**Overview**

Characterizing clouds and their larger-scale influence is central to accurately modeling many physical processes spanning ranges from localized precipitation to global albedo affects. A more thorough understanding is required despite many years of focused work and rapid advances in computing and in-situ probe capacities. Continued improvement of cloud, weather, and climate models requires a detailed understanding of how processes influence deviations with respect to adiabatically-predicted values (Boucher 1995). Investigations are complicated by fine temporal and spacial scales, complex feedbacks, and incomplete instrument limitation characterization.

Cloud droplet size distributions (DSDs) are nearly ubiquitous in microphysical studies because they provide insight into formation, precipitation, and dynamical processes (Lamb and Verlinde 2011). Characteristic distributions are related to specific cloud traits and processes. DSDs under 100 um diameter are especially useful for droplet activation and primary precipitation formation studies. Because vapor diffusion growth rate is inversely proportional to droplet diameter, clouds composed of newly-activated droplets rapidly progress to a near-monodisperse small diameter distribution. Growth to precipitation-sized droplets by vapor diffusion alone would require timescales far longer than are observed, implying the importance of primary precipitation processes. One such process, droplet collection and coalescence, alters narrow newly-activated droplet distributions to a more disperse bi-modal shape (Lamb and Verlinde 2011). Distribution widening can create positive coalescence feedbacks (fall speed is proportionally related to droplet size) which accelerate droplet growth. Extra-tropical clouds are rarely composed solely of liquid water therefore another vapor diffusion effect, the Bergeron process, further complicates precipitation formation theory. Vapor diffusion is driven by the fact that saturation vapor pressure over ice is less than saturation pressure over supercooled liquid water. Water vapor is preferentially deposited onto ice particles at the expense of liquid droplet mass. The Bergeron process can quickly (with regards to cloud lifetime) progress and acts to narrow and shift DSDs to a greater mean diameter.

----- Add more detail about precipitation formation interactions and mixing.-----

**Significance**

The Droplet Measurement Technologies Cloud Droplet Probe (CDP) is a backscatter spectrometer commonly flown during cloud microphysical studies. The probe retrieves sub-precipitation sized cloud droplets (up to 50 um diameter) size distributions and derived LWC values (Droplet Measurement Tech. 2014). Manufacturer specifications state the CDP is capable of retrieving concentrations up to 2,000 particles cm-3 but studies have shown sample area size uncertainty, inhomogeneous instrument response, and coincidence error (error caused by simultaneous detection of multiple droplets) significantly impacts retrieval capabilities at concentrations as low as 200 particles cm-3 (Lance 2012). The afore-mentioned uncertainty sources contribute to systematic deviations from truthful DSDs and can significantly reduce useful CDP operational ranges.

The Nevzorov hotwire probe capable of retrieving bulk liquid and total water content by monitoring the power consumption of a constant-temperature coil sensor. Water content values are calculable using sensor power consumption due to hydrometeor evaporation and basic thermodynamic principles. The Nevzorov has several advantages over similar hotwire designs including phase discrimination capability, a movable vein to decrease bias caused by aircraft orientation, and paired collector/reference coil architecture. The latter simplifies water content calculations, significantly reduces baseline noise, and increases retrieval confidence in low water content environments (Korolev 1997). A few well-characterized bias sources including power limitations in high water content situations (sensor saturation), non-unity particle collection efficiency, and energy losses attributed to sources other than particle evaporation (dry air heat losses) can compromise Nevzorov measurements. Fortunately, these major bias sources can be compensated for using straight-forward methods.

CDP calibration is traditionally performed using glass beads or polystyrene spheres; both of which introduce complexities due to differential (with respect to water) refractive indexes, inability to precisely place particles, and volume control difficulty. A handful of institutions and instrument manufactures have developed water droplet calibration devices (or droplet generators) to mitigate calibration challenges. Droplet generators are capable of creating pure liquid water particles of repeatable size, velocity, and placement; attributes which allow for calibration and uncertainty investigations free of the refractive index and spacial uncertainty complications. Generally, designs are based on previous work by Lance et. al. (2010) in which a piezoelectric print head (typically used for circuit printing or biomedical applications) dispenses pure water droplets into a sheath airflow. Droplets are accelerated by the flow, focused through a nozzle, and passed through an instrument sample area. High speed cameras and imaging software independently verify droplet size, velocity, and trajectory while precision micro-stages alter sample area injection location. Generator setups can produce a range of droplet sizes, velocities, and concentrations by altering the point at which droplets are introduced in the airflow, changing print head size, and modifying print head jetting parameters.

