AN OBSERVATIONAL STUDY OF CLOUD PARTICLE SPLASH/BREAKUP ARTIFACTS ON AIR SAMPLING FROM INLETS

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1. INTRODUCTION

Air inlets are used on research aircraft for sampling trace gases and aerosol particles. During passes through clouds, artifact particles can be generated when cloud drops or snow crystals collide with edges of the inlet. These artifact particles are passed to instruments downstream and will evaporate enroute. There can be some non-volatile residue that is measured by aerosol instruments, and this residue is an accidental contamination of the ambient aerosol.

The performance of "standard" inlet types for particle sampling is well understood in clear air. Processes leading to splash/breakup artifacts, however, are not. The goal of this investigation is to improve the understanding of these issues and work toward improved inlet designs.

This paper presents measurements of aerosol particles from recent projects and compares data from clear air and cloud passes. Future studies will attempt to identify the critical parameters that affect the generation of artifact particles.

2. FIELD PROJECTS

The U.S. National Science Foundation supports airborne research projects and the operation of instrumented aircraft for atmospheric research. For the present investigation, data were from the C-130 in two different projects.

Inlet geometries that were used in these projects include several types: forward-facing blunt and sharp-edged; aft-facing; and forward cone. Clouds in these studies include tropical strato-cumulus, super-cooled winter stratus, wave clouds that were mixed phase or ice, and cirrus. Air speeds ranged from ~100 to 150 m/s, and temperatures were +15 to -40℃. The aircraft were equipped with a variety of instruments to detect cloud particles, state parameters, kinematics, and aerosol size distributions.

3. INSTRUMENTATION

Primary measurements included thermodynamics, kinematics, position keeping, water and ice cloud particles. For the research described in this paper, the primary microphysics instruments are listed in Table 1. In all of these projects, there were additional instruments not listed here, that generated rich and diverse data sets. These included aerosol sensors for ice nuclei, size distributions ~10-1000 nm, trace gas sensors (O_3 and CO), and more.

project & aircraft	clouds	inlets	particle instruments
RICO C-130	marine Sc	forward-facing cone, aft-facing gooseneck	CN, CCN, RDMA, PCASP, FSSP, 260X, 2DC
ICE-L C-130	supercooled wave clouds	flow-through sharp edge diffuser with interior fwd-facing tube	CN, CCN, RDMA, UHSAS, CDP, 2DC

Table 1. Microphysics instrumentation

4. THEORY

The production of spray artifacts is a complicated process that depends on a number of variables. These include:

- particle phase (ice or liquid)
- particle size & shape
- inlet tip shape (blunt, sharp, rounded)
- surface properties of inlet tip (dry, wet)
- depth of flow boundary layer and distance from inlet tip to aircraft skin
- aircraft speed
- surface tension of water

Particles will impact the inlet or other aircraft structures upstream if they have sufficient inertia to cross the flow streamlines. Snow particles will break into fragments upon impact where the shear strength of ice is exceeded. For liquid particles, there are several possible results of impact. The drop can rebound, it can stick and flow as a surface layer, or it can be drawn into a thin sheet or filaments that break into smaller droplets.

The Weber number is used to predict the shape or breakup of liquid drops that are in motion relative to air -- free floating, not impacting on surfaces. It is the dimensionless ratio of particle kinetic energy to surface energy. For a spherical drop of unit density,

$$We = U^2 D / \sigma$$

where U is its velocity relative to the air, D is diameter, and σ is surface tension (Baron et al., 2001). Droplets with We > ~6-10 will deform and can break apart (Lefebvre, 1989). Note that it is not necessary for droplets to impact a surface in order to break up. They need only experience a significant acceleration. Break up may occur at We ~ 6 in turbulent flow.

Recent advances in high-speed video imaging and fluid dynamics modeling studies are improving the understanding of droplet impact and breakup. For example, Cossali et al. (1999) used high-speed CCD camera to study the impact of water drops on a liquid film. Over a range of We ~300-800, they characterized the shape and size of the splash "crown" from 3.8 mm diameter droplets. The number and size of secondary droplets depends on We and the Ohnesorge number,

$$Oh = \frac{\mu}{\sqrt{\rho \sigma L}}$$

where μ is liquid viscosity, ρ is liquid density, and L is a characteristic dimension (diameter). Shan et al. (2007) performed mathematical simulations of droplet breakup in two-particle collisions.

In earlier airborne studies, Hudson and Frisbie (1991) reported that measurements of CN concentrations were enhanced inside of warm marine Sc clouds, and they ascribed this to artifacts that were created by droplet impingement and breakup at the inlet tip. They estimated We >20 for all cloud drops (>1 μm), and asserted that all cloud droplets will breakup.

