An Axial-Flow Cyclone for Aircraft-Based Cloud Water Sampling

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ABSTRACT

A new aircraft-based cloud water collection system has been developed to provide samples of cloud water for chemical analysis. The collection system makes use of centrifugal separation in an axial-flow cyclone to remove cloud drops from the airstream. An automated sample storage system allows up to seven independent samples to be obtained during a single research flight. The entire collection system is housed in a Particle Measurement Systems (PMS) canister to permit the collector to be used on a range of research aircraft without extensive modification to the collector or the aircraft structure. Computational fluid dynamics (CFD) analysis was used extensively throughout the development of the new collector for component design and to predict internal flow dynamics. CFD-based cloud drop trajectory simulations provided an estimate of collection efficiency as a function of drop size. Based on the numerical modeling, the 50% cut diameter was predicted to be 8 μm. Through a quantitative laboratory calibration using fluorescein-tagged monodisperse drops, CFD predictions of drop deposition patterns in the interior of the axial-flow cyclone were verified. The numerical and experimental evaluations were performed to ensure that the population of collected cloud drops is well characterized. Initial flight testing of the system occurred during the Dynamics and Chemistry of Marine Stratocumulus, Phase II (DYCOMS-II) field project in July 2001. Although the major components of the prototype collection system operated as expected during flight testing, sample collection rates were lower than expected because of the inefficient removal and storage of cloud water collected in the axial-flow cyclone. Actual sample collection rates ranged between 0.1 and 1.2 mL min⁻¹.

1. Introduction

Interest in cloud drop formation mechanisms and the role of clouds as processors of trace species has prompted the development and use of a wide range of instrumentation specifically designed to collect samples of cloud water for chemical characterization. Cloud water collectors have been developed for both ground-based and aircraft-based use. While ground-based cloud water collectors have seen broader application, aircraft-based samplers have extended sampling capabilities to include cloud types and environments not accessible from the surface. Cloud water samples acquired from aircraft platforms have been used for the investigation of cloud nucleation mechanisms, aerosol and trace gas scavenging, sulfate production, cloud water acidification, the influence of anthropogenic pollution, the distribution of trace species in the atmosphere, and the general characterization of cloud water composition at geographical locations around the world.

Historically, the most common instruments for collecting warm-based cloud water samples from an aircraft have been the slotted-rod collector and the modified slotted-rod collector, which rely on inertial impaction (Watanabe et al. 2001; Couture et al. 1998; Leaitch et al. 1996; Richards 1995; Macdonald et al. 1995; Liu et al. 1993; Leaitch et al. 1992; Kim and Boatman 1992; Isaac et al. 1990; Barth et al. 1989; Strapp et al. 1988; Huebert et al. 1988; Hegg and Hobbs 1988; Tanner 1987; Isaac and Daum 1987; Leaitch et al. 1986a,b; Kelly et al. 1985; Huebert and Baumgardner 1985; Hegg et al. 1984a,b; Daum et al. 1984a,b; Richards et al. 1983; Mohnen 1980; Winters et al. 1979). The slotted-rod collector is relatively simple in concept, design, and construction, making its use attractive. Slotted-rod collectors typically consist of multiple cylindrical Teflon or Delrin rods, each having a narrow slot at its forward stagnation point. As air flows around the cylinders during flight, cloud drops are collected through inertial impaction, coalesce in the slot, and flow under the influence of gravity and aerodynamic drag down the slot and into a storage container.

Apart from slotted-rod collectors, the majority of aircraft-based collectors have been developed for specific field projects and have seen limited use. These collectors

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have generally employed inertial impaction on cylindrical rods or flat plates for cloud drop collection. Examples include a sampler with liquid-nitrogen-cooled cylindrical rods (Parungo et al. 1982), several rectangular jet impactors (Maser et al. 1994; Maser and Jaeschke 1992), a two-stage drop size segregating impactor (Jaeschke and Gunther 2001), funnel-shaped devices (Scott 1978; Khemani et al. 1987, 1982), and several designs mentioned but not described in detail in the literature (Lei et al. 1997; Hegg and Hobbs 1981; Scott and Laulainen 1979; Petrenchuk 1973; Petrenchuk and Drozdova 1966). Several aircraft-based collectors have also relied on centrifugal separation to remove cloud drops from the airstream (Hegg et al. 1984a; Walters et al. 1983; Hegg and Hobbs 1981; Scott 1978). These devices typically employ vanes extending outward from a central hub that actively or passively interact with the airstream to generate a rotating airflow field in which centrifugal action moves entrained cloud drops to a collection surface.

The counterflow virtual impactor (CVI) (Laucks and Twohy 1998; Twohy et al. 1997, 1989; Dixon and Charlson 1994; Strom et al. 1994; Noone et al. 1993; Ogren et al. 1985) has also been used to investigate cloud water chemical composition from an aircraft platform. Unlike the collectors described above, which provide cloud water samples for the direct measurement of aqueous phase chemical concentrations, the CVI exposes cloud drops to a heated, dried gas stream to evaporate volatile components. The remaining nonvolatile residuals can then be counted, sized, or collected on filters for postflight chemical analysis. The evaporated water and volatile species can also be measured in the sample stream if desired. Finally, a number of early instruments were developed for aircraft-based cloud drop research, though not necessarily for the study of cloud water chemistry or to retrieve cloud water samples for postflight analysis (e.g., Jiusto 1967; Woodcock and Spencer 1957; Woodcock 1952; Vonnegut 1949).

