, 2000) and Argentina (Rosenfeld et al., submitted).

Many scientists likely will be interested and/or involved in this component of HEAT. In addition to the Woodley/Rosenfeld/Williams/Khain research team. This includes the team from the South Dakota School of Mines and Technology consisting of Andy Detwiler, John Helsdon, Donna Kliche, and Dick Farley. Their interest is in testing the hypothesis that the increased CG lightning activity in urban storms compared to rural ones is due to microphysical or chemical differences between the two classes of storms, which in turn are caused by differences in aerosol concentration and chemistry between rural and urban air.

They do not expect to observe sufficient numbers of storms to rigorously test this hypothesis. Rather, they plan to use detailed case studies to look in an exploratory fashion for trends in aerosol chemistry and microphysics correlated with trends in cloud chemistry, microphysics, electrification and lightning.

The SDSMT research team will require several classes of observations, including sounding data to monitor atmospheric stability and profiles of winds and humidity, surface and low-level sampling of air chemistry and aerosol characteristics, and airborne measurements in the mixed phase region of flanking towers and developing main convective regions. Dual-Doppler polarimetric radar data will allow identification of hydrometeor classes within thunderstorms and computation of storm circulations. Airborne electric field data are desirable. In addition, LDAR II and NALDN data will be required to monitor storm electrical processes.

The observations likely will be insufficient to reach a clear understanding of the relative importance of non-inductive, inductive, and other charge separation processes in storm electrification, and how these might have varying relative importance in ultimately influencing lightning activity. They plan to use the SDSMT Storm Electrification Model (SEM) to simulate cloud development for a range of cases. Model output will be used to diagnose more quantitatively the dominant microphysical and charge separation mechanisms in each storm analyzed, and how the relative importance of the various mechanisms might vary between urban and rural storms. The SEM has a hybrid microphysics package, combining sophisticated bulk parameterizations with bin representation of the distribution of graupel and hail. It has a sophisticated lightning discharge mechanism in it, and detailed chemical equations for transformations among oxides of nitrogen, oxygen, ozone, and other species of interest.

The planned SDSMT HEAT work will build on the work they are doing now with data from STEPS. Houston storms should contrast distinctly with the high-based storms observed over the semi-arid cropland of eastern Colorado and western Kansas.

Dr. V.N. Bringi of Colorado State University hopes to play a role in the remote sensing of hydrometeor microphysical properties using polarimetric radar for the rain DSD retrievals and observations of  $Z_{DR}$  intrusions. These can then be compared to the aircraft measurements. Collaborating with Dr. Bringi in this research area will be Drs. Larry Carey (TAMU), Walt Petersen (University of Alabama, Huntsville), Daniel Rosenfeld and William Woodley and with Drs. William Cotton (Colorado State University) and Van den Heever (Colorado State University) for the proposed RAMS simulations.

The research will focus on polarimetric radar-based retrievals of the normalized intercept parameter and mass-weighted mean diameter in the rain layer (assuming a gamma DSD shape). Results already in hand show that it is possible to clearly separate maritime DSDs from continental DSDs (on average) in the log  $N_w$  vs.  $D_m$  space using both radar retrievals and disdrometer measurements from a wide range of convective storm climatologies (equatorial to mid-latitudes). Any process that modifies that DSD (e.g., aerosol concentrations, giant CCN, or updraft strength) should be evident as excursions in the log  $N_w$  vs.  $D_m$  space and may be used to study the implications of the Rosenfeld aerosol hypothesis or other hypotheses related to the effects of aerosol concentrations on the evolution of the DSD. The RAMS simulations proposed during HEAT would add much value in understanding not only the radar-based DSD retrievals but also the DSD effects ‘clean’ vs. ‘polluted’ convective events on the warm rain processes; in turn, the radar data can be used to validate the RAMS rain DSD retrievals from the 2-moment scheme.