Weber (1998) analyzed observations from the NSF/NCAR C-130 and asserted that inlets with smaller openings will have higher concentrations of spray artifacts. This is because the fraction of artifacts entering the inlet hole scales with the ratio of volume to area. Their assertion was borne out by comparing artifact concentrations from the two different size inlets on the aircraft. Concentrations of in-cloud CN from the smaller inlet hole (1 mm dia) were 10-20X larger than out of cloud values. Artifact particles as small as ~3 nm were detected.

5. FIELD STUDIES

Examples are presented from two field projects. The first case from RICO shows consistent production of CN aerosol resulting from splash artifacts. The second case from ICE-L does not.

5.1 RICO – Marine Stratocumulus

The Rain In Cumulus over the Ocean experiment (RICO) occurred in Antigua-Barbuda December 2004-January 2005. The CN inlet was an aft-facing gooseneck tube, ~10 mm i.d. on the belly of the aircraft (Figure 1).

An example of data from the NSF/NCAR C-130 is in Figure 2. It shows that CN enhancement in clouds was ~10X greater than the out-of-cloud values. This enhancement does not seem to depend on the size of cloud drops, the presence of drizzle drops, or the amount of LWC. In addition to the leading edges of inlet probes, it is possible to generate drop splash artifacts when drops hitting the numerous surfaces on the belly of the aircraft. This spray of small particles will mix within the flow boundary layer and may be drawn into air sample inlets.

Figure 1. Belly of C-130 shows assortment of gooseneck inlets, antennas, and other instruments

5.2 ICE_L– supercooled wave clouds

The Ice in Clouds Experiment – Layer clouds (ICE-L) took place Nov-Dec 2007 in Colorado and Wyoming, USA and also used the NSF/NCAR C-130. In this project, the inlet was a sharp edge, forward-facing diffuser with interior pick-off tube – see Figure 3. The inlet tip was 6 mm i.d., and the inlet was mounted on the belly of the aircraft, 29 cm from the skin.

Figure 4 shows 21 minutes of data with three penetrations of a wave cloud at -25 to -32°C. The wave cloud had super-cooled liquid water (Rosemount icing probe). This case does not show enhancement of CN aerosol. There is considerable structure in the CN trace, but it is connected with crossing the air mass boundary that separates the upper dry layer (theta > 319 K) from the lower moist layer (CN > 100, theta < 319 K). Note the abrupt changes in CN and theta as the aircraft crosses cloud edges. In addition to the liquid water, these clouds also had many snow particles (2DC probe).

6. DISCUSSION

On-going studies are using similar data from several projects and different airplanes. These offer a wide variety of inlet types, particle instrumentation, cloud types, altitudes and airspeeds.

7. ACKNOWLEDGEMENTS

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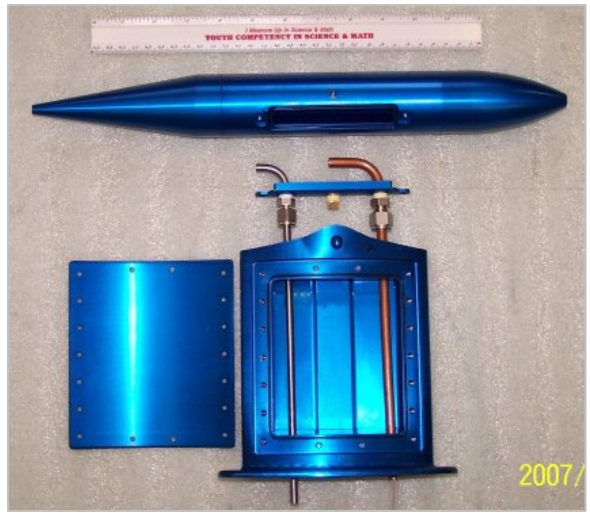

Figure 3. Component view of iinlet used in ICE-L CN sampling. Airflow is left to right.

8. REFERENCES

Baron, P.A., M.K. Mazumder and Y-S. Cheng, 2001: chapter 17 in Aerosol Measurement Principles, Techniques, and Applications, Baron and Willeke (eds), Wiley-Interscience, New York, 1131p.

Cossali, G.E., G. Brunello, A. Coghe, M. Marengo, 1999: Impact of a single drop on a liquid film: experimental analysis and comparison with empirical models. Italian Congress of Thermofluid Dynamics UIT, Ferrara, 30 June-2 July.

