p. 3009
ASRC collector: 720 strings, 0.41 mm diam

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$720 \times 0.41 \times 10^{-3} m \times 0.42 m = 0.124 m^2$

TESTS OF MODELS OF CLOUDWATER DEPOSITION TO FOREST CANOPIES USING ARTIFICIAL AND LIVING COLLECTORS

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Abstract—Mechanistic cloud deposition models are very useful in the routine quantification of cloudwater deposition to forest canopies. In order to test, in a natural field situation, several assumptions in these models, a passive string cloudwater collector, a small artificial tree, and a living Norway spruce were exposed to cloudwater on a raised platform at the summit (elevation, 1686 m) of Whitetop Mountain, Virginia over a 5 month period. Cloudwater collection rates by these three collectors were used to examine relationships between these rates and measured values for two important meteorological variables in the models, liquid water content and wind speed, the product of which is the horizontal cloudwater flux. Collection rates for all three collectors were predicted moderately well by horizontal cloudwater flux (R^2 ranged from 0.54 to 0.73; $p<0.0001$) across all hours of observation, but were least strongly related when liquid water content was low, probably because of various measurement uncertainties under this condition. For all three collectors, simple linear regressions using the horizontal water flux to predict collection rates were not appreciably improved by inclusion of a cloudwater collection efficiency term or by conversion to binomial or curvilinear models. Cloudwater collection efficiency for all three collectors was related to the logarithm of horizontal water flux, as predicted by the models, only when this relationship was analyzed within individual cloud events. Between individual cloud events, collection efficiency varied across a wide range (0.12–0.50 for the spruce tree), with efficiencies much higher during events of short duration. Cloudwater collection efficiency was often lower than predicted by cloud deposition models, possibly because the models use wind speed measurements which do not take into account reductions in wind speed occurring within needle clusters on branches. Collection rates for all three collectors correlated highly with each other (R^2 ranged from 0.72 to 0.88; $p<0.0001$), as well as with a mature red spruce canopy. It was concluded that either the string collector or an artificial tree such as the one used in this study would serve as a good surrogate collector for living spruce tree crowns.

Key word index: Cloudwater deposition, collection efficiency, liquid water content, wind speed, cloud droplet size, horizontal water flux, modeling, forest canopy.

1. INTRODUCTION

The importance of cloudwater in the delivery of water and a number of ionic species to mountaintop ecosystems has been consistently reported (Vogelmann *et al.*, 1968; Lovett *et al.*, 1982; Dollard *et al.*, 1983; Dollard and Unsworth, 1983; Lindberg *et al.*, 1988; Mueller and Weatherford, 1988; Saxena and Lin, 1988; Kroll and Winkler, 1989). However, the difficulties in estimating the quantities of ions deposited by cloudwater deposition have also been noted by the same investigators (see also Lovett, 1988). As is the case with dry deposition, accurate direct quantification of cloudwater deposition to forest canopies is virtually impossible to achieve, especially over long time periods and in regions of complex terrain. Attempts to infer cloud deposition using throughfall (water passing through the canopy to the forest floor) have been made (Lovett, 1984, 1988; Mueller and Imhoff, 1989). However, this approach is especially unsatisfactory for measurements of the deposition of *ions* because of canopy exchange and the wash-off of previous deposition. Difficulties are also encountered in the measurement of cloudwater deposition *volumes* because of interception loss—that portion of deposited water held on plant surfaces and eventually returned to the atmosphere by evaporation. This interception loss is important because the dissolved chemicals in the deposited water which evaporates remain in the ecosystem. Interception loss is often a large fraction of total cloudwater deposition because: (1) forest canopies, particularly conifer canopies, have very large surface areas and (2) cloud events frequently involve small volumes of water relative to precipitation events. In fact, cloud events often end prior to any water reaching the forest floor (Lovett, 1984; Joslin *et al.*, 1988).

The difficulty of measuring cloudwater deposition directly necessitates the use of deposition models. Models recently developed by Lovett (1984, 1988) and Mueller (1990) are based upon the earlier theoretical postulations set forth by Shuttleworth (1977), who in turn credits Hori (1953) and Merriam (1973) with pioneering work on the basic physical processes involved in cloudwater deposition. These models are highly mechanistic ones and require numerous assumptions for field application. In order to test, in a natural field situation, several assumptions in these models of cloudwater deposition, we exposed artificial and living collectors to cloudwater on a raised platform at the summit (elevation, 1686 m) of Whitetop Mountain, Virginia. The collection of throughfall drip from single, exposed, small (1.5 m tall) trees, living or artificial, reduces the problems of directly measuring cloudwater deposition from throughfall that are inherent in mature forest canopies. With such small tree collectors positioned in the open, virtually all of the foliar surface area is the active collecting surface. In a mature canopy, it is predominantly the upper portions of the crowns—exposed to the higher wind speeds and liquid water contents—which are the active collecting surfaces, though the entire foliar mass is involved in interception losses. Also, all the water dripping from a small tree can easily be collected, eliminating the problems of spatial variability in collecting such throughfall from a forest canopy. Although the problem of interception loss still remains with such collectors, for most long cloud events it is a small error, and the rate at which net deposition water is collected below such collectors (C_n) approximates the rate of total gross cloudwater deposition (C) to them.

In order to develop better estimates of bulk cloudwater collection efficiency (ε)* for tree crowns, this study of the collection behavior of crown-like collectors—a young spruce tree and an artificial tree—was undertaken. Both artificial and living collectors were used to address the following questions. (1) Is the relationship between horizontal cloudwater flux (F) and C_n best described as linear, as the models assume, or do binomial or curvilinear models improve prediction appreciably? (2) How important is the inclusion of a factor reflecting the variability of ε in the determination of the actual rate of cloudwater deposition (C)? Or, alternatively phrased, how much does the modeled estimate of ε as a function of the Stokes number (S)† contribute to the prediction of the rate of cloudwater collection (C_n) over and above predictions using horizontal cloudwater flux (F) alone? (3) What is the relationship of ε to the key variables in the Stokes number equation, i.e. wind speed (u) and droplet size (D_p), and what is the actual cloudwater collection efficiency of these surrogate tree crowns taken in their entirety (rather than as an aggregate of individual twigs and needles)? None of the above relationships have been tested across the wide range of meteorological conditions occurring on cloud-dominated mountaintops.

An additional question, unrelated to the assumptions in the cloud deposition model, was also posed for this study: what is the degree of correlation among an ASRC‡ "string collector" (Falconer and Falconer, 1980), a commercial artificial 'Christmas tree', and a living Norway spruce tree? Do either or both of these artificial collectors perform as a reasonable surrogate for a real tree? Evidence of strong relationships would support the use of such surrogate collectors: (a) as deposition indices for comparisons between different sites or between different time intervals at the same site or (b) as collectors of cloudwater samples which are representative of the cloudwater actually deposited on forest trees.

2. BACKGROUND INFORMATION ON CLOUD DEPOSITION MODELS

In the Lovett (1984) model, and a modified version developed for studying cloud deposition to forests in the eastern U.S. (Mueller, 1990), canopy-top wind speed (u), liquid water content (W), and a cloud droplet size distribution selection parameter are three of the most important inputs. The last variable is important in estimating the percentage of deposition due to sedimentation and in determining the droplet collection efficiency of a surface (Lovett, 1984; Mueller and Imhoff, 1989). Sedimentation is usually a minor fraction of total cloudwater deposition, except under certain circumstances such as very low wind speeds (Mueller, 1990), and it is ignored in our investigations here. Aside from sedimentation, the model computes deposition in a manner that is proportional to the canopy-top horizontal cloudwater flux (i.e. the product of u and W, hereafter called "F"). Cloud droplet diameter (D_p) is also an important factor because, in the model, D_p affects the collection efficiency of a given object.