Dr. Bringi intends also to be involved in hydrometeor classification using the full complement of polarimetric radar measurements, in particular, the appearance and intensification of the mixed phase region via the positive  $Z_{DR}$  columns (which loft supercooled raindrops into the cold regions of the cloud) and the  $L_{DR}$ -cap signature which signifies the freezing of drops, the appearance of wet graupel/hail or wet growth of hail. These signatures can be used to evaluate the various competing hypothesis regarding ‘clean’ vs. ‘polluted’ air and its effect on the depth and intensity of the mixed-phase region. These radar observations will be useful also in “calibrating” and/or validating the cloud microphysical simulations of the RAMS model, which makes use of cloud microphysical parameterizations.

Drs. Petersen and Carey intend also to be involved in this research component. A widely accepted hypothesis advanced to explain convective precipitation maximums located downwind of urban areas during METROMEX, and highly relevant to HEAT, concerns the influence of the urban heat island (UHI) on convective frequency and organization. Specifically, coarse radar observations from METROMEX suggested enhanced merging and associated intensity of radar echoes generated over and downwind of the urban corridor. To the extent that UHI convergence acts to initiate convection over large cities and create the right environment for enhanced system merger downwind, Petersen and Carey hypothesize that convective intensity (kinematic and microphysical) will adjust symbiotically to UHI dynamic/thermodynamic effects to create a local maximum in lightning activity just downwind of the Houston metroplex. Most importantly, they hypothesize that this juxtaposition of convective intensity, enhanced mixed phase microphysics, and lightning relative to the complex combination of urban corridor, land-surface and sea-breeze effects takes place regardless of the aerosol content of the urban boundary layer. As such they serve as the alternative explanation to the aerosol hypothesis attributed to Rosenfeld.

Petersen and Carey propose to use both S-pol and CHILL dual-polarimetric radar observations in coordination with SMART-R Doppler measurements to retrieve Lagrangian 4-D convective kinematic (e.g., updraft strength) and microphysical (e.g., ice and mixed phase mass) parameters in convection as it evolves and moves over both urban and non-urban environments, and as the UHI environment and convection interact with the sea-breeze front. In addition to providing concrete physical evidence to the respective roles of the UHI/land surface and the aerosol influences on convective merger and intensity downwind of Houston, the proposed radar analysis also bridges a much broader set of HEAT objectives. More specifically, their research will directly support mesoscale observational and modeling studies of the UHI-sea breeze-cold-pool interactions (e.g., Nielson-Gammon et al.) by providing statistics on high resolution 3D low-level environmental flow (via multi-Doppler synthesis) and cell evolution over the urban area and sea-breeze front.

Drs. Andrew Detwiler and John Helsdon of the South Dakota School of Mines and Technology want to be involved in this component of the HEAT research effort as well. Dr. Detwiler is interested in studying the conditions in the mixed phase regions on the fringes of updrafts where charge separation is likely to occur by the non-inductive charging mechanism. He is interested also in microphysical differences between high flash rate storms and low flash rate storms, and correlations between CCN spectra and cloud microphysical evolution. In situ aircraft microphysical and electrical measurements are important for this purpose, as well as polarimetric radar, LDAR II, and NLDN data. The radar data in addition will allow bulk estimates of the volume of the mixed phase region, which may vary between storms with higher flash rates and those with lower flash rates. Multiple Doppler radar wind field analyses will also be performed as needed to delineate the updraft region. Dr. Detwiler's colleague Dr. John Helsdon is interested in using the HEAT data set as a basis for comparing observed storm behavior to storm behavior simulated with his Storm Electricity Model. By doing sensitivity studies with the model, the dominant processes linking microphysics, electrification, dynamics and lightning can be more clearly identified. In many respects it appears that the mission profiles for the Rosenfeld and Detwiler research teams will be quite similar and likely can be accomplished on the same flight provided the two teams coordinate their efforts beforehand.

