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Physical attributes of some clouds amid a forest ecosystem's trees

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Abstract

Cloud or fog water collected by forest canopies of any elevation could represent significant sources of required moisture and nutrients for forest ecosystems, human consumption, and as an alternative source of water for agriculture and domestic use. The physical characteristics of fogs and other clouds have been well studied, and this information can be useful to water balance or canopy–cloud interaction model verification and to calibration or training of satellite-borne sensors to recognize atmospheric attributes, such as optical thickness, albedo, and cloud properties. These studies have taken place above-canopy or within canopy clearings and rarely amid the canopy. Simultaneous physical and chemical characteristics of clouds amid and above the trees of a mountain forest, located about 3.3 km southwest of Mt. Mitchell, NC, were collected between 13 and 22 June 1993. This paper summarizes the physical characteristics of the cloud portions amid the trees. The characteristic cloud amid the trees (including cloud and precipitation periods) contained 250 droplet/cm^3 with a mean diameter of 9.5 μm and liquid water content (LWC) of 0.11 g m^{-3}. The cloud droplets exhibited a bimodal distribution with modes at about 2 and 8 μm and a mean diameter near 5 μm during precipitation-free periods, whereas the concurrent above-canopy cloud droplets had a unimodal distribution with a mode near 6 μm and a mean diameter of 6 μm. The horizontal cloud water flux is nonlinearly related to the rate of collection onto that surface amid the trees, especially for the Atmospheric Sciences Research Center (ASRC) sampling device, whereas it is linear when the forward scattering spectrometer probe (FSSP) are is used. These findings suggest that statements about the effects clouds have on surfaces they encounter, which are based on above-canopy or canopy-clearing data, can be misleading, if not erroneous.

Keywords: Cloud microphysics; Amid-canopy clouds; Cloud–canopy interactions

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1. Introduction

Cloud or fog water collected by forest canopies of any elevation could represent significant sources of required moisture and nutrients. Fogs provide an important portion of the moisture required by northern Californian redwoods during the winter season (e.g., Schemenauer, 1998). Clouds that engulf the Mt. Mitchell Fraser fir/red spruce above-cloudbase ecosystem provide as much moisture to this ecosystem as do rain events during the growing season (Saxena et al., 1989). Fog water collections on the coastal mountains of South America and Arabia have been used for human consumption (e.g., Cereceda and Schemenauer, 1998) and may be appropriate for consumption in South Africa (Olivier, 1998). Fog water has also been used as an alternative source of water for agriculture and domestic needs (e.g., Sabinon and Mareno, 1998). Thus, the potential for widespread impact on people and plants is high and provides an impetus for knowing the physical and chemical characteristics of cloud or fog water.

The physical and chemical characteristics of fogs and other clouds have been well studied (e.g., Kulp and Herrick, 1987; Saxena et al., 1989; Schemenauer, 1998), and the information from these studies can be useful to acid deposition, water balance, or canopy–cloud interaction model verification (e.g., DeFelice, 1998a) and to calibration or training of satellite-borne sensors to recognize atmospheric attributes, such as optical thickness, albedo, and cloud properties (e.g., Kidder and Vonder Haar, 1995; Rao et al., 1995; Reinking, 1995; Saxena et al., 1996; Wetzel et al., 1996; DeFelice, 1998b; Menon and Saxena, 1998; Cahalan et al., 2001).

The physical and chemical characteristics of fogs and clouds are primarily available for above-canopy or canopy-clearing sites and are rarely obtained amid the canopy (e.g., Table 1). This means, for example, that the statements made concerning the effect clouds have on deposition surfaces using the above-canopy or within-canopy-clearing data are misleading, if not erroneous. Similarly, accurate water quantity and quality reports available from the

Table 1
Field Studies of above-canopy, within-canopy-clearing and amid-canopy clouds

Study	Location	Physical measurements	Where made
Lindberg et al. (1986)	Tennessee	Particulates	amid- and above-canopy
		Meteorological data	above-canopy
		Precipitation	collected in adjacent forest, clearings
		Throughfall	amid-canopy
Joslin et al. (1988)	Whitetop Mt., Virginia	Cloud water	above or outside canopy
		Throughfall	amid-canopy, and offset from cloud water
Mueller and Imhoff, 1989	Whitetop Mt.	Cloud water	above-canopy
		Wind and Temp.[a] amid to above canopy thoughtfall	vertical profiles from
		Throughfall	automated amid canopy

Table 1 (*continued*)

Study	Location	Physical measurements	Where made
Saxena et al. (1989)	Mt. Mitchell, North Carolina (above cloud base forest)	Cloud water	above-canopy
		Cloud drop size spectra	above-canopy
		Meteorological data	above-canopy
Collett et al. (1990)	Sierra Nevada, California	Cloud water	outside or above-canopy
		Liquid water content	outside or above-canopy
		Meteorological variables	above or outside canopy
Joslin et al. (1990)	Whitetop Mt.	Cloud water	above trees (artificial; live)
		Windfield	above trees (artificial; live)
Lindberg et al. (1990)	Tennessee; north Germany	Particulates	amid- and above-canopy
		Meteorological data	above-canopy
		Precipitation	collected in adjacent forest clearing
		Throughfall	amid-canopy
Beswick et al. (1991)	Dunslair Heights	Cloud drop size spectra	above-canopy
		Temperature	above-canopy
		Humidity	above-canopy
		Wind	vertical profiles from amid- to above-canopy
Mueller et al. (1991)	Whitetop Mt.	Cloud water	above or outside canopy
		Meteorological variables	above or outside canopy
Gallagher et al. (1992)	forest	Cloud	above-canopy
		Snow	above-canopy
		Wind and Temp.	vertical profiles from amid- to above-canopy
DeFelice (present study)	Mt. Mitchell, North Carolina	Cloud water	above, amid-canopy
		Cloud drop size spectra	above, amid-canopy
		Windfield	above-canopy
		Temperature, Pressure	above-canopy
		Humidity	above-canopy
Vong and Kowalski (1995)	Cheeka Peak, Washington	Cloud drop size spectra	above-canopy
		Liquid water content	above-canopy
		Temperature, Windfield	above-canopy
		Cloud water	above-canopy
		Condensation nuclei	above-canopy
Rao et al. (1995)	Below cloudbase	Precipitation[b]	above-canopy
Walmsley et al. (1996)	Roundtop Mt., Quebec	Standard meteorological data including precip.[c]	above and outside canopy
		Cloud water	above and outside canopy

[a] Temp. = temperature.
[b] The precipitation samples were 24-h samples, and the throughfall samples were event samples.
[c] precip. = precipitation.

cloud water collection technology are important when this collected water is used for human consumption. Water quantity and quality estimates are affected by collector location relative to the free troposphere, the meteorology of the site, and the collector's characteristics (e.g., DeFelice and Saxena, 1990b).