Cloudwater collection efficiency (ε) is an important characteristic of any collecting surface because of its influence on inertial deposition rate (C). Specifically,

$$C = \varepsilon A F = \varepsilon A u W, \qquad (2)$$

where A is the cross-sectional area of a collector.

In order to estimate ε, the model by Lovett (1984) uses an empirically-derived relationship between ε and

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* Throughout this paper, cloudwater collection efficiency (ε) refers to the 'bulk removal' of cloudwater by a collection surface rather than to the collecting efficiency of the surface with regard to individual droplet size classes.

† The Stokes number parameterizes droplet inertia and represents the degree to which a particle moving in a fluid will continue to follow a single streamline of the fluid as it flows around an obstacle. The particle will tend to follow the streamline as long as its inertia is not too large. As particle size increases, so does its inertia, and the deviation of the particle's motion from that of the fluid increases. The value of S is given by

$$S = \frac{\rho u D_p^2}{18 \mu D_c} \qquad (1)$$

where ρ is the density of the particle, u is the free-stream fluid velocity, D_p is the effective particle diameter, μ is the fluid viscosity and D_c is the characteristic length scale of the obstacle.

For a conifer, D_c usually represents the effective diameter of the predominant collecting surface—the needles.

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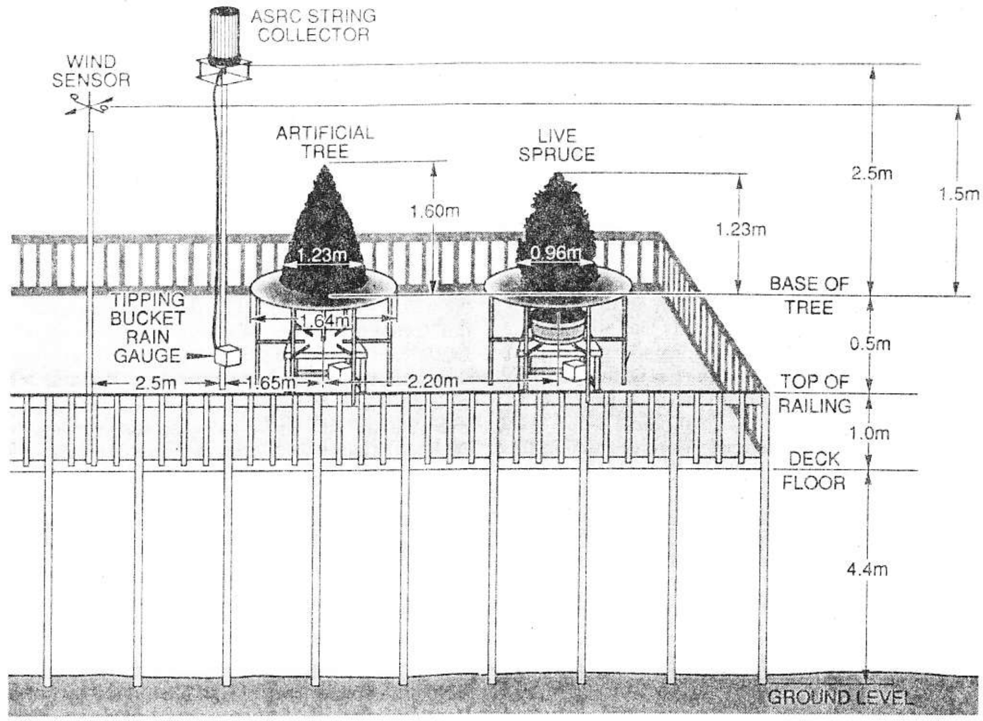


Fig. 1. Schematic diagram showing location and dimensions of the three cloud collectors and wind sensor on the elevated deck.

the Stokes number (S) for individual tree components (needles, twigs, branches, etc.) wherein $\varepsilon = f[\ln(S)]$.

3. METHODS

3.1. *Site description*

The experiments described herein were all conducted on the summit of Whitetop Mountain in southwestern Virginia between 10 May and 27 September 1988. Collectors and meteorological instruments were all located upon a deck constructed at the summit of the mountain at an elevation of 1686 m (Fig. 1). The floor of the deck was approximately 4.4 m above ground level and located within a fenced compound. The tops of the nearest trees to the deck (10 m to the west) were 2 m below the floor of the deck. Cloud frequency during this May–September interval averages about 32% (3-year average); during the particular year of study (1988) cloud frequency was actually 25%. Temperature during the study period ranged from -0.4°C to 25.3°C, with a mean value of 13.9°C. Wind speeds, measured at 7.4 m above ground level, averaged 2.7 m s^{-1} during the May–September period with a median value of 2.5 m s^{-1}; during the cloud events measured in this study wind speeds averaged 6.4 m s^{-1}. The 3-year mean and median measured hourly liquid water content values for Whitetop were both 0.20 g m^{-3}; during the hours measured in this study, W averaged 0.24 g m^{-3}.

3.2. *Cloudwater collection*

Cloudwater throughfall was collected below a live Norway spruce (*Picea abies* L.), an artificial Christmas tree (American Tree, Co. of Pittsburgh, model no. 78-903-175), and an ASRC passive string cloudwater collector. The ASRC collector consisted of a cylindrical Plexiglas frame to which 720 vertically oriented and closely spaced (approximately 2 mm apart) Teflon strings (0.41 mm diam.) had been mounted in two concentric circles (Falconer and Falconer, 1980). The collector in vertical cross-section was 42 cm by 24 cm (diam.). The gross morphology of the Norway spruce and the artificial tree were similar, both being conical. The cross-sectional area of the artificial tree, with crown dimensions of 160 cm (ht) by 127 cm (base diam.), was 1.7 times greater than that of the spruce, 123 cm by 96 cm. Needles of the spruce were approximately square in cross-section, with average dimensions of 12.3 mm by 0.38 mm by 0.38 mm; estimated total surface area* of spruce needles plus branches was 9.40 m^2. The plastic artificial tree needles were much flatter and wider, with average dimensions of 21.8 mm by 1.08 mm by 0.17 mm; estimated total surface area was 35.48 m^2. Needle density, in terms of the ratio of surface area to cross-sectional area, was 2.2 times greater with the artificial tree. The strings on the ASRC collector were sufficiently taut that vibration in strong winds would not cause significant 'flinging off' of droplets. In

*In order to determine the total surface area of the spruce tree, subsamples of needles and of six size classes of branches were used to establish separate regression equations between surface area and oven-dry weight. The surface area of the needle subsamples was determined through repeated measurements of circumference and length of individual needles under a microscope. Total surface area of the spruce tree was determined by applying the various regression equations to the oven-dry weights of each class of plant material and summing. A similar procedure was followed to estimate needle surface area for one branchlet of the artificial tree. This surface area estimate was then multiplied by the total number of branchlets on the tree and added to the surface area of the wire 'stems' to give a total surface area.

comparison, the motion of needles on the tree collectors, and the associated potential for droplet 'fling off', were greater.