Dr. Tony Grainger of the University of North Dakota is interested in looking at the microphysical characteristics of the anvils produced by electrically active storms and is, therefore interested in having access to the electric field measurements from the field mills on the jet cloud physics aircraft and particle size distribution as a function of downwind distance from the storms. He also hopes to be able to verify a model for the relaxation time of the charge in an anvil cloud. This would be a continuation of some research he has done in Florida over the past several years. Repeated passes through the anvil where there are enhanced fields as well as spirals through these regions are desired. According to the model, the relaxation time of the charge center should depend upon the thickness and size distribution of the hydrometeors in the cloud. Also of interest is the presence or absence of supercooled liquid water in the anvil regions. The Florida work has shown a significant variation of the fields in anvil clouds and it is not clear whether this is regeneration of some sort or whether this is due to the changing characteristics of the parent storm. Other scientists may be involved with Dr. Grainger with this research. At this point it appears that Dr. Hugh Christian or some of his colleagues from Marshal will be working

on this effort with him. Studies in the anvil region also are important to the chemists, who want to see what species are in the "exhaust" from these storms.

Considering the needs of the various scientific teams, there may have to be different mission profiles, one for studies of updrafts and their flanking regions of the sort in which the Rosenfeld and Detwiler flight teams are interested, another for anvil regions, and possibly others. Coordination with other aircraft or sounding systems may be needed for some of these. An effort will be made to integrate several mission objectives into the same flights. This is important, because, for example, the vertical evolution of the cloud microstructure and hydrometeors surely has an important impact on the composition of the anvils. Different missions may or may not involve different mission scientists on the aircraft.

Another aspect that should be considered is the length of HEAT. Many participants may not be in the field for the entire 2 (3 for some) months. It may be necessary to work out a schedule of rotating mission scientists just to handle the length of the project. Discussions like this will get more focused once the funding decisions are made and it is clear who will be the different players in HEAT.

#### **4.0 SELECTION OF A HIGH PERFORMANCE CLOUD PHYSICS AIRCRAFT**

Meeting the scientific objectives of HEAT will require a high performance cloud physics aircraft. The various HEAT documents mention the University of North Dakota Citation aircraft and the Lear jet of Weather Modification, Inc. (WMI) as possibilities. Each has its advantages. The WMI Lear has better performance in severe convection and a higher service ceiling. This aircraft has been in clouds where few jet aircraft have gone before intentionally. On the other hand, the UND Citation has, as of this writing, a more complete complement of instrumentation, including 6 field mills (see Appendix A for a listing of the Citation instrumentation). The technical expertise to install and operate the mills resides at NASA MSFC, has spent a long period of time calibrating the aircraft geometry for electric field measurements. Other aircraft installations will require the same intensive and time-consuming calibration. NASA MSFC has developed software to retrieve the ambient Ex, Ey and Ez from the airborne field mills. Another big advantage of the Citation aircraft is that it also carries the requisite precipitation and aerosol microphysics probes that are an essential part of the HEAT program. However, an aircraft will only be able to measure the electric field in the region of the cloud through which it is flying. In order to obtain the vertical charge structure of a thunderstorm, the aircraft will have to make many passes at different altitudes through the storm, while avoiding for safety reasons the zones with large hydrometeors, causing reflectivities in excess of about 40 dBZ.

All of the above having been said, WMI has let it be known that they intend to configure their Lear jet cloud physics aircraft for HEAT (see listing of the planned Lear instrumentation for HEAT in Appendix B), and they asked that the following be included in this write-up:

“The WMI Lear 35A has been involved in several atmospheric research projects requiring specific instrumentation installations. WMI has initiated a plan to equip the Lear 35A with an airborne field mill system, and an air intake system that will facilitate an array of air chemistry instruments.

“Instrumentation and measured parameters included are Total Temperature, Reverse Flow Temperature, Dew point, Liquid Water, 2DC, FSSP, PCASP, Pressure, Differential Pressure, IVSI, GPS, Pitch, Roll, Yaw, Sideslip, Magnetic Heading, Icing Rate, O<sub>3</sub>, SO<sub>2</sub>, NO, CO, CN, CCNC, and Electric Field.

