AIRCRAFT MICROPHYSICAL DOCUMENTATION FROM CLOUD BASE TO ANVILS OF HAILSTORM FEEDER CLOUDS

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I. INTRODUCTION

Documentation during January and February 2000 of the structure of severe convective storms in Mendoza, Argentina, with a jet cloud physics aircraft penetrating the major feeder clouds from cloud base to the -45ºC isotherm level is reported. The main research goal was the description of the microphysical evolution of the convective feeders of the hailstorms from cloud base to the anvil in an attempt to gain insights into the microphysical evolution of the clouds that are associated with the high frequency of large hail in the region. The aircraft penetrated preferentially the tops of young growing elements, which were typically the major feeders to severe hailstorms, producing large (> 3 cm) size hail. Cloud bases typically were at 6 to 14°C with typical base updrafts of 4 to7 m s^{-1}. The cloud updrafts increased with height, exceeding 25 m/sec at heights > 7 km and occasionally 40 m s^{-1} at heights > 8 km. Thermal buoyancies of 5 to 8°C were measured in the convective towers at heights of 8-10 km. The vertical wind shear was weak below 6 km, but increased strongly above that level as the west winds cleared the Andes barrier, which averages 6.1 km to the west of Mendoza. The clouds had very little coalescence and contained no detectable precipitation sized particles > 100 µm at T > -15ºC. Nearly adiabatic cloud water with most cloud water still not converted into precipitation-sized hydrometeors (> 100 microns diameter) was found in cloud filaments within the strongest updrafts up to the level of homogeneous freezing, reaching 4 g m^{-3} at –38°C in one cloud before vanishing abruptly at colder temperatures. Graupel > 1 mm appeared at the tops of growing new towers at temperatures < –27°C in agreement with radar first-echo heights of about 8 km. This extended abstract contains selected parts of the full paper of Rosenfeld et al. (2006).

II. THE MAIN RESULTS

The WMI Lear jet Model 35A was equipped with a FSSP-100 probe for sizing particles in the range of 2-44 µm and an OAP-2DC probe for imaging particles in the range of 25-800 µm. In addition, the aircraft had a DMT hot wire instrument to measure liquid water contents, temperature and dew point probes, and a Ball variometer for the inference of cloud drafts. The detailed measurements are provided in Rosenfeld et al. (2006).

The authors are not aware of any publications documenting previously the microstructure of hailstorm clouds from cloud base to –45°C. Specifically, the amount of documented highly supercooled liquid cloud water and the thermal buoyancies are the largest that the authors have found in the published literature so far (Figs 1).

The combination of the following conditions observed in the measured clouds constitute the potential for severe hailstorms:

- Microphysically continental cloud microstructure, having little coalescence and warm rain with the formation of only a few precipitation embryos at low levels, as evident from the drop size (Fig. 2).
- Little loss of cloud water to warm rain and glaciation, leading to a very deep layer of supercooled cloud, containing nearly adiabatic water contents in extreme cases.

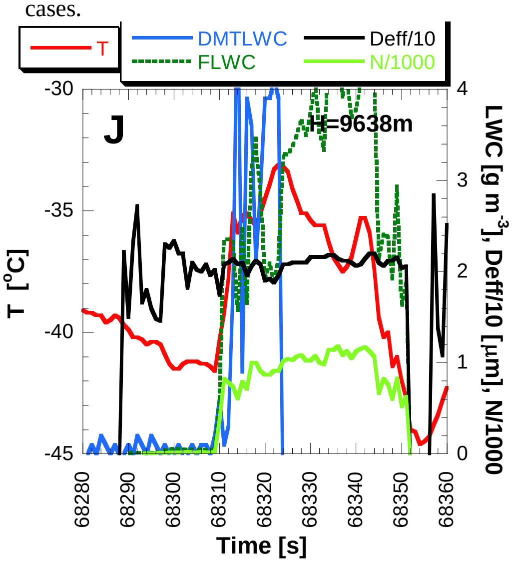

Fig. 1. Cross section of convective element of severe hailstorms on 1 February 2000, over Mendoza, Argentina, as measured by the WMI Lear Jet. This penetration is in vigorously growing convective tower at the level of homogeneous freezing. The presented measurements are temperature [ºC]; DMT hot wire liquid water content [g m^{-3}], adjusted FSSP liquid water content [g m^{-3}]; particle number concentrations (2-44 µm diameter) as measured by the adjusted FSSP [cm^{-3}], divided by 1000 to fit the right scale; effective radius (r_e) of the FSSP measured particles, divided by 3 to fit the right scale. The abscissa is in seconds from 00:00 GMT. Note the thermal buoyancy of 9°C, and LWC of 4 g m-3 at -35°C. The hot wire LWC probe broke in the middle of the pass, probably by impacts of large graupel or a hail stone.