Although aircraft-based bulk cloud water collectors have been deployed on numerous field projects and have yielded useful cloud water composition data, there are a number of potential limitations associated with previous collector designs. In the majority of cases, an assessment of the collection characteristics of aircraft-based cloud water collectors has been neglected. A few collectors have published 50% cut diameters derived from theoretical considerations but lack experimental evaluation (e.g., Maser and Jaeschke 1992). The experimentally determined bulk collection efficiencies reported for other collectors (e.g., Huebert et al. 1988; Walters et al. 1983; Parungo et al. 1982; Hegg and Hobbs 1981) do not convey information about collection efficiency for individual drop sizes, a potential shortcoming considering cloud water composition has been found to vary with drop size (e.g., Rao and Collett 1998, 1995; Laj et al. 1998; Bator and Collett 1997; Schell et al. 1997; Vong et al. 1997). If an unidentified subset of the drop population routinely remains uncollected in a bulk sampler, or if an unidentified subset of the drop population is routinely enhanced, cloud water chemical measurements will be biased in an unknown way relative to the sampled cloud. Slotted-rod collectors have received the most extensive performance evaluation of any aircraft-based cloud water collection system, consisting primarily of bulk collection efficiencies derived from wind tunnel and flight testing. Unfortunately, slotted-rod bulk collection efficiencies appear to be sensitive to a range of parameters, including slant changes in true airspeed, angle of attack, and materials used in construction (Huebert and Baumgardner 1985), and widely variable collection efficiency has been observed under well-controlled wind tunnel conditions and flight conditions (Liu et al. 1993; Kim and Boatman 1992; Huebert et al. 1988).

Although rarely discussed, the shattering and re-entrainment of cloud drops can also limit the performance of an aircraft-based collection system. As liquid drops impact on a solid surface with sufficient kinetic energy, the drops can shatter and fragment into small secondary drops (e.g., Rein 1993; Stow and Hadfield 1981). The high speeds required for aircraft flight create favorable conditions for cloud drop shatter for inertial impactors that operate at free-stream velocities. Drop shatter has been suggested to occur for slotted-rod collectors (Huebert and Baumgardner 1985). If the secondary drops are sufficiently small, they may be re-entrained into the airflow rather than being collected, resulting in nonrepresentative cloud sampling.

Finally, many airborne collectors appear to have been designed for deployment on a particular aircraft for a particular field project (e.g., Khemani et al. 1987; Walters et al. 1983; Parungo et al. 1982; Bogen 1974). The mounting structures were not necessarily designed with portability in mind, making it difficult to transfer a single collector from one aircraft to another for use in multiple field projects. Portability is further hindered by requirements for fuselage penetrations for the purpose of moving the instrument into and out of the airstream or for in-flight sample retrieval (e.g., Maser et al. 1994; Huebert et al. 1988; Isaac and Daum 1987; Winters et al. 1979; Scott 1978).

In an effort to overcome the limitations of past aircraft-based cloud water collectors, a new aircraft-based cloud water collection system has been developed with the objective of providing consistent, well-characterized, bulk cloud water samples that can be used to describe the chemical composition of warm-based clouds and ultimately examine cloud processing mechanisms. Cloud drop trajectory simulations based on computational fluid dynamics (CFD) analysis and experimental laboratory calibration were used to determine collection efficiency as a function of drop size in order to ensure a well-characterized sampler. The cloud drop trajectory calculations also permitted drop shatter and re-entrainment to be evaluated and minimized in the final design.
To extend its applicability, the new collection system is portable and can be deployed with little modification of the collector or aircraft structure on any research aircraft with typical cruising speeds of approximately 120 m s$^{-1}$ or less.

2. Collector design

The new cloud water collector makes use of centrifugal separation in a compact axial-flow cyclone to remove cloud drops from the ambient airstream. An axial-flow cyclone was selected to provide more consistent collection characteristics with less susceptibility to drop shatter than inertial impaction devices. The axial-flow cyclone, based in part on the design guidelines presented by Walters et al. (1983), consists of a duct (6-cm inner diameter, 95 cm long) that is placed on the exterior of the aircraft and exposed to the airflow. The duct is aligned with the external airflow and positioned with the inlet facing the direction of flight, allowing ram pressure to drive air and cloud drops through the duct. Mounted inside the duct, approximately 15 cm downstream of the inlet, is a nonrotating vane unit consisting of eight curved vanes that extend radially from a 3.0-cm-diameter center hub to the duct inner wall (Fig. 1). As the incoming air encounters these stationary vanes, the flow is redirected to produce a rotational flow field about the duct centerline.

In the rotating airflow, centrifugal action quickly moves cloud drops to the duct wall. As drops deposit on the duct wall, aerodynamic drag from the rotating airstream drives the drops along the surface of the duct until they reach a circumferential extraction slot located downstream of the vane assembly. Cloud water accumulates in the extraction slot and is drawn out through two ports and subsequently directed to the sample storage system. The collection system has the capacity to store seven sequential samples per research flight to allow variations in cloud water composition with time or location to be studied.

The forward 30 cm of the axial-flow cyclone duct, which is exposed to collected cloud water, is constructed from polycarbonate. The remainder of the duct is aluminum and serves as a support structure for the remaining components of the collection system (Fig. 2). The nonrotating curved vane assembly is mounted in the polycarbonate portion of the duct and consists of a 3-cm-diameter, 9.4-cm-long aerodynamically shaped hub onto which the root of each of the eight curved vanes is secured. In order to minimize distortion of the airflow through the duct, an elliptical leading edge and a tapered trailing edge were specified. At the mounting location of the center hub, the diameter of the duct was enlarged in an effort to avoid an abrupt change in cross-sectional area through the duct. The design of the vane geometry followed guidelines presented by Horlock (1966) and Wilson and Korakianitis (1998) for the optimal design of axial-flow turbine blades. The outlet angle of the vanes, measured with respect to the duct centerline, affects the airflow rate through the collector as well as the ability to extract collected water from the duct wall. As the outlet angle is increased, the incoming airflow is redirected to a greater extent, and the total airflow rate through the duct is increasingly restricted. As the outlet angle is decreased, the water that collects on the duct wall maintains a greater axial velocity, mak-
Cumulated cloud water for the duration of individual research flights. During a single flight, seven separate samples can be stored in individual standard 125-mL polypropylene bottles. These bottles can be easily removed and replaced between flights. To promote the flow of cloud water out of the extraction slot, through the sample transport lines, and into the storage bottles, a suction flow is applied. This flow is generated with a 10-cm-long aluminum tube that is mounted on the exterior of the collector and extends into the free-stream airflow. At flight speeds, the pressure within the tube is sufficiently lowered as a result of the Bernoulli effect to induce the required suction flow through the entire sample storage system (Straub and Collett 2002b).