“The WMI Lear 35A's climb performance and cruise speeds are not penalized by the research equipment probe installations, allowing 450-knot transit speeds between measurement sites. Climb to flight level 410 is attained in 20 minutes, and the aircraft's ceiling is FL 450. The Lear also routinely operates as slow as 160-180 knots during research flight at mid altitudes, and WMI has conducted normal cloud seeding and research operations with the aircraft around thunderstorm environments for the last 5 years.”

The high performance jet cloud physics aircraft to be used in HEAT should be the one that will best meet the needs of the program and that should be decided on a competitive basis. In the interim it is suggested that PI's who intend to work with the cloud microphysical data not identify a specific aircraft at this time.

## 5.0 OVERVIEW

An overview table that summarizes the HEAT measurement program is provided at the end of this document. It identifies what is to be measured and how and where the measurements are to be made. Cost estimates are given when they can be known with some confidence. A tentative priority is assigned to each component of the overall program. This is a draft table and further input is sought from those receiving this document.

## 6.0 REFERENCES OF RELEVANCE

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Measured Parameter	Instrument	Where Measured?	Probable Cost	Priority	Comments
Aerosol Measurements over the study area	CN, CCN counters	Ground & air	\$200K	High	The survey aerosol measurements will require a dedicated aircraft
Lightning Flashes	NLDN	Ground	Network Exists	Essential	
Lightning Flashes	High Speed video, ELF Monitoring	Ground	\$150K	If at all possible	Walt Lyons spoke in favor of this addition
Lightning Flashes	LDAR-2	Ground	Funded by NSF	A Reality	
Rapid Scan Satellite Data	Satellite Sensors	Satellites	No Cost	If at all possible	
Mixed-Phase Region and Electric Fields	FSSP, 2D-C, icing meter, high-volume particle samples, cloud particle imager for very small particles	Jet	\$400K+	Essential	Aircraft must penetrate the active portion of cloud
Mixed-Phase Region	Polarimetric Radar	Radar	Proposals to be written and requests for radar facilities to be made, \$750K in deployment money	Essential	\$150K of the \$600K to be provided by Texas
Cloud droplet spectra	FSSP,	Jet	\$400K +	Essential	The \$400K + covers the use of the jet aircraft
Documentation of the sub-cloud aerosols and the cloud-base droplet spectra	CCN instrument that measures high aerosol concentrations and a FSSP to measure cloud-base droplet spectra.	King Air	\$100K	Essential	The U. of Wyoming CCN instrument saturates at concentrations $> 1,000 \text{ cm}^{-3}$ . DRI instrument is an option but it weighs 200 lbs.
Measure giant and ultra-giant CCN				Desirable	It is not clear how this might be done and by whom
Profiles of cloud "effective radii"	Multi-spectral, polar-orbiting satellite imagery	Inferences over experimental domain	\$100K	Highly desirable	The Rosenfeld methodology will be used to infer cloud effective radii