This paper presents the physical characteristics of the portions of clouds that could be intercepted by the trees of a red spruce/Fraser fir ecosystem canopy within the Mt. Mitchell State Park.

2. Background

Cloud systems traversing the Mt. Mitchell State Park, NC, have been studied since 1985 (e.g., Saxena et al., 1989, 1996; DeFelice and Saxena, 1990a, 1991, 1994; DeFelice, 1997; Menon and Saxena, 1998). There have been concurrent meteorological, chemical (e.g., pH, ions, gaseous-ozone, sulfur dioxide, nitrogen oxides), physical (e.g., liquid water content, droplet size distribution, aerosol concentration, CCN spectra), and related measurements made throughout these studies.

2.1. Experimental platform and measurements

2.1.1. Past studies

Cloud events were found to be a significant source of moisture to this forest ecosystem during the growing season. Days with no events outnumber those with precipitation-only events and make up approximately 30% of the days during the growing season (mid-May through mid-September).

Standard meteorological, physical, and chemical data have been collected (about 17.5 m above ground level, AGL) above a Fraser fir and red spruce stand (average top around 7.5 m AGL) at the Mt. Gibbs site (2006 m above sea level, ASL, and approximately 3.3 km southwest of the 2038 m mean sea level, MSL, summit of Mt. Mitchell—35°44′05″N, 82°17′15″W) since the summer of 1986. The above-canopy platform includes a passive string cloud water collector, developed at the Atmospheric Sciences Research Center (ASRC), Albany, NY (e.g., Winters et al., 1979; DeFelice and Saxena, 1990b), and an optical forward scattering spectrometer droplet-sizing probe (FSSP-100).

2.1.2. Present study

Measurements of the physical and chemical characteristics of the clouds amid the trees were added to the routine above-canopy measurements between 13 and 22 June 1993. The sampling platform contains an ASRC cloud water collector and a FSSP-100, and was situated approximately 3.5 m west of the above-canopy platform and about 5 m AGL. There were only periodic spot measurements of temperature, wind field, pressure, and radiation made amid-canopy. The above-canopy and amid-canopy sampling platforms used in the present study are shown in Fig. 1.

The cloud water collector amid the trees obtains (a) the cloud water and some precipitation water (when applicable) that has not been 'captured' by the trees and which may or may not have made some contact with the trees and (b) some water that is periodically 'flung' off the trees (e.g., Joslin et al., 1990) within the canopy. We visually confirmed that water is 'flung' periodically within the canopy during most cloud events. In contrast, the above-canopy cloud water collector simply collects the cloud water and some rainwater. Please see Stogner and Saxena (1988), Saxena et al. (1989), Saxena and Lin

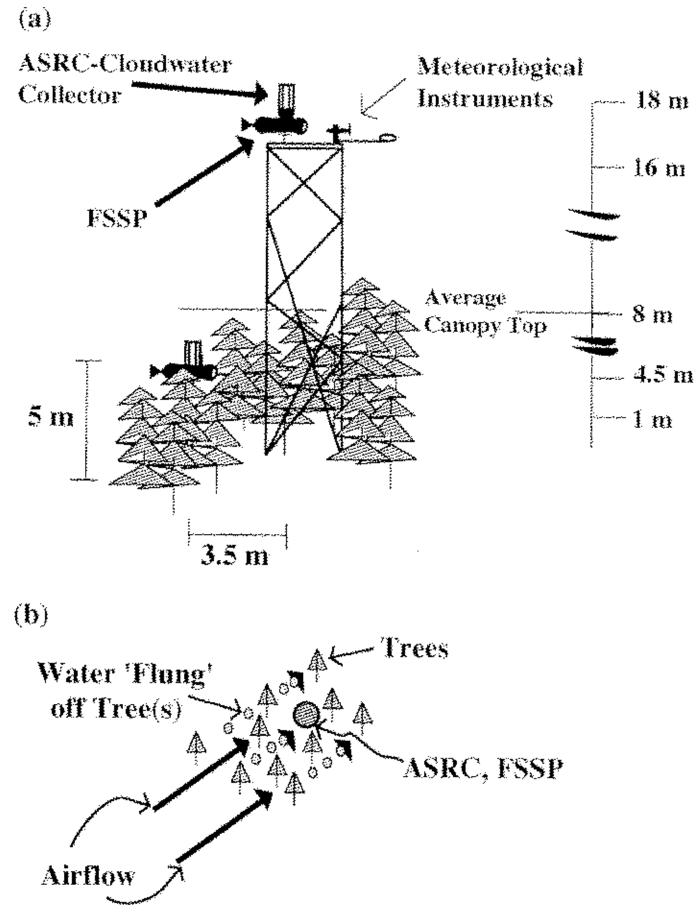

Fig. 1. The location of the amid-canopy and above-canopy sampling platforms.

(1990), and DeFelice and Saxena (1991) for additional details of the canopy, site, sampling apparatus, and procedures.