- Existence of large amounts of cloud liquid water in the strong updrafts up to the -35°C isotherm (Fig. 1) with filaments of undiluted and unfrozen updrafts reaching the level of homogeneous freezing near –38°C (Fig. 1). This extends upward the zone of growth of large hailstones up to that highest possible level.
- Very strong updrafts in the highly supercooled parts (-25°C to –38°C) of the cloud at least 40 m s^{-1}. Such an updraft can support a hailstone with a diameter of 6.0 cm at a temperature of about -25°C (Macklin, 1977).
- Strong vertical wind shear to separate the updraft from

the downdraft, leading to long-lived cell circulations and potential for recirculation of hydrometeors, which has been shown to be a mechanism involved in the formation of large hail (Foote, 1984, 1985).

- The drop size distribution expanded with height and reached the warm rain threshold only near the homogeneous freezing level, where it was too high for coalescence to create precipitation and hail embryos (Fig. 2).
- The microphysical continentality is essential to keep a small number of hydrometeors that grow with practically unlimited supply of supercooled water up to the homogeneous freezing level. Therefore microphysically maritime clouds are improbable producers of large hail (Fig. 2).

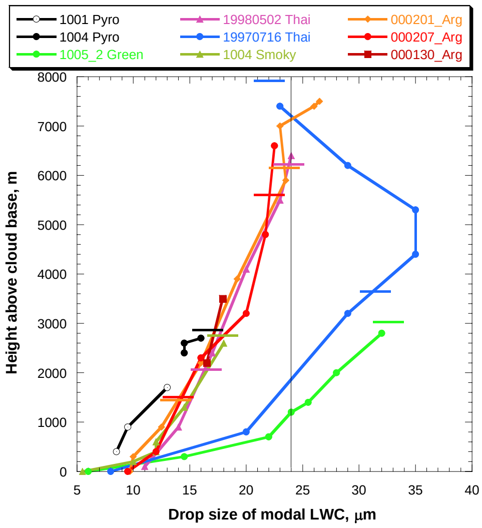

Fig. 2. The dependence of the drop size modal LWC (D_L) on height above cloud base and temperature, for: Red and orange: Argentina hailstorms; Black: Pyro-clouds in the Amazon; Gray: Smoky clouds in the Amazon; Purple: Smoky clouds in Thailand; Blue: Monsoon smoke-free clouds in Thailand; Green: Pristine clouds in the Amazon. The lower and upper horizontal bars represent the 0º and -30ºC isotherm cloud depths. The vertical line at DL=24 µm represents the warm rain threshold. The Argentina curves are from this study. The rest are from Andreae et al., 2004).

The combination of these conditions can create large (i.e., > 3 cm) hail, which was observed from the storms in which the measured clouds acted as feeders. Cloud electrification is the result of collisions between graupel and ice crystals in supercooled clouds with greater charging at colder temperatures. The enhanced vigor of the storm results in a deeper mixed-phase zone and hence could result in greater charging as well as greater vertical transport of the separated charges. However, the observations that the very strong updrafts delay the onset of mixed phase processes to the very high levels or even prevent them altogether may lead to the suppression of lightning due to a lack of graupel and ice crystal collisions within the cores of such updrafts. There is presently no objective measure of this effect, but lightning discharges were not visibly observed in the vigorous, young, growing, cloud towers that were penetrated during the Argentine cloud physics campaign. While this might be ascribed to chance in such a short research effort, the lack of encounters with lightning during the 6 years of operational seeding of such convective elements (Roger Tilbury, the seeder pilot of the Lear Jet, private communication) cannot reasonably be ascribed to chance. Similar observations of weak electrical charging in the intense updraft cores of severe storms in the US high plains was reported by Lang et al. (2004). This suggests that the measured clouds in this study possess properties of the core updrafts of severe hailstorms. In contrast, occasional lightning was encountered in the feeders of significantly less severe and less continental storms, such as in Israel winter thunderstorms over the East Mediterranean region, as experienced by the author who also conducted the research flights in Argentina.

It is suggested that severe hailstorms in a microphysically continental air mass have very low precipitation efficiency because much of the cloud water escapes through the anvil during homogeneous freezing or is evaporated due to the small sizes of the hydrometeors other than the low concentrations of the large hailstones

III. CONCLUSIONS

Most of the conclusions are summarized in the introduction. The complementary information obtained from rawinsondes reinforced these findings. Calculations using atmospheric soundings as input, gave maximum updraft speeds (51 m s^{-1} to 66 m s^{-1}) that exceeded those observed. First echo tops were noted at 8 to 9 km, and these were followed by hail formation in as little as 15 minutes. The aircraft measurements documented intense supercooling of the cloud water to near the point of homogeneous nucleation, indicating a vast reservoir of supercooled water available for the growth of large hailstones.

IV. ACKNOWLEDGEMENTS

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