The concentrations of relevant species in cloud water are on the order of micromolar, requiring the use of inert materials for all components exposed to sampled cloud water and the ability to prevent those components from being contaminated before and after sampling occurs. The glass-filled nylon and polycarbonate materials used in the axial-flow cyclone and the Teflon and polypropylene sample storage system do not present any interference for the species of interest [major ions, formaldehyde, hydrogen peroxide, $\text{Si(IV)}$, iron, and manganese]. Multiple blank measurements taken from the collection surfaces and from the storage system were found to be at or below the minimum detection limits for the analytical methods used. To prevent contaminants such as runway debris and aerosol particles from entering the axial-flow cyclone, a motor-driven inlet cover mechanism is used. The inlet cover also prevents gas-phase nitric acid, which can be effectively captured by nylon, from entering the system while sampling is not occurring.

In order to satisfy the criteria that the collector be portable between multiple research aircraft, a Particle Measurement Systems (PMS) canister was selected to house the entire cloud water collection system. Because these canisters are used on a wide range of aerosol and cloud microphysics field programs, many research aircraft have standard mechanical mounts and electrical interfaces to accommodate PMS canisters. By placing the cloud water collector in one of these canisters (Fig. 4), the system can potentially be used without major modification on any aircraft of suitable flight speed that supports PMS optical probes. The use of a PMS canister enclosure and associated mounting location also made fuselage modifications and cabin penetrations unnecessary.

Because the cloud water collector is housed in a PMS canister located on the exterior of the aircraft, direct access to the collection system is not possible during flight, and all components of the collection system are controlled and monitored remotely. For this task, a stand-alone LabVIEW-based control and data acquisition system was developed.

3. Collector evaluation

Several evaluation techniques were used to quantify the collection characteristics of the airborne cloud sam-
spooling system. These evaluation techniques included CFD analysis to predict flow dynamics and cloud drop trajectories, experimental calibration to quantitatively determine drop deposition patterns within the axial-flow cyclone, and preliminary flight testing to examine system operation and sample collection rates under flight conditions.

1. Numerical flow modeling

An analysis of the axial-flow cyclone design was performed with the finite-volume-based CFD software package, FLUENT v5.0 (Fluent, Inc., Lebanon, New Hampshire). CFD analysis was used extensively throughout the development of the new collector for component design and to predict internal flow dynamics, the flow rate and pressure drop through the collector, and profiles of temperature and pressure in the interior of the collector. In addition, simulations of cloud drop trajectories enabled predictions of collection efficiency, drop shatter, and evaporation. In the past, CFD modeling has been applied successfully to a range of multiphase flows (e.g., Laucks and Twohy 1998; Asgharian and Godo 1997; Chen and Ahmadi 1997; McFarland et al. 1997; Muyschondt et al. 1996; Swanson et al. 1996; Jurcik and Wang 1995). Straub and Collett (2002a, 2001, 1999) applied FLUENT’s multiphase capabilities to the analysis of two ground-based multistage cascade inertial cloud drop impactors with satisfactory results. In the following discussion, the term “continuous phase” refers to air and “discrete phase” refers to cloud drops.

1) Continuous phase

The continuous phase flow field is resolved by decomposing the flow domain into finite control volumes to which the Navier–Stokes equations can be applied, thereby conserving mass and momentum on a control volume basis. The mass and momentum conservation equations are integrated over each control volume in the computational domain to produce a set of algebraic equations that can be linearized and solved numerically. FLUENT employs the Semi-Implicit Method for Pressure Linked Equations (SIMPLE; Fluent, Inc., 1999; Patankar 1980) algorithm in the sequential solution of the momentum and mass conservation equations. The iterative solution process proceeds until residuals, which represent summations of the imbalance in the governing equations over all control volumes, satisfy convergence criteria.

For this work, a second-order interpolation method, the Quadratic Upstream Interpolation for Convective Kinematics (QUICK) scheme (Leonard 1979), was used to reduce the effects of numerical diffusion (Ferziger and Peric 1999; Freitas 1995). Continuous-phase turbulence was taken into account through Reynolds averaging of the governing equations followed by closure of the turbulent equation set with a Reynolds Stress Model (RSM; Fluent, Inc., 1999). Explicit calculation of flow properties in the viscosity affected region near wall surfaces was avoided through the use of nonequilibrium wall functions (Fluent, Inc., 1999; Launder and Spalding 1974), which have been successfully utilized in previous modeling efforts designed to investigate gas/particle flows (Grif®ths and Boysan 1996; Gong et al. 1993).

Compressibility effects can become important for flows characterized by a Mach number greater than 0.3 (Munson et al. 1990). For typical research flight speeds of 120 m s$^{-1}$, the Mach number is approximately 0.3, so compressibility effects were included in the numerical modeling.

To reduce model run time, a 90° sector of the axial-flow cyclone duct was modeled at steady state, with rotationally periodic boundary conditions to simulate the existence of a full cyclone duct (Fig. 5). In addition to the interior of the axial-flow cyclone, regions upstream of the inlet and downstream of the outlet were included in the model in order to apply free-stream boundary conditions and to study free-stream airflow interactions with the inlet and exit geometries.
tire computational domain was discretized with an unstructured mesh.

Continuous-phase properties were selected to match the standard atmosphere for two altitudes, 3000 and 1000 m. Air density was calculated via the ideal gas law and continuously updated throughout the solution procedure. In order to study the effects of evaporation in the axial-flow cyclone, the continuous phase was assumed to be a mixture of air and water vapor. The thermal conductivity and viscosity were assumed to be independent of temperature and pressure and were calculated by a mass-weighted mixing law.

The velocity at the domain inlet boundary was specified to be 115 m s\(^{-1}\) along the axis of the axial-flow cyclone to simulate collector operation at typical research flight cruising speeds. The boundary temperature was 268 K for the 3000-m case and 281 K for the 1000-m case. Air at the domain inlet boundary was assumed to be saturated at the boundary temperature. A turbulence intensity of 3% and a turbulence length scale of 1 cm were selected, although previous work suggests that the model is fairly insensitive to these parameters when internally generated turbulence dominates (Straub and Collett 1999; Muyshondt et al. 1996).