The amid-canopy and above-canopy sampling platforms are separated by a horizontal distance of 3.5 m, and the cloud water samples are typically an hour long. Can either platform be expected to sample cloudy air from the other platform? The horizontal transit time between platforms would be no faster than 0.4 s, and in this 0.4 s, the vertical displacement would be 0.36 m (all things ideal and excluding sedimentation). The latter assumes that the average wind speed is approximately 9 m s^{-1} above the canopy (or about 12 m above the amid-canopy collector) and the vertical wind component is approximately 0.9 m s^{-1} (e.g., DeFelice and Saxena, 1990a). The vertical displacement from the collector amid the trees to that above them would take around 13 s (assuming the vertical velocity is a tenth of the horizontal velocity, implying that the 13 s is on the fast side). Furthermore, in 13 s, a particular air volume traveling at 9 m s^{-1} would be 117 m downwind of the above-canopy collector position. The equivalent amid-canopy downwind distance would be approximately 50 m. This simple calculation alone suggests that perturbations in the amid-canopy cloud structure are not likely to be in phase with the concurrent above-canopy structure. The hour-long sampling period will favor the mean larger scale cloud structure, which should generally coincide above and amid the canopy unless the cloud–canopy interaction persists throughout most of the particular sample period.

Information summarizing the operational expectations and maintenance of instrumentation used in gathering these data is important and provides an indication of the care that was taken to obtain the measurements used in this study. As a result, the operational expectations and maintenance of the instrumentation used in this investigation are summarized as follows.

2.2. *FSSP and ASRC data collection*

A Forward Scattering Spectrometer Probe (FSSP) photo-electronically determines the droplet size distribution of the clouds. Baumgardner (1983) and Dye and Baumgardner (1984) provide a comprehensive description of the FSSP and its operation. The FSSPs were laboratory calibrated before and after each growing season, but no significant change was found. The calibration was spot-checked in the field before and after each event to ensure that the probe was sizing properly. The field spot check involved the injection of beads with known size into and through the center of the sampling area. This procedure was repeated with a similar number of the same size beads two more times. The alignment of the optics was also checked before and after each event, but realignment was never necessary. Each FSSP was equipped with an inlet horn, sample tube accelerator, and honeycomb flow straightener.

The FSSP data may be affected by the following factors: (1) coincidence (two particles counted as one), (2) dead time (particles not counted while the probe is processing data), (3) wind gust, (4) reduced cutoff size due to low flow rate, and (5) probe orientation. These factors result in (1) oversizing and undercounting, (2) undercounting, (3) overcounting, (4) biasing toward smaller sizes, and (5) biasing towards small sizes of droplets and undercounting, respectively. The first two depend on the droplet concentration. The probe was continuously pointed into the wind ($< \pm 10°$) so the effect from probe orientation would be negligible.

The FSSP data used here have been dynamically corrected by processing the total actual counts and the total strobe counts. This correction was necessary because the transit time of droplets through the probe depends on the droplet concentration and the wind speed (Choularton et al., 1986). A droplet that passes through the center of the laser beam produces the longest transit time. Higher droplet velocities, due to an increase in sample flow, decrease the transit time of the droplet. The percentage of time during which the FSSP is analyzing particles in the laser beam, or the activity ratio, equals the "actual number of valid counts" divided by the "total strobe count". The total strobe count indicates every droplet within the entire depth of field. The activity ratio was multiplied by the total sample area to yield an effective sample area. The activity increases as droplet concentration increases causing coincidence losses of actual counts on an increasing percentage basis with activity. The effective sample area multiplied by the ventilation speed (25.2 m s^{-1}) gives the volume sampled. The volume sampled multiplied by the concurrent activity ratio yields the actual volume used when calculating the microphysical parameters, such as the concentration. The

June 1993 amid-canopy FSSP data were similarly acquired but were only available in the form of 10–60 min averages, and there were no above-canopy FSSP data for 13 June 1993.

The Atmospheric Sciences Research Center (ASRC) passive string collector obtains a bulk water volume measurement consisting of cloud droplets plus small precipitation-sized hydrometeors, if present. The ASRC collector transforms the water deposited on its collection surface into a depth or volume measurement over a particular period analogous to direct measurement of the cloud water deposition flux at its surface.

The maximum collection efficiency of the ASRC collector occurs for typical cloud droplet sizes and is dependent on wind speed (e.g., Winters et al., 1979; McLaren et al., 1985). The collection efficiency of this collector increases with time once collection begins (i.e., before the collected water has begun to fall into the collection bottle below this instrument), and it becomes independent of wind speed once the collected cloud or precipitation water starts falling into the collection bottle (DeFelice and Saxena, 1990b). An oscillation of collected drops on the strings may arise within a few centimeters of the ends of the ASRC collector during wind speeds near and above 12 m s^{-1}. Some water falling along the strings toward the collection bottle has been observed to fly off the ASRC collector at wind speeds exceeding 12 m s^{-1} (DeFelice and Saxena, 1990b). There were no wind speeds above 16 m s^{-1} and no observations of suspended water on the strings of the ASRC collectors or water flung off the ASRC collectors during the June 1993 field campaign.

2.3. Cloud liquid water content and flux determination

The FSSP drop size distribution data are related to the cloud liquid water content, LWC, by

$$\mathrm{LWC} = 0.5236 \int \rho N_{\mathrm{D}} D^3 \mathrm{d}D, \tag{1}$$

where ρ is the density of liquid water, N_{D} is the droplet number concentration as a function of droplet diameter, D, and $\int$ indicates the integration over all droplet sizes usually generalized as ranging from zero to infinity. Saxena et al. (1989) found the integrated liquid water content from FSSP to agree within 7% of the empirical liquid water content determined from the volume of water collected by the ASRC. An empirical relationship between the collected cloud water volume and LWC (DeFelice and Saxena, 1990b) is

$$\mathrm{LWC} = \{17.374 \times ((\text{collected cloud water volume}) \times (\text{wind speed} \times \text{time})^{-1})\} + 0.059, \tag{2}$$

where LWC in expressed in g m^{-3}, time in seconds (s), wind speed in m s^{-1}, and the collected water volume in milliliters.