Cloudwater throughfall from the two trees was separately collected by 6 mil polyethylene skirts (1.64 m diam.), mounted and supported by polyvinylchloride pipe frames. Skirts were supported at the stem by foam rubber collars which were sealed at the stem with silicone. Each skirt sloped from the frame edge towards a drain opening near the stem; the opening was fitted with 1.6 cm Tygon tubing which led to a tipping bucket rain gauge. Trees were elevated 1.5 m above the deck floor so that the base of their crowns was 0.5 m above the deck railing, minimizing disruption of airflow (Fig. 1). The ASRC collector was mounted 3 m above the deck railing. Tubing from each of the collectors led into separate covered tipping rain gauges (Qualimetrics model no. 6011-A). The data output from each rain gauge was continuously monitored through a data logger system (Monitor Labs no. 9302), and 5-min averages were recorded. These 5-min averages were later converted to the hourly averages used in this report.

Hourly periods with measurable rainfall were removed from the data base. Data collected during periods when collecting tubes were not properly delivering water to the tipping bucket rain gauges were also deleted; the data set for the spruce tree is smaller than that for the other two collectors for this reason.

The data set was also reduced by removing all events lasting 5 h or less. During these events W was often quite low at the beginning and end of the event, and the lag time involved in wetting up the collecting surface (particularly for the two tree collectors) occupied a larger fraction of the total event than during longer events. Such short events were therefore removed from the data set because they were not considered ideal for testing model assumptions or for comparing collectors. The resulting data set provided a total of 448 h of data; Table 1 lists the number of hours used for each data manipulation.

3.3. *Meteorological measurements*

Wind speed was measured by a Climatronics Wind Mark III cup anemometer mounted from the sampling deck about 3 m above the deck floor and 7.4 m above the ground (Fig. 1). This placed the instrument at nearly the same height as the ASRC cloudwater collector. Sensor outputs were recorded every 20 s and averaged over 1-h periods. An annual factory calibration was performed on the instrument, along with annual field audits. Accuracy of the wind speed measurements was better than $0.1\ \mathrm{m\,s^{-1}}$, based upon numerous calibration checks. During the particular hours of collection used in this study, wind speed ranged from 0.9 to $12.7\ \mathrm{m\,s^{-1}}$, with a mean of $4.9\ \mathrm{m\,s^{-1}}$. The measured wind speed was higher than the actual speed to which the trees were exposed because of their slightly lower elevation. By logarithmic extrapolation of measured wind speed differences between 7.4 and 17.7 m down to the actual average tree exposure height of 6.2 m, a wind speed bias of approximately +18% was calculated.

Cloud liquid water content (W) was measured by a gravimetric technique developed specifically for ground-based measurements (Valente, 1990). The technique employs a high-volume blower and inlet cones designed for isokinetic collection of cloud droplets on a polypropylene mesh. The mesh is packed inside a plastic cartridge which is weighed hourly during cloud events so that W can be calculated from the weight change divided by the sampled air volume. While this technique agrees with other methods (Valente *et al.*, 1989), all inertial droplet impaction techniques tend to underestimate W in very thin (low W) and intermittent clouds because of evaporation from the cartridge mesh. The overall uncertainty in W values is approximately +/−25% (Valente *et al.*, 1989). During the period of data collection, W ranged from −0.04 to $0.55\ \mathrm{g\,m^{-3}}$, with a mean of $0.23\ \mathrm{g\,m^{-3}}$. Two hourly periods having negative values for W were converted to zero values. The horizontal cloudwater flux (F), computed from the product of u and W, ranged from 0.03 to $5.62\ \mathrm{g\,m^{-2}\,s^{-1}}$, with a mean value of $1.55\ \mathrm{g\,m^{-2}\,s^{-1}}$.

3.4. *Model modification for estimating* ε

In order to compare the collection efficiency of the spruce tree with that of the crown portion of the Lovett model, the model was modified to compute the mean collection efficiency in each 1-m layer within the canopy. The mean collection efficiency was determined by weighting the individual collection efficiencies of each combination of droplet size and tree component by the quantity of droplets in each size category and the surface area of each component type. The canopy structure (vertical surface area profile and leaf-to-total surface area ratio) input to the model was that estimated for a dense, closed red spruce canopy on Whitetop Mountain. Collection efficiency (ε) was used from only the top three levels (leaf-to-total surface area ratio = 0.95) because these were considered most comparable to the small spruce tree (ratio = 0.90) used for experimental collection of cloudwater on the deck. Model simulations of cloudwater deposition were computed for all realistic combinations of wind speed ($u = 1$–$12\ \mathrm{m\,s^{-1}}$) and liquid water content ($W = 0.05$–$0.50\ \mathrm{g\,m^{-3}}$).

The cloud droplet size distribution used by Lovett was replaced by a set of distributions selected to vary with W, based on droplet size data collected on Whitetop using a Particle Measuring Systems (PMS) forward scattering spectrometer probe (FSSP). This instrument, described by Knollenberg (1981), was operated during September–October

Table 1. Number of hours of data used in various regressions performed

Regression type	Constraints	Collector: ASRC	Collector: Artificial tree (no. of h)	Collector: Spruce tree
Vs horizontal flux (F)*	$W<0.2$; $u>6$	21	21	11
	$W<0.2$; $u<6$	17	17	17
	$W>0.2$; $u>6$	51	51	38
	$W>0.2$; $u<6$	26	26	26
	Total with W data	115	115	92
Vs ASRC		—	372	232
Vs spruce		232	308	—

* Linear, curvilinear and binomial regressions all run with same data sets (entire data sets where W available). Linear regressions only were run with W- or u-constrained data sets.

1987 (unfortunately not coinciding with the cloudwater collections reported herein) over a 24-d period, sampling more than 80 h of cloud occurrence from six events. Frequent glass bead calibration checks (provided by the National Bureau of Standards and PMS) were made to keep the FSSP properly adjusted and cleaned. Liquid water content inferred from FSSP data was compared with W measured by the gravimetric technique described above as an additional check on the proper operation of the FSSP. Droplet size data, integrated over 1013 5-min sampling periods, were analyzed to determine the relationship between D_p^2 (mean square of D_p) and W. Data were sorted into various intervals of W (0–0.05 g m^{-3}; 0.05–0.10 g m^{-3}; etc.) corresponding to the intervals used to characterize droplet size distribution as a function of W in the modified Lovett model. The value of D_p^2 was then computed for each interval of W. Results of this analysis are plotted in Fig. 2. This plot illustrates the relationship between droplet size and W in a way that also suggests how collection efficiency, which depends on D_p^2 by way of S, is expected to vary with W.

3.5. *Statistical comparisons*

3.5.1. *Predicting collection rate from* u *and* W. In order to evaluate the relationship between horizontal flux ($F = uW$) and net collection rate (C_n) to each collector, separate regressions were performed for each of the three collectors across the hours when W data were available. Liquid water content data were available approximately 25% of the time (Table 1). Regression equations took three forms:

(a) Simple linear, univariate of the form

$$C_n = a(uW) + b.$$

(b) Binomial, of the form

$$C_n = a(uW)^2 + b(uW) + c.$$

(c) Curvilinear, of the form

$$C_n = au + bW + c(uW) + d.$$

Simple linear regressions of the form in (a) were also run under various conditions, always separately for each collector. Firstly, for each of the 10 individual events in which W data were available, linear regressions on horizontal flux were performed. Secondly, across the entire data set (with W available), regressions on horizontal flux were performed separately under the following four constraints: (a) $W < 0.20$ g m^{-3}; (b) $W > 0.20$ g m^{-3}; (c) $u < 6$ m s^{-1} and (d) $u > 6$ m s^{-1}. Finally, using the same four data subsets described by these four constraints, stepwise multiple regressions were performed using the three variables listed above in the curvilinear model (3), plus u^2 and W^2, to determine which variables contributed the most to a multivariate model under each set of conditions. Appropriate number of hours of data for each comparison are summarized in Table 1. Finally, regressions employing the product of F and either of two different terms relating to collection efficiency, ln(u) and ln(uW), were performed against C_n for comparison with the simple linear regression above (a). These were performed across the full set of data, as well as across the two subsets, based upon subdividing W at the 0.20 g m^{-3} value.