Hudson, J.G., 1993: Cloud condensation nuclei near marine cumulus. J. Geophys. Res., 98, D2, 2693-2702.

Lefebvre, A.H., 1989: Atomization and Sprays. Taylor and Francis, Bristol, PA.

Shan, Y., T.W. Coyle, and J. Mostaghimi , 2007: Numerical simulation of droplet breakup and collision in the solution precursor plasma spraying. J. Thermal Spray Techn., 16, 698-704.

Weber, R.J., A.D. Clarke, M. Litchy, J. Li, G. Kok, R.D. Schillawski and P.H. McMurry, 1998: Spurious aerosol measurements when sampling from aircraft in the vicinity of clouds J. Geophys. Res., 103, D21, 28337-28346.

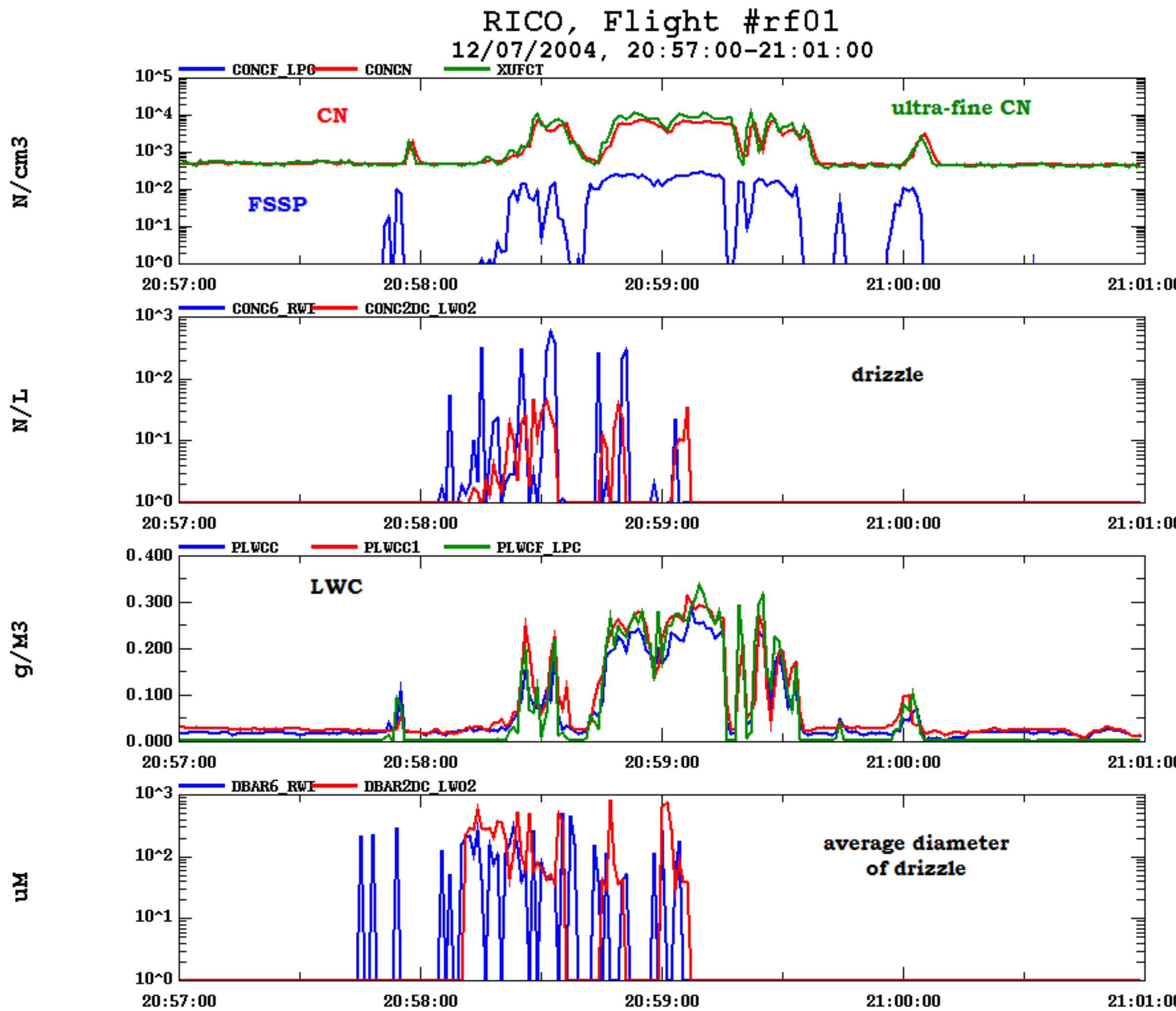

Figure 2. Four minutes of particle data during RICO project. CN concentrations enhanced during penetrations through marine strato-cumulus clouds. Altitude 800m MSL, airspeed 105 ms-1. The presence of drizzle-size drops did not affect the CN enhancement