The FSSPs used in this study do not have a sizing capability beyond 47 μm, and the ASRC collectors have been designed to collect cloud and small precipitation hydrometeors, suggesting that the FSSP-derived LWC (Eq. (1)) for periods of precipitation and cloud are likely to be lower than those generated from Eq. (2). Thus, periods with droplet diameters >47 μm (such as, precipitation and perhaps water flung from the canopy) could yield uncorrelated LWC values.

The total flux of droplets to a surface at a given height contains two additive components, the turbulence-driven droplet flux plus the sedimentation-driven flux of droplets (e.g., Lovett, 1984). Lovett (1984) defines total flux as the sum of turbulent and sedimentation fluxes. He further assumes that (1) the turbulent deposition flux to the canopy is linearly related to droplet concentration gradient, (2) drop size spectra based on above-canopy or outside-canopy measurements adequately describe that amid the canopy, and (3) the cloud water deposition by sedimentation is insignificant compared to the turbulent component.

Water fluxes were determined (using Eq. (3a)) for comparison with studies discussed with the assumptions in cloud–canopy interaction models. The cloud water flux (g m^{-2} s^{-1}) is a measure of the total amount of analyte from the atmosphere to a receptor through a unit area during a prescribed time interval (Kulp and Herrick, 1987) and is commonly estimated from

$$F = I_c \times C_c, \tag{3a}$$

where I_c is the rate of cloud water flux (m s^{-1}), and C_c is the mass concentration of the desired species in the cloud water sample (g m^{-3}). For example, in the case of water flux, F is WF, I_c is approximately the horizontal wind speed, U (m s^{-1}), and C_c is the liquid water content or

$$\mathrm{WF} = \mathrm{LWC} \times U. \tag{3b}$$

The assumptions inherent in Eq. (3b) include: (1) that the collector efficiency is 100%, and (2) the local topography has no influence on the flux. Consequently, WF is the maximum possible water flux (e.g., Mueller and Imhoff, 1989, Joslin et al., 1990). The acid flux can be similarly determined.

The amid-canopy wind speeds, when not available, were determined by assuming steady flow (termed stationary air flow by Raupach and Thom, 1981) with no mean streamwise pressure gradient, constant vertical fluxes with height, negligible vertical molecular transport compared to turbulent transport, and a horizontally homogeneous canopy. The ratio of the mean height of the cloud water collection amid the canopy (z) to the mean height of the canopy (h, 7.5 m AGL) is 0.65 ($\pm$0.1) for the site used in this study. Raupach and Thom (1981) show a z/h of 0.5 to be at the base of a near linear portion of the wind profile in an example of a mean wind profile obtained in a pine forest canopy (h = 16 m) under near-neutral atmospheric conditions. Consequently, the wind speed estimates at the amid-canopy cloud water collector level are reasonable.

3. Results and discussion

3.1. Amid-canopy cloud attributes

The amid-canopy cloud had a characteristic droplet number concentration, N_D, of 250 ($\pm$65) drops cm^{-3}, diameter, D, of 9.5 ($\pm$2.9) μm, and liquid water content (LWC), of