3.5.2. *Collection efficiency comparisons.* Empirically-derived cloudwater collection efficiencies were determined for all three collectors using Equation (2) (i.e. $\varepsilon = C_n/AF$). In calculating ε for the two tree collectors, measured wind speed was multiplied by a factor of 0.82 to account for the difference in height between the wind sensor and each tree center. This adjustment is based on the assumption of a standard logarithmic wind speed profile under the neutral conditions expected during cloud events, and is recognized to be only an approximation. Any error in this adjustment will cause a small bias in estimates of ε. These hourly values were used in calculating mean ε values for each cloud event. The SAS General Linear Models Procedure (Spector *et al.*, 1985) was used to evaluate the statistical significance of 'event' as a factor in determining the variability of ε. Hourly values of ε were also used in regressions of ε vs ln(u) and ln(F) across the entire data set, and then separately within individual cloud events of 10 h or longer. The first hour of each event was not used in the determination of these regression equations.

3.5.3. *Correlations between collectors.* To determine the degree of agreement between collectors, hourly volume data across the entire period of collection were used to calculate

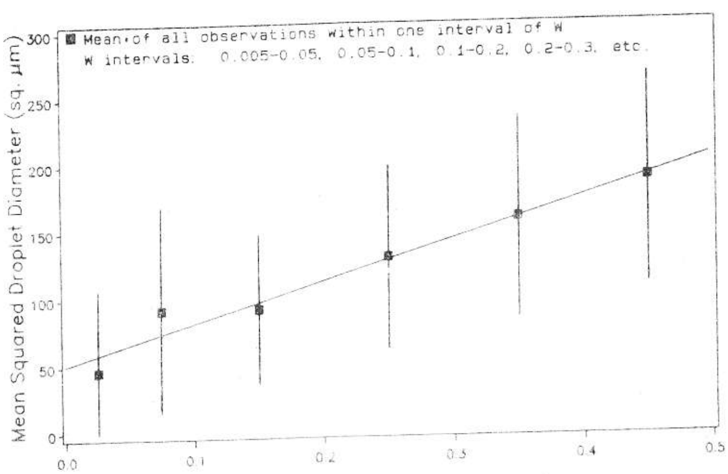


Fig. 2. Measured variation of mean squared droplet diameter (D_p^2) with liquid water content (W) for clouds impacting the summit of Whitetop Mountain. The sloping line represents the linear regression equation fit by the method of least squares to the average of D_p^2 over all observations within a W interval. The slope of this regression line is significantly ($p < 0.01$) different from zero. Vertical lines represent the variability (+/− one standard deviation) of D_p^2 within each W interval.

Table 2. Strength of regression equations (R^2 values), using horizontal flux (F) in simple linear regressions to predict hourly volumes from the three collectors under various constraints upon wind speed or liquid water content. Regressions are significant at $p < 0.0001$ unless otherwise indicated

Collector	Constraint $W < 0.2$	$W > 0.2$	$u < 6$ (R^2 values)	$u < 6$	All values
Spruce tree	0.23*	0.51	0.45**	0.58	0.58
ASRC	0.39**	0.46	0.29**	0.53	0.53
Artificial tree	0.34**	0.63	0.66	0.69	0.73

* $p = 0.005$.
** $p < 0.001$.

correlation coefficients between each pairwise combination of collectors. Correlation coefficients for each collector pairing were also determined separately for each of 25 individual events in order to examine the particular event characteristics that might affect the degree of agreement between collectors. Correlations between collectors and canopy throughfall data were similarly determined, using hourly volume data over simultaneous periods.

Over certain periods of collection, data collected by the spruce and artificial trees were deemed unacceptable, usually because of blockages in delivery tubes to the tipping bucket rain gages. These periods were noted by direct observation and were apparent in the data because of large differences between the timing of water delivery to the gages and the actual occurrence of cloud events. Following data quality assurance procedures, the data set for statistical analysis consisted of the following number of hours of cloud events without rain for each collector: 232 h for the spruce tree, 448 h for the artificial tree, and 372 h for the ASRC string collector.

3.6. *Mature canopy cloud event throughfall collection*

In a mature stand of red spruce (*Picea rubens* Sarg.) located approximately 100 m from the deck containing the artificial collectors, a grid system of 10 funnels (25 cm diameter) connected to graduated cylinders was established to collect throughfall drip underneath the spruce canopy at a height of 1 m above the forest floor. Funnels were placed at 5.5 m intervals following two concentric circles (10.5 m and 5.25 m, diam.), with one funnel at the center of the resulting 0.01 ha plot. The average height of the stand was 15 m, and the canopy of the stand was situated so as to be within 3 m of the elevation of the deck collectors. The stand was located near the summit and adjacent to the clearing created by the compound containing the deck and was thereby exposed to the wind in every direction. On 11 August during two cloud events, separated by a 5-h period of no clouds, the volume collected by each of the funnels was recorded hourly. The average collection volume per funnel was then determined for each hour. Simultaneous collection rates by the artificial collectors were determined as usual, using the recording tipping bucket rain gauges. During the two events, values for both W (mean = 0.21, range = 0.05–0.36 g m^{-3}) and u (mean = 7.7, range = 6.2–9.7 m s^{-1}) were slightly above average.

4. RESULTS AND DISCUSSION

4.1. *Prediction of collection rate (C_n) from horizontal flux*

As expected, volumes collected by all three collectors were strongly related to the horizontal flux. Across all hours when W data were available, the strongest simple linear relationship was exhibited between F and C_n by the artificial tree ($R^2 = 0.73$), followed by the spruce tree ($R^2 = 0.58$) and the ASRC collector ($R^2 = 0.54$) (Table 2; $p < 0.0001$ for each of the collectors). Figure 3 depicts this relationship for each of the collectors, along with linear and binomial regression lines.

Data sets were broken into subsets with limited ranges of W (<0.2 or >0.2 g m^{-3}), or of u (<6 or >6 m s^{-1}) (Table 1). F best predicted C_n when W was high or when u was high (Table 2 and Fig. 4). When $W < 0.2$, F was a particularly poor predictor of C_n for the two tree collectors. The failure of F to predict C_n at low W is probably the result of several factors. One is the limited number of hours when $W < 0.20$ g m^{-3} and the limited range of F values when $W < 0.20$ g m^{-3} that were available to test this relationship. The variance in D_p^2 was large over the narrow range of $0 < W < 0.2$ (Fig. 2). In addition, there was a partial interdependence of W and u during the observed periods. When W was >0.20 g m^{-3}, the full range of u was observed; in contrast, low W and high u were rarely concurrent (Table 1, Fig. 4). Thus under the constraint of $W < 0.20$ g m^{-3}, a narrow range in F was observed.