2) DISCRETE PHASE

Lagrangian particle trajectories are predicted in FLUENT by constructing and then integrating a force balance on individual particles. The force balance relates the acceleration of a particle to the forces acting on it, on a per mass basis. Included in the force balance for this work were the drag, gravitational, and virtual mass forces, and a force that results from continuous-phase pressure gradients. Other forces that can influence particle motion under certain conditions, such as the Bassett and Magnus forces, were considered negligible at the continuous and discrete phase conditions present in the axial-flow cyclone (Shirolkar et al. 1996). In addition, thermophoresis, diffusiophoresis, and Brownian motion were neglected due to the supermicron size of the drops studied (Seinfeld and Pandis 1998). Turbulent continuous-phase velocity fluctuations, as calculated with an available stochastic eddy lifetime model ( Fluent, Inc., 1999), were not included in the particle force balance because of the potential for the eddy lifetime model to overpredict drop deposition to wall surfaces in flow conditions similar to those encountered in the axial-flow cyclone (Straub and Collett 2002a, 2001, 1999). Supplemental trajectory simulations indicated that drop deposition patterns did not differ appreciably with or without the inclusion of the eddy lifetime model. Although particle–particle interactions are not captured in FLUENT’s Lagrangian discrete-phase modeling scheme, the volume fraction of liquid water in a cloud is several orders of magnitude below the threshold (\(\sim 10\%\)) for which such interactions can be safely neglected.

FLUENT offers a vaporization scheme that allows the evaporation from liquid drops to be evaluated. The change in mass for an evaporating drop is proportional to the gradient in water vapor concentration from the drop surface to the bulk continuous phase. The bulk continuous-phase water vapor concentration was dictated by the mass concentration specified at the domain upstream boundary, which in this case corresponded to water saturation at the boundary temperature. The bulk continuous-phase water vapor concentration was not modified by evaporation from the discrete phase. The water vapor concentration at the drop surface was derived from the saturation vapor pressure corresponding to the temperature of the drop. The drop temperature was calculated through a simultaneous solution of a mass transfer equation and a heat transfer equation, which balances the heat storage in the drop, the convective heat transfer to the drop, and the latent heat required for evaporation.

Drops were injected into the continuous phase from a surface located 30 cm upstream of the inlet and were given an initial velocity of 115 m s\(^{-1}\) to match the free-stream air velocity. Wall surfaces in the model were set to an escape boundary condition for the discrete phase. This boundary condition halts trajectory calculations when drops come into contact with a wall surface, simulating the deposition of cloud drops on the surfaces of the collector without splashing or rebound.

b. Experimental laboratory evaluation

A quantitative calibration technique was employed to investigate the internal collection efficiency of the axial-flow cyclone in a rigorous manner. For this calibration, fluorescein-tagged monodisperse drops were injected into the inlet of the axial-flow cyclone, which was operated with an inlet velocity of 30 m s\(^{-1}\) to simulate flight conditions. The fluorescent tracer allowed the number of drops that deposit on individual surfaces in the collector to be quantified, permitting drop deposition patterns in the interior of the collector to be accurately determined. After repetition of this procedure for various drop sizes, a collection efficiency curve that describes collection efficiency as a function of drop size was constructed. This technique has been used successfully in the past to calibrate aerosol impactors (Marple et al. 1995, 1987; Hillamo and Kauppinen 1991, 1989) and ground-based cloud water collectors (Straub and Collett 2002a, 2001), and to verify numerical modeling results (McFarland et al. 1997; Muyshondt et al. 1996). For this work, the calibration procedure was performed using drops 4, 5, 6, 8, 10, and 20 \(\mu m\) in diameter with replicate analyses to ascertain 95% confidence limits.

Monodisperse calibration drops were generated with a Model 3450 vibrating orifice aerosol generator (VOAG; TSI, Inc.), which is capable of producing drop diameters accurate to \(\pm 2\%\) (Berglund and Liu 1973). The liquid solution used to generate the calibration
drops consisted of a volatile component that quickly evaporates and a nonvolatile component that remains behind to produce the final calibration drop. Isopropyl alcohol was selected as the volatile component, and a mixture of oleic acid and fluorescein was selected as the nonvolatile component. Oleic acid (ρ = 0.90 g cm⁻³) is characterized by low volatility and approximates the density of water; fluorescein (ρ = 1.53 g cm⁻³) was included as the fluorescent tracer. Drop sizes of interest were produced by altering the nonvolatile fraction of the liquid solution. Microscope visual analysis was used to confirm the drop sizes produced by the VOAG, within the accuracy of the imaging system.

In order to quantify drop deposition patterns resulting from this calibration procedure, surfaces onto which the fluorescein-tagged drops deposited were soaked in a known volume of extract solution into which the fluorescein would dissolve. The extract solution could then be analyzed fluorometrically to ascertain the mass of fluorescein, and therefore the number of drops, on any given surface. Doublets and triplets, which inevitably form due to drop collision and coalescence in the calibration stream, were taken into account following the procedure described in Straub and Collett (2002a). A 0.001 N NaOH solution was used for extraction because of its effectiveness in removing the oleic acid/fluorescein from the surfaces of the collector (Straub and Collett 1999; Marple et al. 1987).