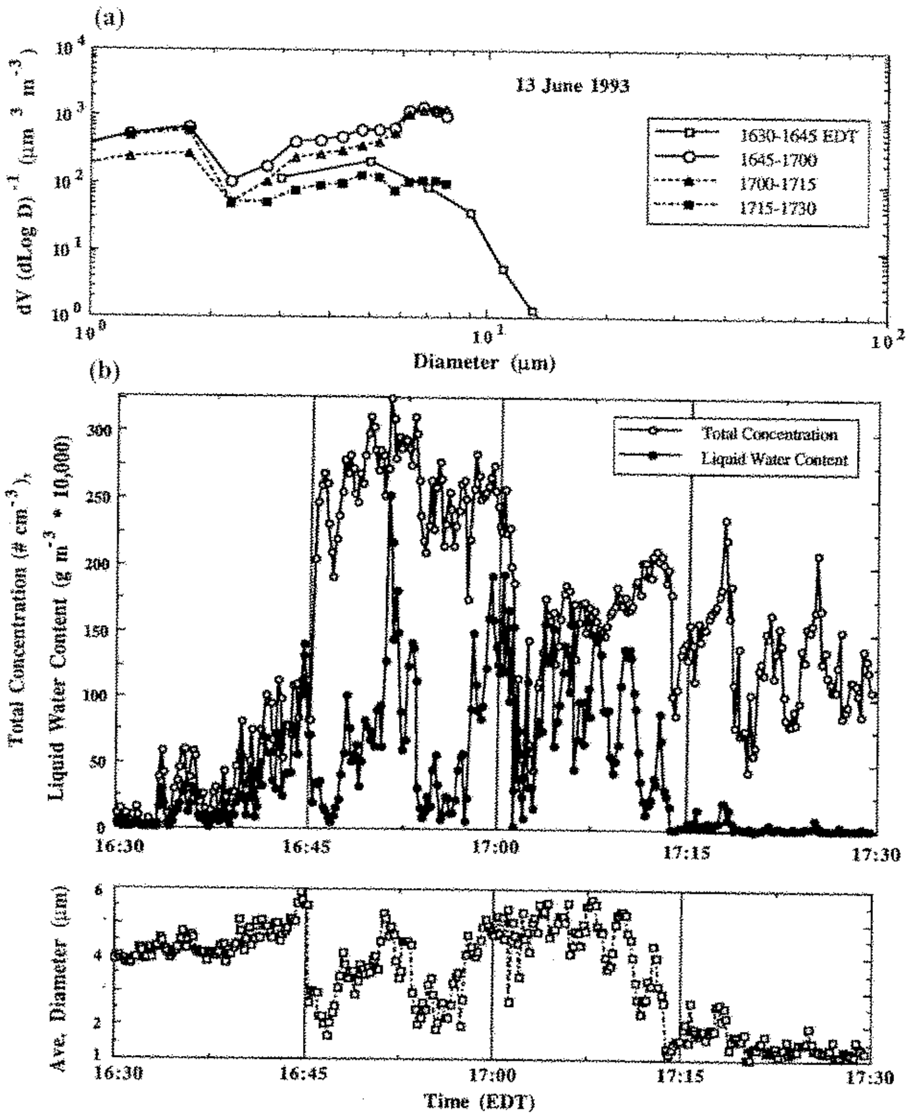

Fig. 2. A representative example of how the canopy influences the structure of the cloud amid the trees. (a) The volume distributions, $dV\,(d\log D)^{-1}$, versus D for amid-canopy clouds during 16:30–17:30 EDT 13 June 1993 are based on 15-min averages of 12-s data. (b) The temporal variation of total droplet concentration, N_d, mean value of liquid water content, LWC, and the mean value of diameter, D, based on 12-s data for the amid-canopy cloud between 16:30 and 17:30 EDT 13 June. There are neither spectral nor temporal N_d, LWC, and D data available for the above-canopy during this period. The curves in part b were made to fit within a similar vertical range to maximize their temporal details.

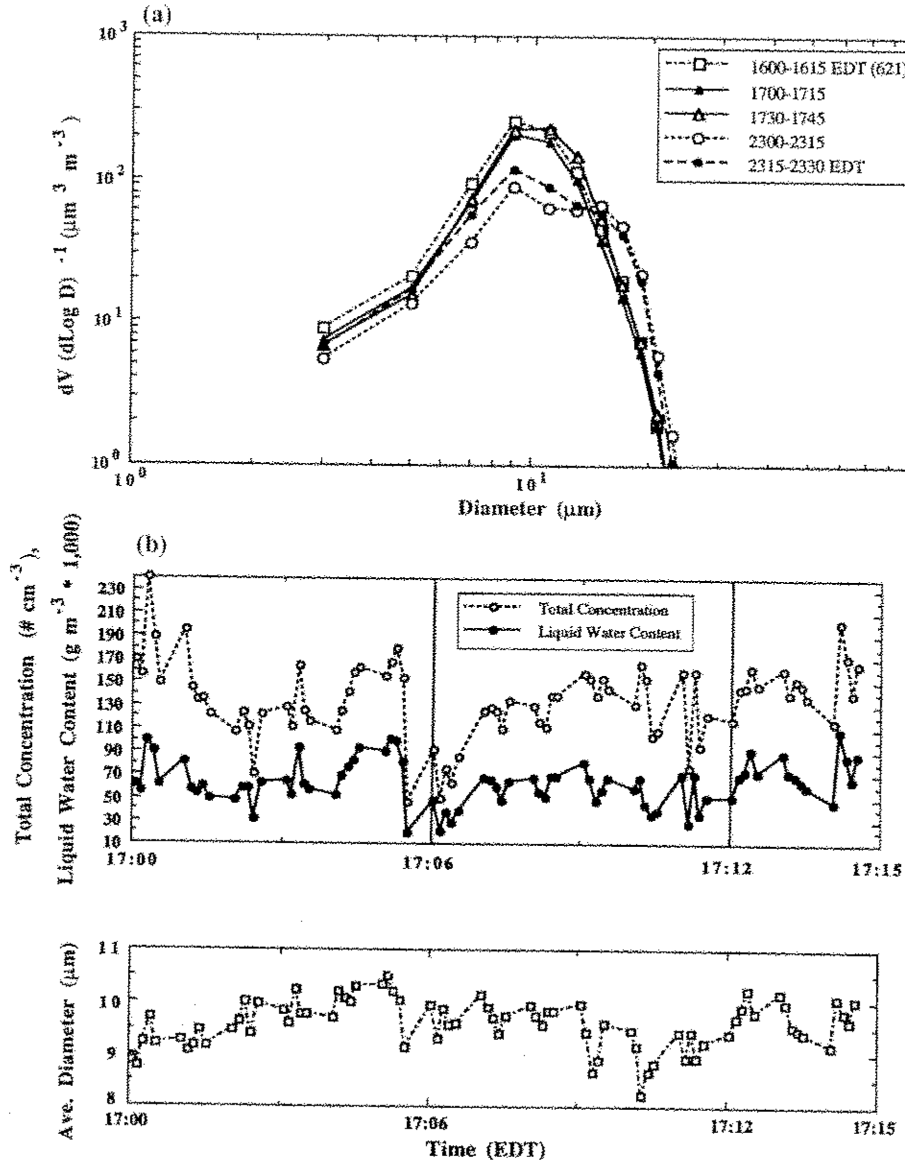

Fig. 3. Representative examples of how the microstructure of the cloud amid the trees varies during a period of cloud with precipitation. Examples of 15-min-averaged $dV(d\log D)^{-1}$ versus D for amid-canopy clouds during 16:00–23:30 EDT 21 June 1993 (a). The temporal variation of N_d, LWC, and D, based on 12-s data for the amid-canopy cloud between 17:00 and 17:15 EDT 21 June (b) and between 23:00 and 23:30 EDT 21 June 1993 (c). The curves in panel b were made to fit within a similar vertical range to maximize their temporal details.