In-situ analysis by Sulskis (2016) has demonstrated typical CDP and Nevzorov LWC values to be in statistically good agreement. The two instrument’s LWC similarity and retrieval of separate droplet distribution moments (the CDP senses the first moment whereas the Nevzorov senses the third) provides opportunity for probe uncertainty assessment and performance constraint. Of particular interest is the relative impact of CDP LWC error contributed by droplet mis-sizing and mis-counting. More recent work by Lance et. al. (2012) demonstrated the pinhole mask modification significantly reduces droplet sizing and counting uncertainty but further investigation is pertinent for more completely defining CDP limitations. Furthermore, it is expected the magnitude of mis-sizing and mis-counting uncertainty is, to a certain extent, probe specific. UWKA CDP uncertainty investigation can provide tailored knowledge for in-situ studies and future UWKA missions.

**Background**

Lance et. al. (2012) have shown the CDP is subject to response inhomogeneity and coincidence effects contributing to as great as 27% undercounting and 30% oversizing bias at concentrations as few as 500 droplets cm-3. A simple pinhole mask modification substantially reduced coincidence error but the effect remains significant for truthful droplet size distribution retrieval. Bias is present especially for droplet concentrations greater than 500 cm-3 or small diameter droplet populations (~ 2-20 μm) (Lance 2012).

In-situ CDP, Nevzorov, LWC-100, and PVM-100A cross-analysis preformed by Sulskis (2016) investigated inter-probe LWC agreement. The Nevzorov was found to be in the best agreement with CDP LWC with percent differences often an order of magnitude less compared to the LWC-100 or PVM-100A. Furthermore, CDP and Nevzorov LWC were the most similar across all concentration and droplet diameter ranges. Very little Nevzorov LWC bias was found for LWC values less then 1.3 g m-3 (where sensor saturation becomes significant). Many Nevzorov uncertainty sources have been previously characterized and found to behave predictably. Bias sources include baseline drift dependence upon airspeed and altitude deviations which can bias measurements by as much as 2.0\*10-3 g m-3 / 10 m s-1 and 5.\*10-3 g m-3 / km respectively (Korolev 1997). Collection efficiency effects introduce significant bias for particle volume mean diameter (VMD) less than 5 μm or greater than 25 μm (Korolev 1997, Schwarzenboeck 2009) and significant sensor saturation effects are apparent for particle mass-weighted mean diameter (MVD) greater than 50 μm (Strapp 2003) or LWC 1.3 g m-3 and greater (Sulskis 2016).

Nevzorov data processing IDL routines have been developed and tested against well-established COPE-MED 2013 calculations provided by Alexi Korolev, an expert directly involved in Nevzorov development. Calculated and Korolev’s independent LWC values have been shown to be in good agreement despite being computed with slightly different methods. Algorithms include dry air heat loss corrections, pressure-dependent baseline drift compensation, and parameterization of uncertainty attributed to various sources. The software is also built to ingest output from aircraft systems, additional probe data, and run CDP DSD statistics. Processed output can easily be incorporated into future operational and experimental routines. Summer/Autumn 2016 research flight data will provide further validation of algorithm and calibration procedure robustness.

Routines calculate Nevzorov LWC using

---Insert LWC formula----

where Pliq (liquid sensor power) is

----Insert Power equation----

Neglecting dry air heat loss airspeed and pressure dependence introduces mean uncertainty on the order of 180.0% (assuming Korolev’s COPEMED calculations are truthful). For clear air points the dry air heat loss coeffecient (k) is simply (SkyPhysTech)

---Insert K equation----

Algorithm testing and k compensation require clear air (baseline) point identification. In order to isolate clear air points, each flight’s collector sensor voltage is split into 30 second subsets and each subset’s baseline voltage is defined as the minimum value contained within each 30 second period. A clear air voltage threshold is defined as the 75th percentile of all voltage values. A point is considered clear air if Vpoint – Vsubset baseline is less than the voltage threshold.