**APPENDIX A**  
**UND Citation Instrumentation Specifications - HEAT**

Parameter Measured	Instrument Type	Manufacturer & Model #	Range	Response Time	Accuracy	Resolution
Temperature	Platinum Resistance	Rosemount Model 102 Probe	-65°C to +50°C	1 s nominal	0.5°C	0.03°C
Dew Point	Cooled Mirror	EG&G Model 137	-50°C to +70°C	2°C S <sup>-1</sup>	0.5°C>0°C 1.0°C<0°C	0.03°C
Water Vapor	Tunable Diode Laser	Maycomm	0.5 to 50,000 ppmv	0.5 s	± 3%	0.5 ppmv
Static Pressure	Absolute Pressure	Rosemount 1201F1	0 to 1034 mb	15 ms	3.1 mb	0.25 mb
Altitude	GPS	Applanix	0 to 20 km	10 msec update	0.1 km	1 m.
Attack Angle and Sideslip	Differential Pressure	Validyne P40D	± 34.5 mb	20 ms	0.09 mb (0.05°)	0.02 mb (0.01°)
Indicated Airspeed	Differential Pressure	Rosemount 1221F	0 to 172 mb	10 ms	0.55 mb (0.8 m s <sup>-1</sup> )	0.04 mb (0.06 m s <sup>-1</sup> )
Heading	POS	Applanix	0-360°	10 ms update	12 arc min	6 arc min
Pitch, Roll	POS	Applanix	-90° to +90°	10 ms update	2 arc min	0.25 arc min
Vertical Acceleration	POS	Applanix	-10 to 30 m s <sup>-2</sup>	42 ms	0.1 m s <sup>-2</sup>	0.01 m s <sup>-2</sup>
Lateral, Longitudinal Acceleration	POS	Applanix	5.0 m s <sup>-2</sup>	10 ms	0.1 m s <sup>-2</sup>	0.002 m s <sup>-2</sup>
Ground Speed	POS	Applanix	0 to 500 m s <sup>-1</sup>	10 ms update	0.5 m s <sup>-1</sup>	0.05 m s <sup>-1</sup>
Position	POS	Applanix	90° Lat 180° Long	10 ms update	0.1 km	1 m
Liquid Water Content	CSIRO Liquid Water Detector	PMS	0-9 g m <sup>-3</sup>	0.05 s	5%	0.005 g m <sup>-3</sup>
Icing Rate	Vibrating Cylinder	Rosemount Model 871FA	0-0.0251 cm before recycle	7 s recycle	±0.13 cm	0.003 cm
Cloud Droplet Spectrum	Forward Scattering Spectrometer Probe	Particle Measuring Systems (PMS) FSSP-100	0.5-47µm	4 Hz sampling	-	0.5-3.0µm variable
Cloud Particles	Optical Array Probe 1D-C	PMS OAP-230X	20-600 µm	4 Hz sampling	-	20 µm
Cloud Particles	Optical Array Probe 2D-C	PMS OAP-2DC	30-960 µm	4 Hz sampling	-	30 µm
O <sub>3</sub>	Eosin Y Chemiluminescent	Scintrix L0Z3	0.2 to 400 ppb	<1 s	±10%	0.1 ppb
CCN	Alcohol Condensing	TSI 3760	0-10 <sup>4</sup> cm <sup>-3</sup>	2 s	±6%	1 count

**APPENDIX B**  
**WMI Lear Jet 35A Instrumentation Specifications - HEAT**

Parameter Measured	Instrument Type	Manufacturer & Model Number	Range	Response Time	Accuracy	Resolution
Temperature	Platinum Resistance	Rosemount Model 102 Probe	-70°C to +50°C	1 s nominal	0.5°C	0.03°C
Dew Point	Cooled Mirror	Buck Research 1011B	-50°C to +70°C	1 s	0.5°C > 0°C 1.0°C < 0°C	0.03°C
Water Vapor	Tunable Diode Laser	Maycomm	0.5 to 50,000 ppmv	0.5 s	± 3%	0.5 ppmv
Static Pressure	Absolute Pressure	Setra 270	0 to 1100 mb 0-20 psia	<10 ms	0.05%	0.055 mb
Indicated Airspeed	Differential Pressure	Setra 239	0 to 172 mb 0 to 30" WC	<10 ms	0.14%	0.01 mb
Magnetic Heading	Flux Valve	Sperry	0-360°	10 ms update	0.1°	0.1°
Position	WAAS DGPS	Aventech AIMMS-20		5 Hz	2 m (2 σ)	< 1 m
Barometric Pressure	MEMS Pressure Sensor	Aventech AIMMS-20	0 – 110000 Pa	20 Hz	100 Pa	10 Pa
GPS Altitude	WAAS DGPS	Aventech AIMMS-20	-300 – 18000 m	5 Hz	5 m (2 σ)	< 1 m
Reverse Flow Temperature	0.038" DIA. Bead Thermistor	Aventech AIMMS-20	-70 C to +50 C	< 1 s	0.05 C / 0.3 C incl. Dynamic Heating Corr.	0.01 C
Relative Humidity	Thermoset Polymer Capacitive RH Sensor	Aventech AIMMS-20	0 – 100 %RH	5 s @ 20 C	2 %RH	0.1 %RH
North / East Wind Velocity Component	Kalman Filter	Aventech AIMMS-20		5 Hz	0.5 m/s @ 75 m/s TAS	0.01 m/s
Vertical Wind Velocity Component	Kalman Filter	Aventech AIMMS-20		5 Hz	0.5 m/s @ 75 m/s TAS	0.01 m/s
Inertial Velocities (u,v,w)	MEMS IMU / GPS / Kalman Filter	Aventech AIMMS-20	0 – 514 m/s	5 Hz	0.1 m/s	0.01 m/s
Inertial Accelerations (a_x,a_y,a_z)	MEMS IMU / GPS / Kalman Filter	Aventech AIMMS-20	-5 g to +5 g	5 Hz	0.005 g	0.001 g
Electric Field	Airborne Field Mill System	SRI International	±2 to 1.1 Mv/m	10 Hz	±2.5%	