A major reason for the poor prediction of C_n from F when W is low is the greater role of evaporation—both in terms of absolute volume and as a percentage of total gross deposition. The various factors influencing evaporation and its quantification have been discussed in depth in Shuttleworth (1977), Unsworth (1984) and Lovett (1984). Under conditions of 'wispy clouds', the air is often subsaturated and net radiation (during daylight) relatively high. Evaporative losses can become major sources of variability under these conditions because the collectors register net deposition (C_n) rather than total deposition (C). Total deposition—the variable of interest—is not being accurately measured as a result. Furthermore, net deposition which is negative (evaporation > deposition) is impossible to detect with this simple measuring technique. Also, the gravimetric technique used to measure W tends to underestimate W across the lower end of its range because of evaporation from the cartridge mesh (see Methods). If these explana-

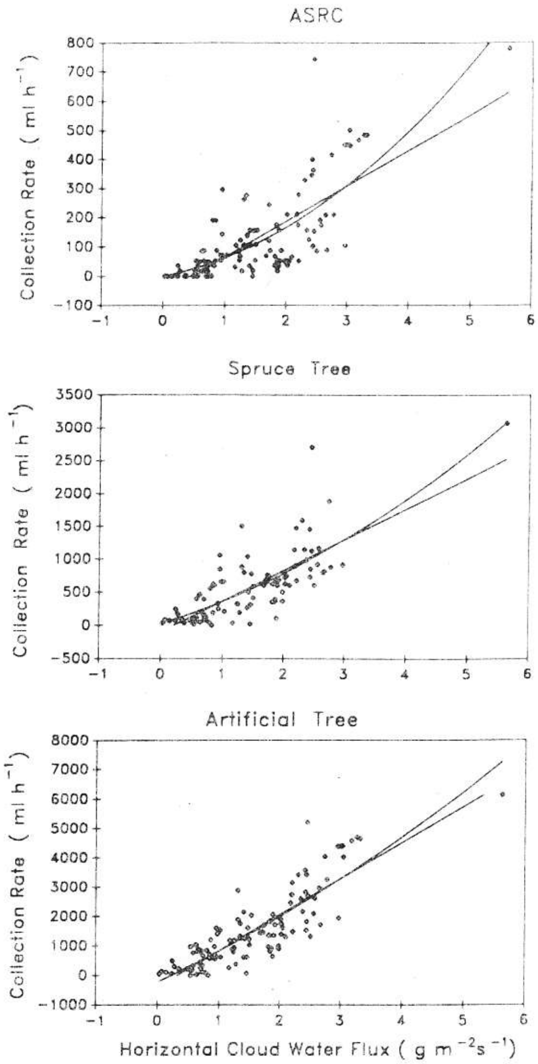


Fig. 3. Collection rate as a function of horizontal cloud-water flux (F) for the three collectors across all hours when liquid water content (W) data were available. Linear and binomial regression lines shown for each. See Table 4 for R^2 values.

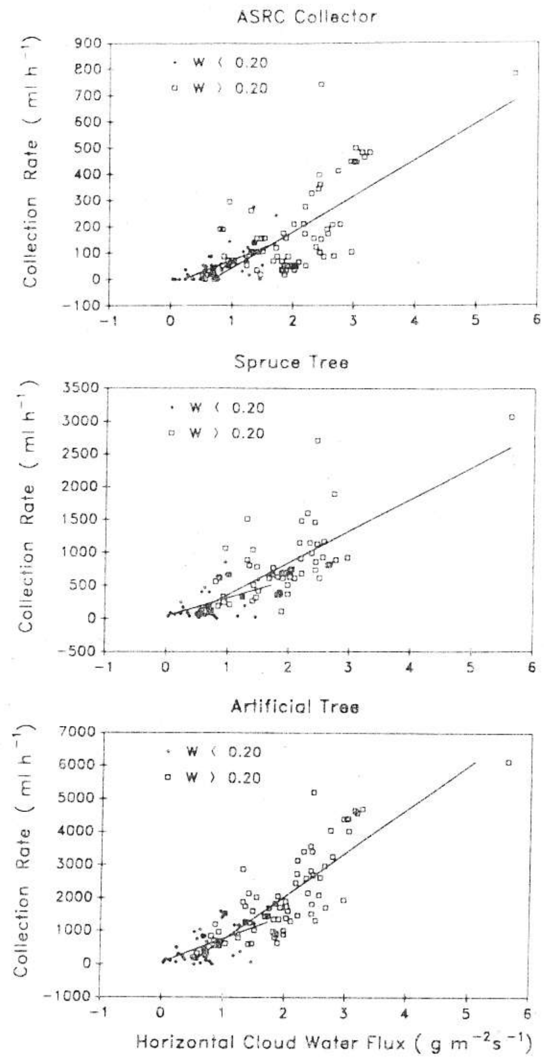


Fig. 4. Collection rate as a function of horizontal cloud-water flux (F) for the three collectors, broken down into two subsets, (a) when $W<0.20$ g m^{-3} and (b) when $W>0.20$ g m^{-3}. Linear regression lines shown for each. See Table 2 for R^2 values.

tions are correct, the lack of prediction of C_n by F at low W is chiefly a result of weaknesses in the techniques employed in this study rather than a breakdown in the linear relationship of total deposition with F.

4.2. *Prediction of cloudwater collection efficiency*

Cloudwater collection efficiency (ε) is an important component in the Lovett (1984) model and is estimated in the model from a logarithmic relationship with the Stokes number (S) developed by Thorne *et al.* (1982). That relationship is supported by the work of Ranz and Wong (1952) in which detailed studies of particles impinging on cylinders suggested that the relationship between ε and S could be linearized using ln (S). Therefore, if $\varepsilon = f[\ln(S)]$, then from (2), it is evident that, on average for cloud droplets suspended in air, $\varepsilon = f[\ln(u\overline{D_p^2}/D_c)]$. With W proportional to $\overline{D_p^2}$, this relationship becomes $\varepsilon = f(\ln(uW))$ if D_c remains constant. In other words, ε should be dependent on $\ln(F)$.

Using the water collection data from the spruce tree, hourly values of ε were calculated from (2). These values were then regressed against $\ln(F)$. The relationship between ε and $\ln(u)$ was examined as well because measurement uncertainty in u is much less than it is for W. In neither case was a statistically significant relationship detected; in fact, R^2 values in both cases were less than 0.02.