In the absence of a 115 m s⁻¹ wind tunnel to generate airflow through the axial-flow cyclone, three large blowers provided the necessary flow rate through the interior of the collector. One disadvantage of this experimental setup is that inlet conditions matching those experienced during flight could not be generated. In the laboratory setup, air is drawn through the axial-flow cyclone by blowers rather than being forced through the axial-flow cyclone as a result of ram pressure. In both cases the 30 m s⁻¹ inlet velocity is achieved; however, at laboratory conditions quiescent air accelerates from all directions to reach 30 m s⁻¹ in the inlet, while in flight 115 m s⁻¹ ambient airflow decelerates to 30 m s⁻¹. Therefore, the inlet is superisokinetic in the laboratory setup rather than subisokinetic as would be experienced in flight. The superisokinetic inlet conditions create a flow field that focuses drops released upstream of the inlet toward the centerline. These trajectories would reveal little about the true collection characteristics of the axial-flow cyclone. As an alternative, drops were instead released from a location approximately 4 cm downstream of the inlet leading edge, where the flow attains a more uniform and axial structure. Therefore, only internal collection characteristics were evaluated in the laboratory calibration.

c. Flight testing

The Dynamics and Chemistry of Marine Stratocumulus, Phase II (DYCOMS-II) field project took place during July 2001 (Stevens et al. 2003) as a sequel to the original 1986 DYCOMS field campaign (Lenschow et al. 1988). Although the primary focus of the DYCOMS-II field project was to study the entrainment of free tropospheric air into the marine boundary layer and the production and influences of drizzle in marine stratocumulus cloud layers, substantial in-cloud flight time provided an opportunity to test and evaluate the cloud water sampler in clouds under flight conditions. Of particular interest were the logistics of system installation and removal between flights, the operation of individual collector components such as the inlet cover and storage system valves, and actual cloud water sample collection rates. For comparison with actual collection rates, predicted collection rates were derived in part from cloud liquid water content (LWC) measurements (PVM-100A, Gerber Scientific, Inc.), cloud drop size distributions (SPP-100, Droplet Measurement Technologies), and standard instrumentation for meteorological state parameters (Stevens et al. 2003). The PVM-100A has a reported LWC measurement uncertainty of 5%–10% and is sensitive to drops between 4 and 45 μm (Gerber et al. 1994), although a decreased response has been measured for drops at the higher end of that range (Wendisch et al. 2002). The SPP-100 is an upgraded version of a forward scattering spectrometer probe (FSSP-100), which is sensitive to drops between 2 and 47 μm and has reported measurement uncertainties of 20%–25% for diameter and 16%–25% for concentration (Baumgardner 1996, 1989).

The project targeted a region over the Pacific Ocean 400 km southwest of San Diego, California, and was based on the National Science Foundation (NSF)/National Center for Atmospheric Research (NCAR) C-130 aircraft. The collector was mounted in a PMS canister on the instrumentation pod located below the right wing of the C-130, outboard of the two engines. Throughout the duration of the DYCOMS-II project, a stratocumulus cloud deck was present with cloud tops ranging between 300 and 900 m on most flights. Each flight included multiple hour-long in-cloud legs during which the cloud water collector was operated. The LWC ranged from 0.1 to 0.2 g m⁻³ at cloud base and 0.5 to 0.8 g m⁻³ at cloud top, which allowed collector evaluation under various conditions.

4. Results and discussion

a. Continuous-phase flow solution

The axial and tangential components of velocity through the model flow domain are presented in Fig. 6 as a function of distance through the domain. The velocities are extracted from control volume centers along a single line that passes through the solution domain midway between the center hub and duct wall. The velocity at the domain upstream boundary is 115 m s⁻¹ in the axial direction, as prescribed in the model bound-
FIG. 6. Axial (open circles) and tangential (solid squares) components of velocity as a function of position through the cloud water collector. The inlet is located at −18 cm, the vanes at 0 cm, and the exit at +37 cm. The axial component of velocity decreases as the flow approaches the collector inlet because of partial stagnation conditions. The tangential component is negligible before increasing to 85 m s$^{-1}$ immediately downstream of the vanes. The tangential velocity then decays through the remainder of the duct.

Fig. 7. Sample trajectories for (a) 1, (b) 10, and (c) 30-μm drops. A fraction of 1-μm drops follow air streamlines around the inlet of the axial-flow cyclone, while the remainder reach the duct wall downstream of the extraction slot and are therefore not collected; 10-μm drops reach the duct wall upstream of the extraction slot and should be collected; 30-μm drops possess enough inertia to impact on the surfaces of the curved vanes.

b. Discrete-phase solution

Following the steady-state airflow solution, cloud drop trajectories were calculated via integration of a force balance on individual drops. These trajectory simulations were used for predicting collection efficiency, drop shatter, and evaporation. Trajectory calculations for drops 1 μm in diameter and for drops 2–50 μm in diameter, in 2-μm increments, proceeded until a wall was encountered or the drops exited the computational domain. For illustrative purposes, 10 sample trajectories for drops 1, 10, and 30 μm in diameter are shown in Fig. 7.

Due to the subisokinetic sampling conditions of the axial-flow cyclone, some cloud drops approaching the inlet of the collector tend to follow the air streamlines that diverge around the exterior of the inlet (Fig. 7a). This effect is more pronounced for smaller drops with low inertia. The drops that enter the inlet travel axially until reaching the rotational flow field. At that point, centrifugal force acts on the entrained cloud drops to quickly move them to the duct wall. As indicated in Fig. 7, large cloud drops migrate to the duct wall rapidly while smaller drops migrate more slowly. Drops 1 μm in diameter do not reach the wall until well downstream of the extraction slot, while 10-μm drops move quickly to the duct wall in the rotational flow field and deposit on the wall surface upstream of the extraction slot. Drops of 30-μm diameter possess enough inertia that they are unable to follow the airflow past the curved vanes and instead impact on the surfaces of the vanes.

Water drops impacting on the vanes were observed in lab tests to be shed off the vane surfaces and into the rotational flow field, where they are quickly removed to the duct wall.

ary conditions. Due to the partial obstruction that the curved vanes present to the airflow in the interior of the collector, the air decelerates as it approaches the inlet of the collector, reaching approximately 30 m s$^{-1}$ in the inlet region. The flow Reynolds number is approximately $9.5 \times 10^4$ within the inlet. The subisokinetic inlet condition results in a fraction of the flow diverting around, rather than through, the inlet and has implications for cloud drop aspiration efficiency that will be discussed in the following section.

Upstream of the stationary vane assembly, the interior airflow is purely axial in direction; that is, the tangential velocity is negligible. However, as the airflow passes through the vanes, the tangential velocity immediately reaches 85 m s$^{-1}$, indicating the presence of a strongly rotating flow field that persists past the extraction slot and slowly decays through the remainder of the duct.