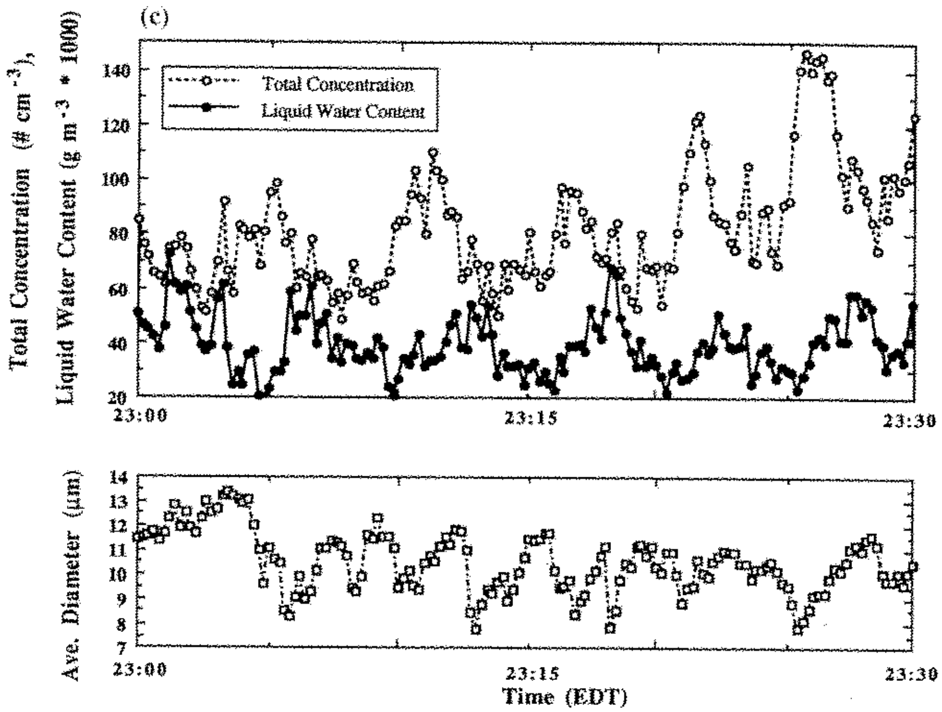

Fig. 3 (*continued*).

0.11 ($\pm$0.08) g m^{-3} during eight events (out of a possible 11) between 13 and 22 June 1993. The events lasted from 1.5 h on two occasions (01:00 and 08:30 EDT events on 18 June 1993) to 24.5 h (21–22 June 1993), or a total of 41 h (out of a possible 52 h). The 11 h of unused data covered periods of both calm and easterly winds, which cause significant errors in the FSSP measurements made from the amid-canopy platform. The concurrent above-canopy cloud had a characteristic droplet number concentration of 600 ($\pm$250) drops cm^{-3}, diameter of 6.5 ($\pm$0.7) μm, and liquid water content of 0.23 ($\pm$0.17) g m^{-3}. Although this data set is small, it does suggest that this canopy has removed half the water and half the droplets from the cloud. However, further research is necessary to determine if these results are typical.

The cloud amid the trees had statistically significant droplet diameter frequency maxima between 1–3 and 4–9 μm during windy portions of the 13–22 June 1993 sampling campaign. The statistical significance is based on Student's *t*-test results, with 97% confidence, degrees of freedom, $df=24$ and $df=9$ for the 15-min-averaged 12 and 30 s data (e.g., Snedecor and Cochran, 1980). The 1–3 and 4–9 μm maxima occurred whether or not rain was present and intermittently during windy periods. Furthermore, maxima near 24 μm and higher were also intermittent and were observed only during periods with both precipitation and cloud, regardless of the wind speed. The droplet diameter frequency maxima, and consequently minima, are not surprising, and their presence results from either (1) a droplet loss to the surface, (2) the physical attributes (geometry, size, spatial