March 2016 calibration flights collected data required to investigate k airspeed and pressure dependence. Four flight legs flown at 700, 600, 500, and 400 mb levels each contained multiple one minute sections of incrementally varying airspeeds (ranging from 80 to 115 m s-1 true airspeed). A power law function fitted to each calibration leg’s indicated airspeed/k relationship provided dry air heat loss estimates across the King Air’s operational airspeed range. k values were fitted against indicated, instead of true, airspeed because indicated airspeed contains a built-in “compensation” for pressure level fluctuation effects. The effectiveness of each flight level’s k parameterization was examined using a subset of clear air points collected at flight levels spanning 400 – 700 mb and true airspeeds covering 80 – 125 m s-1. Fig 1a. shows each of the four calibration level’s median absolute clear air LWC uncertainty binned by data flight level (where LWC uncertainty is equal to LWC for clear air points). The four calibration levels performed quite similarly but the 700 mb k calibration showed the least median absolute uncertainty across all flight levels. Therefore, calculations use the 700 mb k parameterization (regardless of data flight level).

calibrationPerformance.pdf**Fig 1a. Fig 1b.**

-----Figure 1b. will be a scatterplot demonstrating baseline drift due to pressure changes/correction methodology----

*-----Fix fig 1a y title/overall formatting----*

*Fig 1a. shows median absolute LWC uncertainty binned by flight level for values calculated using each calibration flight level. Error bars show first and third quartiles. Note: interquartile ranges are typically inversely related to data/calibration leg pressure difference implying parameterization performance is slightly data pressure level dependent). ----elaborate on fig 1b-----*

Pressure fluxuations cause LWC baseline drift contributing to typical clear air LWC overestimation around 0.03 g m-3 (despite k/indicated airspeed parameterizations including an intrinsic pressure compensation). Pressure related LWC drift is compensated for by first linearly-fitting flight level pressure/Pliq trends for clear air data (clear air as defined in previous paragraphs). Then, linear regression values are differenced from Pliq for all (clear air and signal) data. The aforementioned process typically reduces mean clear air LWC uncertainty by at least an order of magnitude.

-----Add references to fig. 1b------

Particle collection efficiency can be significantly less than unity due to aerodynamic (for particle VMD less than 5 um) and incomplete evaporation (for VMD greater than 25 um) complications.

-----expand on expected collection efficiency impact for typical UWKA droplet distributions. Maybe add VMD-binned histogram overlaid with Korolev’s collection efficiency estimations-----

Several other potential Nevzorov uncertainty sources including aircraft orientation and environmental parameter sources, have been examined and characterized.

-----Add a little detail about which parameters and why they/aircraft orientation seem negligible…-----

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-----Add CDP background section including…-----

-Equipment design (including drop gen CAD drawings and/or system boxplot)

-Best guesses for expected drop size/velocity/concentration ranges

-Progress up to this point (including hang ups/solutions)

**Objectives**

The proposed work will improve King Air in-situ droplet distribution and LWC retrieval capabilities through algorithm development, laboratory equipment setup and testing, and UWKA data analysis. Multi-faceted methodology, focused on both data analysis and laboratory-based experiments, will enhance departmental observational study abilities through improved in-situ probe calibration and definition of CDP and Nevzorov limitations.

A laboratory droplet generator will expand departmental Cloud Droplet Probe (CDP) and 2D-S calibration and characterization abilities. Laboratory efforts will be focused on system development, equipment assembly, operational procedure development, documentation of procedures for in-department use, and data processing software development. Equipment and procedure effectiveness are to be tested using CDP measurements.

Nevzorov IDL data processing software will correct for common bias, quantify uncertainty, output diagnostic and experimental products, and streamline processing workflow. Algorithm truthfulness and robustness have been tested against independent COPEMED 13 Nevzorov calculations and further verification will be performed using Spring/Fall 2016 UWKA flight data. Algorithms will allow for further assessment of both characterized and more obscure uncertainty sources including particle collection efficiency, sensor saturation, pressure and temperature variations, airspeed fluctuations, and aircraft orientation effects.

A combination of Nevzorov/CDP derived LWC and previously refined Nevzorov error characterization will allow detailed in-situ instrument uncertainty and limitation investigations.

--Need to figure out a Nevzorov/CDP limitation method from in-situ data and expand this section a lot—

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-----Add Timeline section-----