4.2.1. *Variability in collection efficiency across events.* One possible reason that the predicted relationship between ε and $\ln(u)$, or between ε and $\ln(F)$, found little support was the large variability in ε from

$1\ \mathrm{g\ m^{-2}\ s^{-1}} \equiv 3600\ \mathrm{g\ m^{-2}\ h^{-1}} \equiv 3.6\ \mathrm{L\ m^{-2}\ h^{-1}} \equiv 3.6\ \mathrm{mm\ h^{-1}}$

Table 3. Characterization of collection efficiency (ε) by individual cloud event and by collector. Correlations of ε with $\ln(F)$ performed only for events with more than 10 h. Standard errors for event mean ε values shown in parentheses. Overall means refer to the average of all hours combined

Event date (Julian)	Event length (h)	Mean u ($m\,s^{-1}$)	Mean W ($g\,m^{-3}$)	Mean ε (Spruce)	Mean ε (ASRC)	Mean ε (Artif)	Correlation: ε with $\ln(F)$ Spruce	ASRC (R value)	Artif
161	5	4.1	0.20	0.50 (0.05)	0.71 (0.12)	0.42 (0.10)	—	—	—
253	5	4.6	0.19	0.46 (0.07)	0.39 (0.10)	0.52 (0.07)	—	—	—
252–253	10	8.3	0.29	0.39 (0.04)	0.48 (0.07)	0.46 (0.04)	—	—	—
262–263	16	8.1	0.26	—	0.42 (0.03)	0.43 (0.03)	—	+0.83 ***	+0.01
263	7	8.0	0.15	—	0.37 (0.07)	0.33 (0.02)	—	—	—
255–256	7	5.3	0.17	0.33 (0.08)	0.23 (0.05)	0.37 (0.08)	—	—	—
259–260	15	6.7	0.29	0.19 (0.05)	0.19 (0.02)	0.29 (0.02)	+0.35	+0.69 **	+0.83 ***
257–258	33	6.9	0.24	0.14 (0.01)	0.10 (0.01)	0.19 (0.02)	+0.65 ***	+0.49 **	+0.74 ***
127–128	15	2.8	0.21	0.12 (0.02)	0.10 (0.03)	0.19 (0.02)	+0.71**	+0.63 *	+0.71 **
Short events†	7	6.1	0.20	0.42	0.44	0.42			
Long events‡	18	6.1	0.25	0.15	0.20	0.28			
Overall means	13	6.4	0.24	0.23	0.25	0.31			

* $p<0.05$.
** $p<0.01$.
*** $p<0.001$.
† Length <10 h.
‡ Length $>=10$ h.

one cloud event to another (Table 3). Mean values for ε for individual events ranged from 0.12 to 0.50 for the spruce tree, and 'event' proved to be a highly significant variable ($p<0.0001$) in the determination of collection efficiency for all three collectors. Furthermore, mean event ε values exhibited a high degree of correlation between collectors: the square of the correlation coefficient (R^2) between spruce tree event mean ε values and artificial tree ε values was 0.86; between spruce tree and ASRC collector, 0.81; and between ASRC collector and artificial tree, 0.58 ($p<0.0001$ for all three collectors). This consistency among the three collectors in their cloudwater collection efficiencies across highly variable events indicates that the factor or factors responsible for the between-event variability in ε were probably meteorological in nature, rather than peculiarities of the collectors themselves.

Inspection of the data revealed that neither time of day, wind speed, solar radiation, nor relative humidity were prominent factors differentiating 'high ε' from 'low ε' events. There does, however, appear to be a strong tendency for ε to be higher during events of short duration (Table 3). This tendency coincides with long events having higher average W than their short (<10 h) counterparts (Table 3). These shorter events may have lower measured values of W because a higher fraction of their event length consists of periods of intermittent cloud exposure. Cloud events typically begin and end with periods of intermittent clouds as cloud base rises or falls through the observer's altitude. Short events are usually associated with orographic ('mountain cap') clouds or very fast moving frontal systems and are more likely than long events to have a large fraction of time when such vertical cloud base undulation is occurring. This higher incidence of cloud intermittency during short events may result in underestimates of actual W by the liquid water content measuring device because of increased evaporative losses from the collection filter. Such underestimates of W would result in overestimates of ε, which is computed as C/AuW. Another possibility is that there may have been a distinct difference between the long and short events in their droplet size distributions. The identification of the factors responsible for the large variability in event ε remains a significant unfinished task.

4.2.2. *Relationship of ε to ln*(F) *and ln*(u) *within events.* Whereas the relationship between ε and $\ln(F)$, when examined across all the data, appeared virtually a random one, when this relationship was examined within individual events, the results were quite different. When events of sufficient length (10 or more hours) were examined, ε was consistently positively related to $\ln(F)$ for all three collectors (Table 3). It appears that, when the dominating factor responsible for between-event variability in ε was eliminated, the relationship between ε and $\ln(F)$ predicted by the models emerged.

Collection efficiency is a major factor affecting cloud deposition flux computed by the Lovett (1984) model. It is valuable to compare the observed values of ε for the spruce tree with the values computed by the model. Observed and computed values are compared in Fig. 5. Values of ε were computed by the model in the manner described in section 3.4. A curve was fitted to the set of points representing all model ε values ($R^2=0.86$), and is reproduced in Fig. 5. The decline in ε for $F>1.5$ is due to the empirical findings of Thorne *et al.* (1982), who speculated that droplet breakup and blow-off occurred at high values of the Stokes number (S) and, thus, F.

All short event values of ε estimated from the

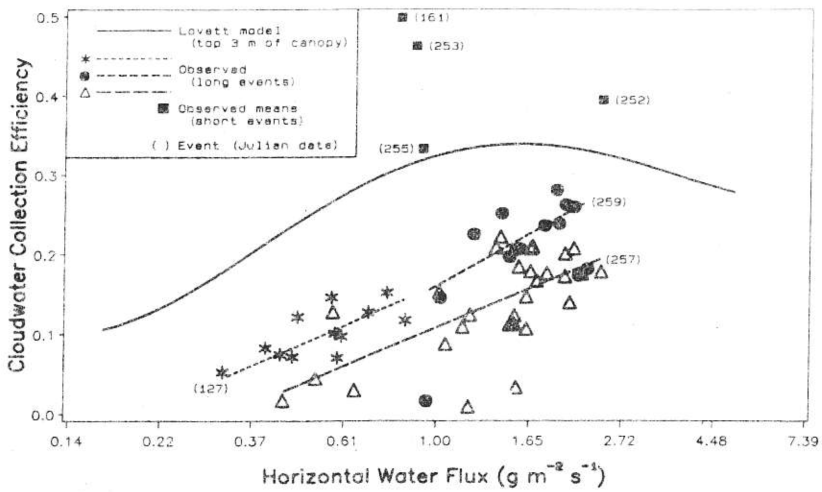


Fig. 5. Comparison between cloudwater collection efficiency (ε) inferred from spruce tree data and that estimated by the Lovett model for a comparable portion of a coniferous forest canopy crown. Horizontal cloudwater flux (F) is plotted on a logarithmic scale. For events > 10 h (long events), individual hourly data points and a regression line of ε vs $\ln(F)$ are plotted; for shorter events, only the mean ε values are plotted. Events are labeled as to the Julian day upon which they began; supplementary data are available in Table 3.

Whitetop spruce data fall above the model curve. For three long events (15–33 h), linear regressions were computed and plotted in the Fig. 5 over the range of observed F. The general decline in ε with event length is apparent, with the three long events having ε substantially below the model curve. The slopes of the long event regressions were very similar to each other (range, 0.10–0.16) and were similar to the mean slope (0.17) of the model curve over $0 < F < 1.5$ g m^{-2} s^{-1}. If one assumes that data from the longer events have the greatest validity because of minimal periods of cloud intermittency, these data suggest that the collection efficiency values which the model generates for a canopy crown are likely to be greater than those determined from the empirical data collected from a comparable small spruce tree.