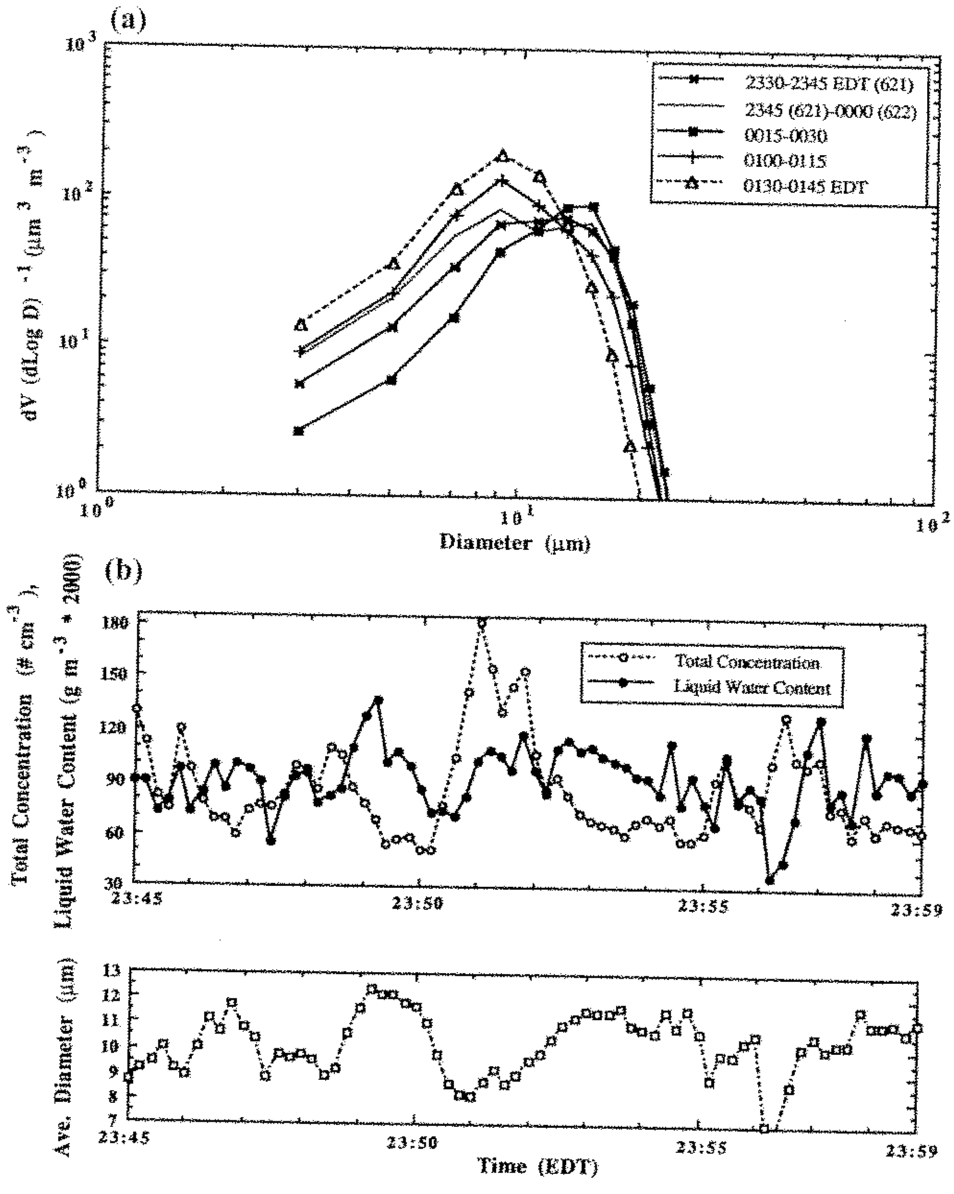

Fig. 4. A representative example of how the structure of the cloud amid the trees varies during a cloud-only period. Examples of 15-min-averaged $dV(d\log D)^{-1}$ versus D for amid-canopy clouds during 23:30–01:45 EDT 21–22 June 1993 (a). The temporal 12-s accumulated values of N_a, LWC, and D data for the cloud amid the trees between 23:45–23:59 EDT 21 June (b) and between 01:30 and 02:00 EDT for the 22 June 1993 (c). The curves in panels b and c were made to fit within a similar vertical range to maximize their temporal details.

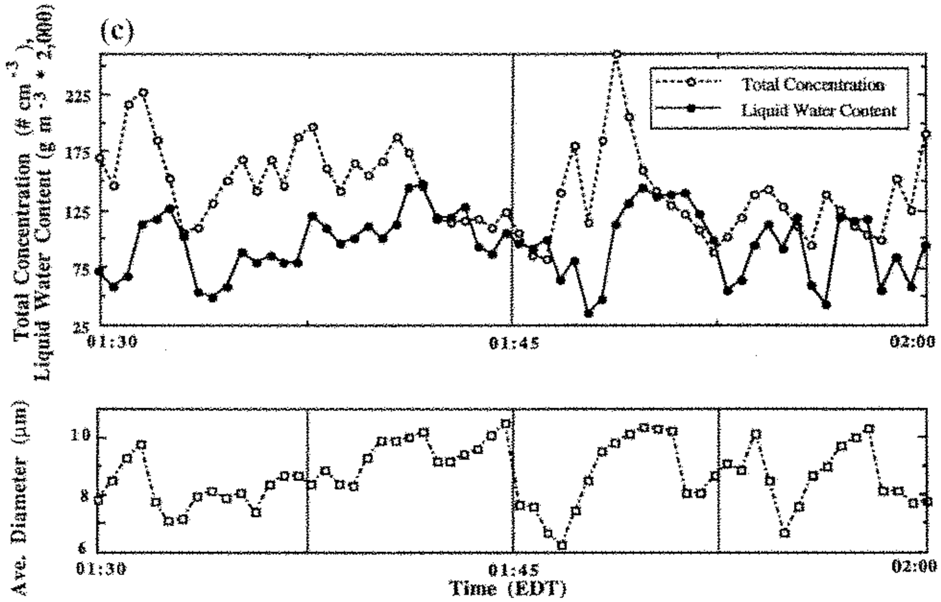

Fig. 4 (*continued*).

distribution of size, etc.) of the canopy itself, (3) a physical canopy-to-cloud interaction (namely the shedding of water from the canopy, as was observed to occur periodically during most events), or some combination of these three. There are insufficient data to determine whether (1), (2), or (3) predominates and under what conditions.

3.2. *Typical amid-canopy cloud structure*

The cloud structure amid the trees is exemplified in Figs. 2a,b–4. Fig. 2a shows the 15-min-averaged volume distribution, $dV\,(d\,\log D)^{-1}$, based on 12-s data for the 16:30–17:30 EDT 13 June 1993 period, and Fig. 2b shows the 12-s LWC, N_d and diameter, D, data for this period. The maxima and minima on a droplet volume distribution plotted versus droplet size curve can be associated with the sources and sinks of the droplets (e.g., Wallace and Hobbs, 1977). Figs. 3 and 4 show similar data for the 24.5 h 21–22 June 1993 event. The 21–22 June event is subdivided into two randomly selected, representative, and well documented portions: i.e., cloud with precipitation, 17:00–17:15 on 21 June 1993 (Fig. 3a,b); and cloud only, 23:00–02:00 EDT 21–22 June 1993 (Figs. 3a,c and 4). It is particularly noteworthy to mention that there were no significant changes in the volume distributions, $dV\,(d\,\log D)^{-1}$, between 16:00 and 23:00 EDT 21 June 1993 (Fig. 3a), and the lowest size bin recorded with the FSSP data during 16:00 and 02:00 EDT 21-22 June 1993 was 2–4 μm (Fig. 4).

Fig. 5 shows the diameter frequency distribution for concurrent periods with only amid-canopy and above-canopy cloud during the June 1993 field campaign when the above-canopy wind speeds were between 5 and 15 m s^{-1}. The cloud amid the trees has two size modes, near 2.5 and 8 μm, with a mean diameter of 5.3 μm. In contrast, the concurrent above-

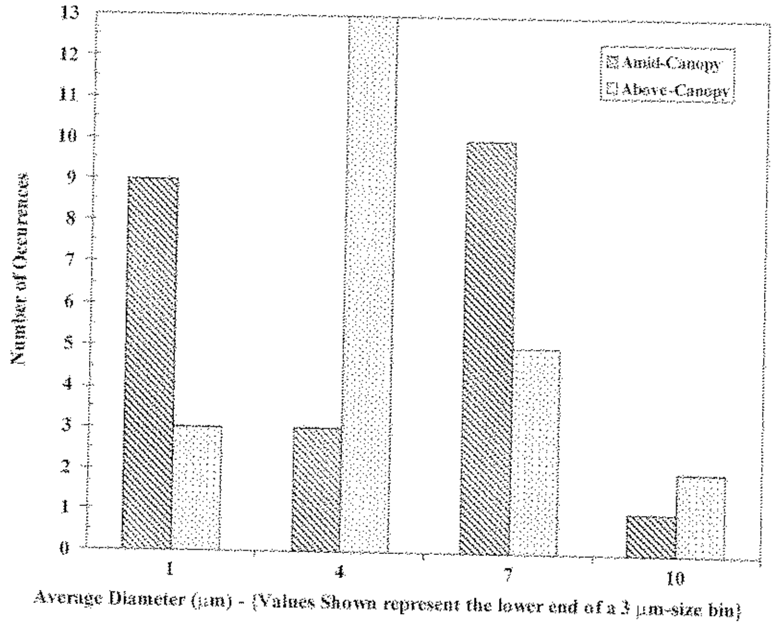

Fig. 5. The frequency distribution of the average droplet diameter above and amid the canopy during periods without precipitation and with winds from the southwest through west-northwest at speeds between 5 and 15 m s^{-1} during the 13–22 June 1993 field campaign.