The deceleration of the airstream in the axial-flow cyclone inlet results in compressional heating of the sample stream. As the air enters the inlet of the collector, dynamic pressure is converted into a static pressure rise of approximately 5600 Pa. This rise in static pressure produces a temperature increase from the free-stream value of 268 to 274 K for the 3000-m case and from 281 to 287 K for the 1000-m case. This temperature rise increases the saturation vapor pressure and has implications for evaporation of the cloud water sample, which will be discussed in the following section.
The following three sections describe the use of the discrete-phase modeling results for the evaluation of collection efficiency, drop shatter, and evaporation of cloud water sample. The latter two factors represent competing issues that influenced the specified distance between the inlet of the axial-flow cyclone and the vane assembly. Because the air velocity within this region is approximately one-quarter that of the free-stream velocity, incoming cloud drops begin to decelerate, which has the beneficial effect of reducing the likelihood of drop shatter. However, because the deceleration of the airflow compresses and warms the incoming air, prolonged exposure of cloud drops to these conditions enhances the potential for evaporational loss. The 15-cm distance between the inlet and the vane assembly was selected as a compromise between drop shatter and evaporation issues.

1) Collection Efficiency

The overall collection efficiency of the axial-flow cyclone was investigated in two parts, an external aspiration efficiency and an internal collection efficiency, which helps to identify the processes that influence the collection of cloud drops in the axial-flow cyclone. The external aspiration efficiency was defined as the percentage of drops released from the injection surface that enter the inlet of the collector. Curves depicting the external aspiration efficiency are illustrated in Fig. 8 for the 1000- and 3000-m cases. Because the collector operates at subisokinetic conditions, aspiration efficiency is lowest at small drop sizes and increases with increasing drop size. As drops become larger, their increased inertia allows additional drops to cross the limiting air streamline and pass through the partial stagnation at the inlet of the collector.

The internal collection efficiency of the axial-flow cyclone was calculated as the percentage of drops entering the collector that reach the duct wall upstream of the extraction slot. This definition of collection efficiency is based on the assumption that all drops that reach the duct wall upstream of the extraction slot flow along the duct wall, into the extraction slot, and are removed for storage. The validity of this assumption was called into question during flight testing, as discussed in section 4d. Two other qualifications were made in the evaluation of the internal collection efficiency based on insight gained during laboratory testing and supplemental CFD analysis (Straub and Collett 2002b). First, cloud drops that impact the stationary curved vanes flow off of the vanes, enter the rotational flow field, and reach the duct wall upstream of the extraction slot, and therefore are collected. Second, drops that impact the center hub of the vane assembly flow along the hub until reaching the downstream tip of the hub. Therefore, these drops are unable to reach the duct wall upstream of the extraction slot and are expected to remain uncollected. If these assumptions are considered, internal collection efficiency increases rapidly with increasing drop diameter as larger drops migrate to the duct wall rapidly, while smaller drops do not (Fig. 9). As drop diameter increases from 10 to 50 μm, a slight decrease in collection efficiency occurs as greater numbers of drops deposit on the hub through inertial impaction.

When the external aspiration efficiency and the internal collection efficiency are combined, the resulting overall collection efficiency for the axial-flow cyclone as a function of drop size is as shown in Fig. 10 for the 1000- and 3000-m cases. This overall collection efficiency can be regarded as the number of cloud drops that reach the duct wall upstream of the extraction slot.
with a 12-ample, the predicted sample collection rate in a cloud flow cyclone operating at various conditions. As an example, the predicted sample collection rate in a cloud with a 12-μm mean diameter, a lognormal size distribution (σr = 1.2), and an LWC of 0.3 g m⁻³ is approximately 8 μm. Based on the model-derived overall collection efficiency, theoretical rates of cloud water collection can be calculated for the axial-flow cyclone operating at various conditions. As an example, the predicted sample collection rate in a cloud with a 12-μm mean diameter, a lognormal size distribution (σr = 1.2), and an LWC of 0.3 g m⁻³ is approximately 4 mL min⁻¹.

Additional numerical modeling indicated that a misalignment between the axis of the collector and the air streamlines of 4°, representing a typical research aircraft angle of attack, does not significantly alter the external aspiration efficiency (Straub and Collett 2002b), and therefore does not alter total collection efficiency. Furthermore, this modeling revealed that flow perturbations created by the blunt forward end cap of the PMS canister are minor and have little effect on inlet aspiration.

2) DROP SHATTER

The numerically generated trajectories contained information about drop impact velocity that could be used to examine the probability of drop shatter in the axial-flow cyclone collector. The primary threat for drop shatter occurs for cloud drops that enter the collector inlet with enough inertia to impact on the curved vanes rather than pass through to the rotational flow field. Dimensionless parameters based on drop and surface conditions have been developed to identify regimes in which the outcome of a drop/surface collision is likely to result in drop deposition or shattering (e.g., Range and Feuillebois 1998; Cossali et al. 1997; Mundo et al. 1995; Rein 1993; Stow and Hadfield 1981). The nondimensional groups commonly used to define the limits of deposition and shattering are the Weber number (We), the drop Reynolds number (Re), and the Ohnesorge number (Oh), which are defined as follows:

\[ \text{We} = \frac{\rho V^2 D_p}{\sigma}, \]
\[ \text{Re} = \frac{\rho V D_p}{\mu}, \quad \text{and} \]
\[ \text{Oh} = \frac{\mu}{(D_p \sigma p)^{1/2}}, \]

where \( \rho \) is liquid density, \( D_p \) is drop diameter, \( V \) is drop velocity at impact, \( \sigma \) is liquid surface tension, and \( \mu \) is liquid dynamic viscosity.

Experimental studies by Mundo et al. (1995) covered a range of conditions for the impact of drops on a solid, dry surface and determined that drop splash occurs when the following condition is met:

\[ (\text{Oh Re}^{1.25})_L > 57.7. \]

If the curved vanes are assumed to be dry, the product \((\text{Oh Re}^{1.25})_L\) exceeds 57.7 for drops larger than 30 μm in diameter, suggesting that drops 30 μm and larger will shatter upon impact.