One factor that may account for the differences between these empirical estimates of ε and the model estimates are reductions in airspeed within the tree. The Lovett (1984) model uses a logarithmic function of S empirically derived by Thorne *et al.* (1982) for balsam fir twigs and branches to estimate cloud droplet collection efficiencies. Estimates of the distribution of surface area by tree component type, an assumed cloud droplet size distribution, and measured wind speed profiles in the forest canopy are also used in the estimation of S. A potential problem with this approach is that wind speed measurements within the forest canopy crown space are more representative of the airflow between trees than the free-stream speed to which individual twigs are exposed. In a dense individual tree crown, it is not unreasonable to expect that, because of the aerodynamic drag of closely-spaced twigs and branches, airspeed may be reduced relative to that outside the crown. Grant (1983) studied the characteristics of airflow around spruce twigs and found that the air speed within the downwind wake of a twig was decreased relative to the upwind free-stream speed by 20–90%, to a distance of approximately 40 cm beyond the twig. This suggests that the airspeed relevant for estimating ε within an individual tree crown is lower than the inter-tree air speed within the canopy crown space. Additional data are needed before such an effect can be substantiated.

4.3. *Best models for prediction of collection rate*

Whereas the objective of cloud deposition models is usually to predict the absolute volume of water deposited to a forest per unit of land surface area, there also exists a need for relative indicators of cloudwater deposition based on some simple monitoring method (e.g. surrogate collectors). Such relative comparisons may, for example, apply to the deposition to a given forest stand over different periods of time, or to the deposition to different stands over the same period of time, with the assumption that the collecting surface remains constant across the compared units. Because the wind velocity (u) and the liquid water content (W) are two important variables driving cloud deposition models, different regression approaches were compared using these two variables to evaluate which would be the most effective surrogate monitoring approach.

4.3.1. *Linearity of relationship with horizontal flux.* When compared to simple linear models using only horizontal cloudwater flux (i.e. $C_n = aF + b$), the additional percentage of the variance that was explained by more complex binomial ($C_n = aF^2 + bF + c$) and curvilinear ($C_n = aW + bu + cF + d$) models was very small for all three collectors (Table 4). The addition of the variables $(F)^2$, W or u (as single variables) generally did not produce a statistically significant improvement. The lone exception occurred with the curvilinear model for the ASRC where the addition of W as a single variable produced a marginally ($p = 0.04$) significant improvement. The data in Table 4 provide support for the assumption that the rate of total gross deposition volume (C), across a wide range of natural conditions, is a simple linear function of F.

4.3.2. *Improvement in prediction by considering collection efficiency.* The cloudwater deposition models treat deposition as a function not only of u and W (and hence F), but also ε. Theoretically, ε should be a function of $\ln(u\overline{D_p^2})$ (see section 4.2), and, because $\overline{D_p^2}$ is a linear function of W, ε should be a function of $\ln(uW)$ [i.e. $\ln(F)$]. Deposition therefore should be a function of F and $\ln(F)$. The simple linear regression models, in which C_n was considered a function of F, were separately compared to models in which C_n was considered a function of $F{*}\ln(F)$ and $F{*}\ln(u)$, to see if R^2 values would be markedly improved. These comparisons were made across the entire data set and across the two subsets of W.

The results of these regression comparisons are displayed in Table 5. The addition of the $\ln(u)$ or $\ln(F)$ term in the regression equation as a surrogate for ε generally resulted in very small improvements in R^2 values across all three collectors when $W > 0.20$ g m^{-3}. The small magnitude of this improvement probably results partially from the fact that the other primary variable was F itself, which already includes u and W as factors, and partially from the fact that droplet size and size-specific droplet collection efficiency could not be determined. The addition of $\ln(F)$ or $\ln(u)$ actually resulted in a reduction of the R^2 value when W was < 0.20 g m^{-3} and had virtually no effect when the data set included the entire range of W. It appears from these regression results that the simple approach of considering cloudwater deposition as a linear function of horizontal cloudwater flux is adequate for most comparative uses. However, it must be noted that the use of a direct measurement of ε, rather than the use of theoretically correlated surrogates, might have revealed a relationship that would have proved useful in the prediction of the net cloudwater deposition.

Table 4. Strength of regression equations (R^2 values), using W and u to predict hourly volumes from the three collectors. All regressions significant at $p < 0.0001$

Regression type	Number of variables	ASRC	Artificial tree (R^2 values)	Spruce tree
		Collector		
Linear	1	0.53	0.73	0.58
Binomial	2	0.58	0.73	0.60
Curvilinear	3	0.57	0.74	0.59

4.3.3. *Strength of the relationship with horizontal cloudwater flux.* Although the prediction of C_n appears to be a simple linear function of F across all observed hours, prediction of C_n was better within individual events than across all hours. Within events, R^2 values ranged from 0.58 to 0.98, with mean values of 0.83 (artificial tree, nine events), 0.78 (spruce tree, nine events), and 0.79 (ASRC, 10 events); across all hours regardless of event, R^2 values were 0.73, 0.58 and 0.53, respectively (Table 5). This improved prediction within individual events suggests that some variable(s), other than u and W, influence C_n. These variables appear to have remained relatively constant during individual events but to have varied across events. Whether these variables were droplet size, evaporation, or something else was impossible to determine with the available data. Although prediction of C_n was quite good for all collectors using F alone, additional testing is needed to determine if cloud-event-specific droplet size distribution or other information might improve prediction appreciably.

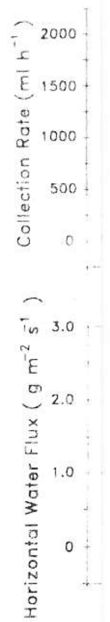
4.4. *Relationships between artificial collectors and live trees*

4.4.1. *Correlations among collectors on deck.* Figure 6 illustrates the pattern in collection volumes recorded by the three collectors during two consecutive cloud events over a 30-h period following a rain event. The excellent correspondence among the three collectors exhibited in these events was reflected in the high correlations between their hourly values across the entire data set. The highest correlation of hourly volumes was between the spruce tree and the artificial tree, where $R^2 = 0.88$. The correspondence of the ASRC with both the artificial tree ($R^2 = 0.76$) and with

Table 5. Comparison of R^2 values for regression equations developed to predict water collection rate (C_n) for each of the three collectors across three ranges of W. Regressions are linear against either: (a) horizontal cloud water flux (F); (b) $F{*}\ln(u)$ or (c) $F{*}\ln(uW)$. Regressions are significant at $p < 0.001$ unless otherwise indicated

X variable	$W < 0.20$	$W > 0.20$ (R^2 values)	Full range
		Spruce	
F	0.22***	0.51	0.58
$F{*}\ln(u)$	0.07*	0.55	0.56
$F{*}\ln(Wu)$	0.16**	0.53	0.58
		ASRC	
F	0.39	0.49	0.53
$F{*}\ln(u)$	0.25***	0.53	0.56
$F{*}\ln(Wu)$	0.36	0.53	0.57
		Artificial tree	
F	0.35	0.69	0.73
$F{*}\ln(u)$	0.16**	0.70	0.71
$F{*}\ln(Wu)$	0.23	0.67	0.72

* n.s.
** $p < 0.05$.
*** $p < 0.01$.