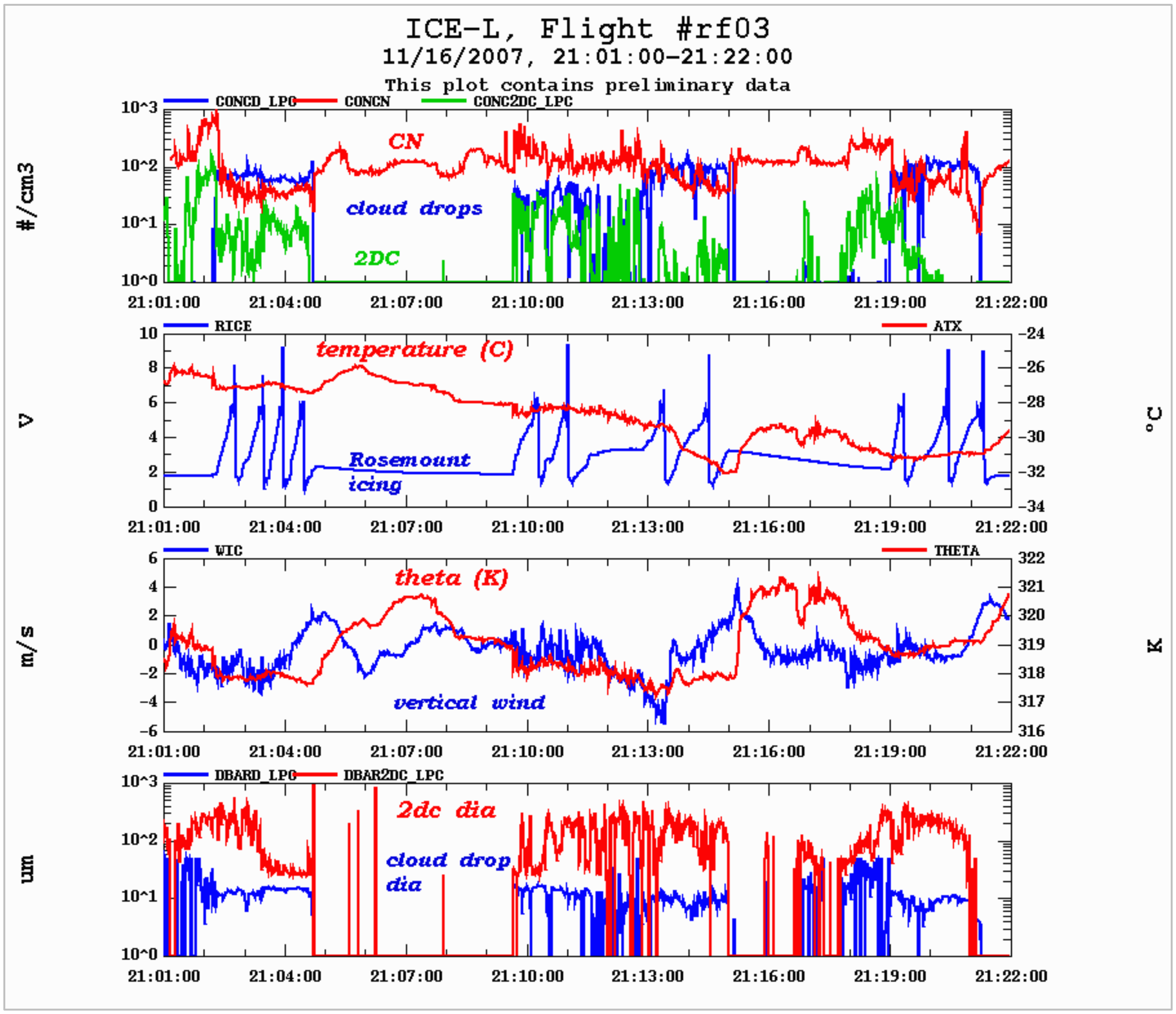

Figure 3. Three penetrations of a wave cloud (upwind/downwind) during 21 minutes, ICE-L project. CN concentrations were not enhanced. Altitude 800m MSL, airspeed 150 ms^{-1} in snow (2DC) and super-cooled liquid water (RICE and cloud drops).