If the curved vanes are initially wetted, drop impact may be influenced by the presence of a liquid film on the vane surface. Cossali et al. (1997) studied the phenomenon of drop shatter for drop impact on a thin liquid film, finding the following relation to describe the deposition/splash limit:

\[ (\text{Oh}^{-0.4}\text{We})_L = 2100 + 5880\delta^{1/4}, \]

where \( \delta \) is the nondimensional film thickness,

\[ \delta = h/D_p, \]

and \( h \) is the film thickness. The drop deposition/splash limit is valid for 0.1 < \( \delta \) < 1.0 and for \( \text{Oh} > 0.007. \)

If a liquid film is present, the calculation of the drop deposition/splash limit is dependent upon the nondimensional film thickness (\( \delta \)), which varies with actual film thickness and drop diameter. If a film thickness of 5 μm is assumed to be present on the vane surfaces, the drop deposition/splash limit of Cossali et al. (1997) predicts that only drops larger than 46 μm will shatter, ensuring that the majority of cloud drops impacting the vane surfaces will simply deposit upon impact. An increase in film thickness will shift the drop deposition/splash limit to larger sizes, while a decrease in film thickness will shift the limit to smaller sizes, although the restricted range of valid \( \delta \) values prevents interpretation of very thin film/large drop diameter impact combinations.

Larger drops, ranging in size from the typical cloud drop limit of 50 μm up to precipitation drops on the...
order of millimeters, are therefore likely to shatter if they impact the curved vanes. However, there is some experimental evidence that the secondary drops produced by the shatter of drops in this size range may be sufficiently large to be collected in the rotational flow field of the axial-flow cyclone (Mundo et al. 1995).

3) Evaporation

The temperature rise in the inlet of the axial-flow cyclone resulting from deceleration of the airflow raises the water saturation vapor pressure and can therefore result in evaporation of cloud drops or cloud water on the cyclone wall. Evaporation of the cloud water sample can lead to biases in the measurement of chemical concentrations. To quantify the extent to which evaporation may occur in the collector, estimates of evaporation were made for suspended drops flowing through the collector and for a liquid water film on wall surfaces of the collector.

The percent loss in mass due to evaporation of suspended drops flowing through the collector was calculated for the period from drop entry into the solution domain until deposition of the drops downstream of the vanes. The CFD-based solution to the coupled mass and heat transfer equations revealed that evaporation of suspended drops is significant at small drop sizes. For example, mass loss through evaporation is predicted to be 23% and 27% for 4-μm drops when the collector is operated at 1000 and 3000 m, respectively. However, drops of that size are assumed to be interstitial aerosol particles or unactivated haze and intentionally remain uncollected, so evaporational loss in that case does not affect sample integrity. Drop evaporation decreases rapidly with increasing drop size such that drops 10 μm in diameter experience a 3%–5% loss and drops greater than 20 μm lose less than 1% of their mass. Because chemical concentrations measured in bulk cloud water samples are typically dominated by large drops, which contribute the most to collected sample volume, the effects of small-drop evaporation on measured concentrations should not be significant.

Cloud water that deposits on the interior surfaces of the axial-flow cyclone may also be subject to evaporation as it flows along the duct wall toward the extraction slot. As an upper bound of evaporation from the wall surfaces in the axial-flow cyclone, mass and heat balances [Bird et al. 1960, Eqs. (13.1-1) and (21.1-2)] were applied to a liquid water film that was assumed to cover all wall surfaces from the inlet to the extraction slot, including the curved vanes and center hub (Straub and Collett 2002b). Based on this analysis, the expected evaporation rates are 0.24 mL min⁻¹ at 3000-m flight conditions and 0.32 mL min⁻¹ at 1000-m flight conditions. These evaporation rates are compared to potential collection rates on the order of 3–5 mL min⁻¹ for LWC in the range of 0.2–0.3 g m⁻³. Consequently, sample evaporation and corresponding solute concentration increases of 10% or less can be considered an upper bound for typical sampling conditions.

c. Experimental calibration results

The internal collection efficiency of the axial-flow cyclone was examined experimentally with fluorescein-tagged monodisperse drops and subsequently compared to the numerically derived results. Calibration drop diameters are reported as equivalent aerodynamic diameters so that experimental and numerical results can be directly compared.

The laboratory calibration revealed that drops released within the inlet do in fact deposit on surfaces upstream of the extraction slot. Because oleic acid drops simply deposit on internal collector surfaces without flowing toward the extraction slot, the experimental drop deposition data was used to construct internal collection efficiency curves based on assumptions similar to those for the CFD-based internal collection efficiency curve, that is, that drops that reach the duct wall upstream of the extraction slot or deposit on vane surfaces eventually reach the extraction slot and are available for storage. The center hub and curved vanes were constructed as a single component so that the center hub could not be separately extracted in the experimental analysis. Therefore, drops that deposit on the center hub are classified as being collected in this calibration procedure, when in fact liquid water drops would more likely flow along the hub past the extraction slot and not be available for collection.

Internal collection efficiency at each drop size was calculated as the ratio of the number of drops recovered from all collector surfaces upstream of the extraction slot to the total number of drops injected into the collector inlet, while correcting for the presence of doublets and triplets. These efficiencies are compiled as an internal collection efficiency curve displayed in Fig. 11. As with the CFD results, the internal collection efficiency increases rapidly with increasing drop diameter. The curve approaches 100% for drops larger than approximately 8 μm. Also included in Fig. 11 are two internal collection efficiency curves based on numerical modeling. The first is the collection efficiency curve for flight conditions at 3000 m presented in section 4b(1), although in this case, drops that strike the center hub are assumed to be collected in order to match the limitations of the experimental calibration procedure. This curve agrees in shape with the laboratory calibration curve, although it is shifted to smaller diameters by about 2 μm. The second numerically derived internal collection efficiency curve displayed in Fig. 11 is based on additional numerical modeling that more precisely matched the laboratory experimental conditions. This additional modeling incorporated ambient air properties at the laboratory elevation of 1500 m, a supersokinetic inlet airflow field, drop injection within the inlet, and a drop injection velocity that matches the VOAG outlet.
velocity. This numerically derived internal collection efficiency curve agrees quite well with the curve obtained through experimental calibration. Furthermore, the deposition of calibration drops on individual surfaces of the collector during the experimental calibration was also found to be consistent with numerical predictions (Straub and Collett 2002b).

d. Flight evaluation results

Participation in the DYCOMS-II field campaign in July 2001 provided the first opportunity to evaluate the operation of the collection system under flight conditions. All of the subsystems worked as intended throughout the duration of the project. Ease of use and straightforward installation and removal of the collection system were confirmed during field usage. However, early in the DYCOMS-II mission, it became apparent that the recovery of water from the axial-flow cyclone was lower than predicted by the numerical modeling and laboratory calibration.