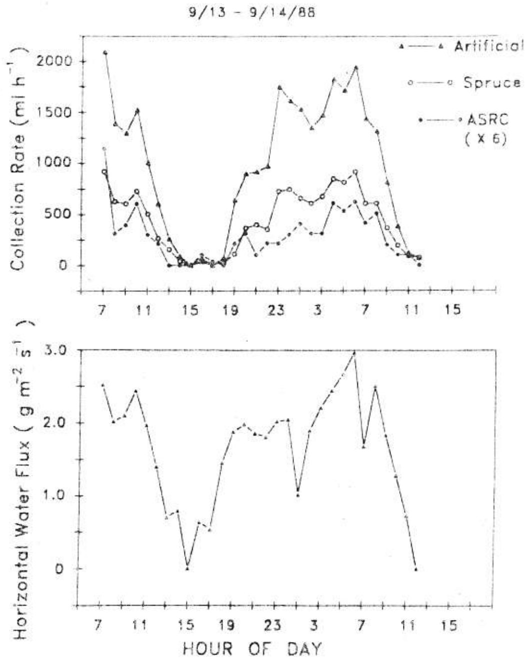


Fig. 6. Hourly volumes (ml h^{-1}) collected by all three collectors during two cloud events of 13–14 September 1988. First cloud event immediately followed rain event which ended at 6 a.m. ASRC rates multiplied by a factor of 6 for ease of comparison. Fig. 6b depicts horizontal flux (F).

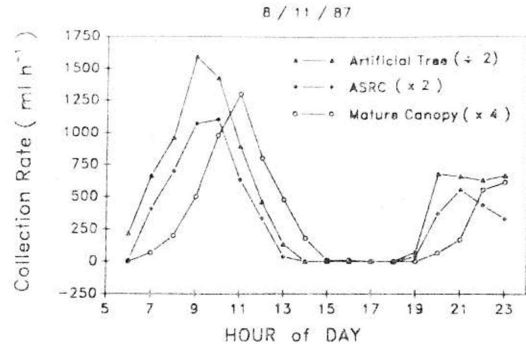


Fig. 7. Hourly volumes collected by ASRC collector, the artificial tree, and as throughfall from a nearby mature red spruce forest canopy during cloud event of 11 August 1987. Mature canopy throughfall expressed as ml h^{-1} collected by 10 funnels. Artificial tree collection rates divided by a factor of 2 and ASRC and canopy rates multiplied by 2 and 4, respectively, to facilitate comparison.

the spruce tree ($R^2=0.72$) was slightly less. When correlations between collectors within individual cloud events were compared, correlations again were highest between the spruce and the artificial tree; the mean of the R^2 values for 17 individual events was 0.85. Again the ASRC agreed slightly better with the artificial tree (mean R^2 for 24 events $=0.69$) than with the spruce tree (mean R^2 for 18 events $=0.62$).

4.4.2. *Comparisons of artificial tree and ASRC with mature canopy.* The limited data that were collected comparing rates of cloudwater collection from the surrogate collectors with rates of cloudwater throughfall generation in a nearby mature red spruce stand indicate strong correlations. Figure 7 illustrates the pattern during a cloud event on 11 August 1987. Note that the canopy throughfall rate typically shows approximately a 1-h time lag relative to the deposition flux to individual collectors. This lag is most likely due to the time necessary for canopy-top inputs to saturate the large collecting surface area and for droplets to drip down through the branches below before reaching the collectors. Applying a 1-h lag to the available 27 h of canopy throughfall data, the strength of the relationship (R^2 values) between hourly canopy throughfall values and hourly volumes, from the collectors located on the deck, ranged from 0.79 to 0.86. A similar strong relationship between ASRC collector volumes and canopy throughfall volumes from a spruce forest was observed during a 19-h event in October 1988 (Mueller and Imhoff, 1989).

4.4.3. *Potential uses for surrogate collectors.* The above experiments demonstrate that the ASRC string collector is a good surrogate cloudwater collector for a living spruce tree across a wide range of meteorological conditions, in that the volumes of cloudwater deposited appear proportional. Although there remains some questions as to whether cloudwater collected by such string collector samples is exactly representative of the chemistry of water deposited to foliage, the above data are also supportive of the use of ASRC collectors to provide samples with concentrations representative of cloudwater actually deposited on conifer forest canopies (Falconer and Falconer, 1980; Daube *et al.*, 1987; Hering, 1987).

The above-described data also support the use of the procedure of *compositing* a collection of periodic samples from the ASRC (or artificial tree) collectors to obtain a chemistry sample representative of cloudwater deposited to the forest over the collection period (Joslin *et al.*, 1988). During individual cloud events (or across cloud events), ion concentrations often vary considerably, as do cloudwater deposition rates. In order for a composite sample from an artificial collector to be representative of the water deposited to the forest over a given time interval, the collector must not only sample cloudwater with a chemistry representative of that deposited to trees, but must also collect volumes over time which are proportional to those collected by the trees. The high correlations obtained in this study between hourly volumes collected by the ASRC or the artificial tree and hourly volumes collected by the living spruce tree support the use of such a compositing procedure. This approach could be further improved by estimating the amount of evaporative loss from the given collector across a particular time interval and correcting the obtained composite concentration for evaporative concentration.

The strong relationship between surrogate collectors and living collectors also supports the use of surrogates as relative indices of the quantity of cloudwater deposition. When placed at the same position relative to the tops of forest canopies, such collectors could be used to compare the amount of cloudwater deposition at various locations over identical time periods. Obtaining absolute quantities of deposition from such data would be difficult, but such data make possible reasonable relative indices for between-site comparisons. Care should be taken in site location that canopy surface areas be similar and that the assumption concerning the dominance of cloudwater impaction over sedimentation be met. Similarly, volumes collected by surrogates could also be used to compare, in a relative manner, cloudwater deposition over different time intervals at the same location. The major challenge in adapting any passive cloud collector to such a purpose remains the exclusion of rain from samples (Daube *et al.*, 1987). Based upon the data reported herein, one other circumstance in which such comparisons might require caution would appear to occur when a period of high W events is compared to a period of low W events.

Although the data indicate that the artificial Christmas tree correlates more highly with a living spruce tree than does the ASRC, the small difference in the strength of these correlations probably does not justify the use of artificial trees in most cases. The performance of the ASRC collector has been well characterized and its physical dimensions are standardized, thereby facilitating comparisons with other studies. The ASRC collector is certainly less cumbersome to store, handle and mount than an artificial tree. It is also much easier to clean if the chemistry of samples is to be determined. Finally, repairs to the ASRC collector are generally easier to make.

5. CONCLUSIONS

(1) Regression models indicate that the rate of collection for all three collectors is best described as a simple linear function of horizontal cloudwater flux (liquid water content times wind speed); adding an additional term to account for the fluctuations in cloudwater collection efficiency improved prediction only slightly or not at all.

(2) For all three collectors, when the entire data set was considered, cloudwater collection efficiency did not appear to be a function of ln(wind speed) or ln(horizontal water flux), as predicted by the models; however, within individual events $\ln(F)$ was a statistically significant factor in the prediction of ε.

(3) A large degree of variation in ε was observed between individual events. This variation probably accounts for the poor relationship between ε and $\ln(u)$ or $\ln(F)$ across the whole data set, and it is also responsible for much of the variance in collection rate that is not accounted for by horizontal water flux alone. Large differences in ε between long and short events may be related to reduced accuracy of the measurement of W during intermittent cloud periods or to distinct differences in droplet size distributions between different types of events.

(4) Empirical data on the cloudwater collection efficiency (ε) of the living spruce tree suggest that existing cloud deposition models often overestimate ε. It is likely that the appropriate air speed for estimating ε within a tree crown is actually lower than the air speed that is commonly measured, i.e. that between individual trees, because of the aerodynamic drag created by the closely-spaced clusters of needles on individual branches.

(5) The high degree of correlation between the collection rates of the two artificial collectors and live spruce trees indicates that the former would serve as good surrogates for the latter, either as indices of cloudwater deposition (volume) or as collectors of cloudwater samples (chemistry).

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