**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.

**--Expand overview. 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 cm-3 (Lance 2012). The afore-mentioned uncertainty sources contribute to systematic deviations from truthful DSDs and can significantly reduce 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. Water content values are calculable using coil power consumption due to hydrometeor evaporation and 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 situations (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 index effects, inability to precisely place particles, and volume control difficulty. A handful of institutions and instrument manufactures have developed water 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. General designs are based on previous work by Lance et. al. (2010) where 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 injection location at micron-scale precision. Generator setups can produce a range of droplet sizes, velocities, and concentrations by altering droplet entry point, changing printhead size, and modifying printhead 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 valuable 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 feature Nevzorov LWC and TWC calculation, dry air heat loss corrections, parameterization of uncertainty attributed to collection efficiency effects, and baseline drift corrections. 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.

Nevzorov LWC is calculated using

---Insert LWC formula----

where P is

----Power equation----

Neglecting dry air heat loss (k) airspeed and pressure dependence introduces mean uncertainty on the order of 180.0% (when compared to Korolev’s COPEMED calculations). For out of cloud (OOC) points k is simply

---Insert K equation----

Liquid collector sensor voltage profiles are used to select OOC points. To compensate for baseline drift, collector sensor voltage is split into 20 second subsets. A point is considered OOC cloud if its voltage is less than 0.033 volts greater than each 20 second period’s minimum value.

March 2016 calibration flights collected data required to probe 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. The effectiveness of each flight level’s k parameterization was examined using OOC LWC values (assuming OOC LWC should equal 0.0 g m-3).

Several potential Nevzorov uncertainty sources including aircraft orientation, environmental parameter sources, and non-unity collection efficiency, have been examined and characterized. The Nevzorov flown during COPEMED 13 featured an experimental “deep cone” total water content sensor designed to reduce crystal “bouncing and splattering”. It was found the modified sensor collects particles at least as effectively as standard designs. Assessment of dry air heat loss airspeed and pressure dependence and best calibration practices have been completed using data taken during fall 2015 UWKA calibration flights. Aircraft orientation, a suspected significant error source, does not appear to introduce significant uncertainty under normal flight conditions.

**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 less explored uncertainty sources including particle collection efficiency, latent heat of water temperature dependence, 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 quite a bit--