Parameter Measured	Instrument Type	Manufacturer & Model Number	Range	Response Time	Accuracy	Resolution
Roll	MEMS IMU / GPS / Kalman Filter	Aventech AIMMS-20	-60 to +60 deg.	5 Hz	0.1 deg.	0.01 deg.
Pitch	MEMS IMU / GPS / Kalman Filter	Aventech AIMMS-20	-60 to +60 deg.	5 Hz	0.2 deg.	0.01 deg.
Yaw / Heading	MEMS IMU / GPS / Kalman Filter	Aventech AIMMS-20	0 – 360 deg.	5 Hz	0.1 deg.	0.01 deg.
True Air Speed	MEMS Pressure Sensor	Aventech AIMMS-20	0 – 150 m/s	20 Hz	0.2 m/s	0.01 m/s
Ground Speed	WAAS DGPS	Aventech AIMMS-20	0 – 514 m/s	5 Hz	0.035 m/s	0.01 m/s
Angle of Attack	MEMS Pressure Sensor	Aventech AIMMS-20	-15 to +15 deg.	20 Hz	0.03 deg. @ 150 m/s TAS	0.001 deg. @ 150 m/s
Sideslip Angle	MEMS Pressure Sensor	Aventech AIMMS-20	-15 to +15 deg.	20 Hz	0.03 deg. @ 150 m/s TAS	0.001 deg. @ 150 m/s
Liquid Water Content	CSIRO Liquid Water Detector	Particle Metrics Inc. KLWC-5	0-5 g m <sup>-3</sup>	0.05 s	5%	0.005 g m <sup>-3</sup>
Icing Rate	Vibrating Cylinder	Rosemount Model 871FA	0-0.0251 cm before recycle	7 s recycle	±0.13 cm	0.003 cm
Cloud Droplet Spectrum	Forward Scattering Spectrometer Probe	Particle Metrics Inc. FSSP-100	2-47 µm 0.5-8 µm 1-16 µm 2-32 µm	4 Hz sample rate	-	2 µm .5 µm 1 µm 2 µm
Aerosol	Passive Cavity Spectrometer Probe	Particle Metrics Inc. PCASP	0.1-3 µm	4 Hz sample rate	-	0.1 µm
Cloud Particles	Optical Array Probe 2D-C	PMS OAP-2DC	25-800 µm	4 Hz sample rate	-	25 µm
O <sub>3</sub>	UV Photometric	TEI	0 to 1000 ppb 0 to 200 ppm	<1 s	±10%	1 ppb
Condensation Nuclei	Alcohol Condensing	TSI 3060	0-10 <sup>4</sup> cm <sup>-3</sup>	2 s	±6%	1 count
Condensation Nuclei	Light Scattering	CCNC-100B	0.2% to 2.0%		5%	0.2%

Note: Measured parameters can be customized for specific experiments. Instruments may be added or removed as required.