After returning from the field, a rigorous estimate of the expected collection rate was made using PVM-100A LWC partitioned according to SPP-100 measured drop distributions for sample periods when the required data was available. The expected collection rates also included estimates of evaporation, external aspiration efficiency, and internal collection efficiency as functions of drop diameter. These postcampaign calculations suggested that collection rates during DYCOMS-II should have been in the range of 1.0–9.7 mL min⁻¹. However, these expected collection rates far exceeded the actual collection rates, which varied between 0.1 and 1.2 mL min⁻¹. For the duration of the DYCOMS-II program, the actual sample collection rates averaged approximately 9% of the expected sample collection rates. Actual collection rates are plotted as a function of expected collection rate in Fig. 12. No meaningful correlations were found between the actual-to-expected sample collection rate ratios and microphysical or flight parameters (Straub and Collett 2002b).

Because the laboratory calibration demonstrated that drop collection efficiency and deposition patterns in the interior of the axial-flow cyclone were as expected, attention was focused on inefficient extraction of accumulated cloud water from the duct wall as the likely cause of reduced collection rates. Unfortunately, the flow of drops after deposition could not be investigated through numerical modeling or quantitatively with the experimental method employed. However, in a separate experiment in which the collector was operated at a flightlike internal flow rate, liquid water flowing along the duct wall upstream of the extraction slot was visually observed to flow over, rather than into, the extraction slot. This observation, while not quantitative in nature, does suggest that the extraction slot design is ineffective in removing the majority of collected water from the wall of the axial-flow cyclone. The inability of the extraction slot to remove the accumulated cloud water persisted despite increases in the suction flow rate applied to the two extraction slot ports.

Because drops of all sizes deposit on the duct wall upstream of the extraction slot and then flow under the influence of aerodynamic drag toward the extraction slot, the accumulated cloud water should be well mixed. Therefore, the incomplete removal of cloud water from the duct wall reduces the collection rate but should maintain a representative cloud water sample. In order to compensate for the reduced collection rate of the system, sample times during flight testing were in-
creased to an average of 25 min for cloud-base samples and 13 min for cloud-top sampling periods. Despite the low collection rate, enough cloud water was collected in nearly every sample period to enable the desired chemical analyses to be performed. Results of DYMOS-II cloud composition measurements will be presented elsewhere.

5. Conclusions

The new aircraft-based cloud water collector is an operational prototype that satisfies the majority of its design goals but will also benefit from continued development. In its current form, the collector is able to obtain well-characterized cloud water samples from an aircraft platform. The collection system is easily transportable between research aircraft by taking advantage of standard PMS canister mechanical and electrical interfaces. The use of an axial-flow cyclone for separation of cloud drops from the airstream reduces the possibility of drop shatter as compared to collectors relying on inertial impaction at free-stream velocities.

CFD analysis of the axial-flow cyclone indicates that inlet conditions are subisokinetic due to the presence of the vane assembly that generates the required rotational airflow. CFD simulations of cloud drop trajectories suggest that the rotational flow field in the axial-flow cyclone is sufficient to quickly move entrained cloud drops to the duct wall. Collection efficiency curves were compiled for operation at 1000 and 3000 m, and the 50% cut diameters were determined to be approximately 8 μm in both cases. The collection efficiency curves were found to be independent of slight misalignments between the inlet and free-stream airflow. The CFD-based trajectory simulations were verified with an experimental laboratory calibration involving fluorescein-tagged monodisperse drops. Experimentally determined internal drop deposition patterns agreed well with the numerical simulations and lend support to the CFD modeling effort.

The shattering of cloud drops due to high-velocity impacts on collection surfaces was also investigated. Free-stream inertial impaction devices are likely to experience drop shatter at nearly all drop sizes. The tendency for drop shatter was reduced in the axial-flow cyclone by decelerating incoming cloud drops in a low-velocity airflow region prior to impact on collection surfaces. Only cloud drops larger than 46 μm are vulnerable to shatter if they impact on a liquid film coated surface. Evaporation of cloud drops suspended in the airstream should be negligible for drop sizes of interest, and evaporation from wall surfaces should be less than 10% for operation in clouds with LWC greater than 0.2 g m⁻³. The final inlet geometry represents a compromise between the competing factors of evaporation and drop shatter.

The first operational field use of any newly developed instrument potentially reveals design limitations not exposed during preliminary analysis and testing. This was true of the axial-flow cyclone cloud water collection system during its initial deployment during the DYMOS-II field campaign. While the majority of the collection system operated as expected throughout the project, the principal deficiency in the system was a lower than expected cloud water recovery rate associated with inefficient water removal by the collector’s extraction slot. While the inefficiency of the extraction slot should still yield a sample representative of the cloud water entering the inlet of the axial-flow cyclone, an increase in the sample collection rate will require future modification of the extraction slot.

Improvement in the sample collection rate is the primary objective for further development of the cloud water collection system. Observations of water flowing along the duct wall in a helical pattern both upstream and downstream of the extraction slot during laboratory operation suggest that a disturbance of the near-wall flow field in the vicinity of the extraction slot may be interfering with the intended flow of deposited cloud water. A slot geometry that minimally disrupts the flow field will likely improve the efficiency of water extraction. Several suggestions for a redesigned extraction slot have been proposed (Straub and Collett 2002b) and will be evaluated through future wind tunnel and flight testing.

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