canopy cloud has one mode around 6 μm, with a mean diameter of 6 μm. It may be that the canopy is a sink for droplets with diameters between 4 and 7 μm, but the source of droplets between 7- and 10-μm diameter amid the canopy warrants further attention. There were observations of water being periodically 'flung' from the middle to upper portions of the trees into the canopy ASRC collector, FSSP-100, and into other trees during the June 1993 field campaign.

3.3. *Amid-canopy cloud water flux*

Theory predicts that the horizontal cloud water flux to a surface is linearly related to the rate of collection onto that surface (e.g., Joslin et al., 1990). The horizontal cloud water flux is non-linearly related to the rate of collection onto that surface amid the trees, especially for the ASRC sampling device, whereas it is linear using the FSSP data (Fig. 6). The ASRC data amid the trees were not affected by problems with sample overflow or suspended water on the collector. It is possible that the nonlinearity is due to the collection of cloud droplets onto the canopy and water shed by the canopy. The collection efficiency of the ASRC in the droplet region believed to be taken out by the canopy (i.e., 4–7 μm diameter) is about 25–30% or about 30–40% at the above-canopy ASRC (McLaren et al., 1985), assuming that the collector is not already transferring its collected water into its collection bottle (DeFelice and Saxena, 1990b). Since the collector is transferring its collected water into its collection bottle, the reported efficiencies are minimum values, and the collections are minimally affected by wind speeds slower than 12 m s^{-1}.

The cloud water deposition rates amid the trees ranged from 0.3 to 0.5 mm/h during the period represented by Fig. 6. The concurrent above-canopy cloud water deposition rates ranged between 1.3 and 3.3 mm/h. These rates are consistent with those obtained during other cloud events at this site (e.g., Saxena et al., 1989; Saxena and Lin, 1990; DeFelice, 1997).

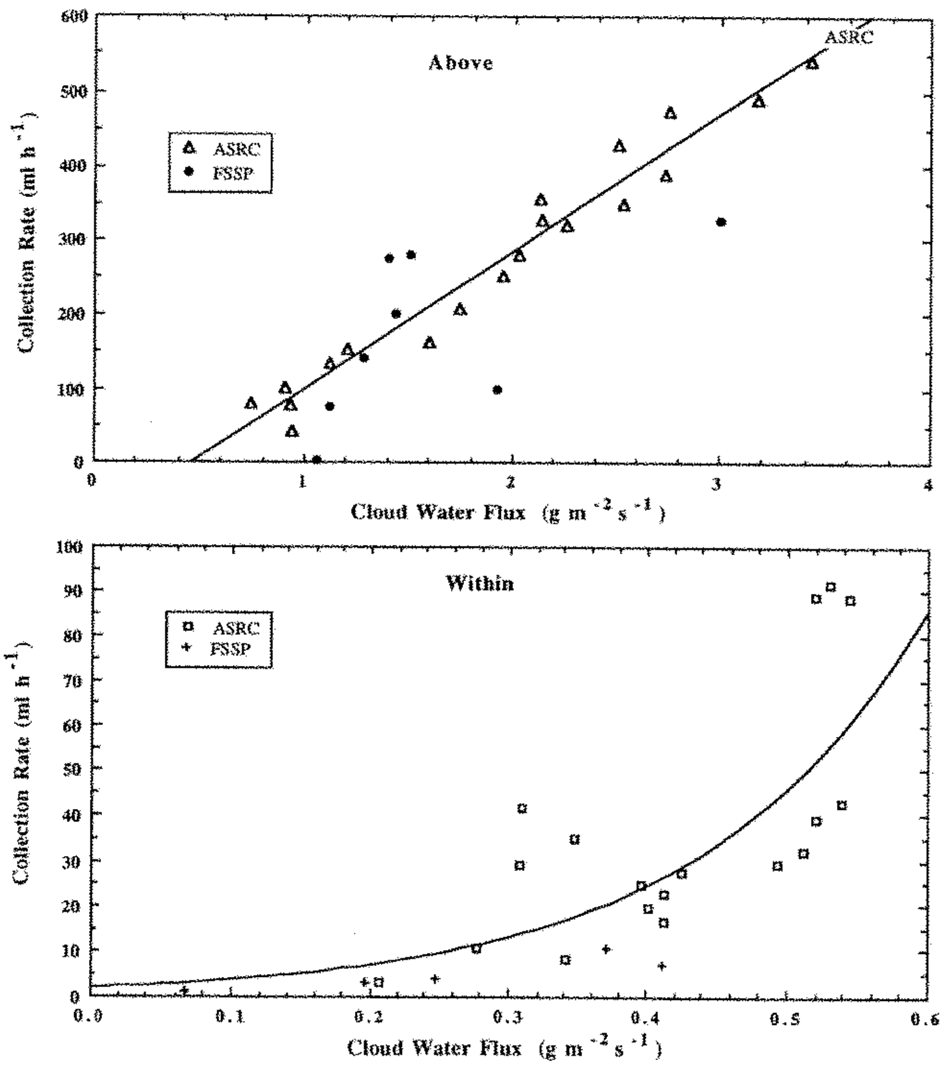

Fig. 6. The cloud water collection rate versus the water flux for the above-canopy and amid-canopy data from this study. These values are derived from cloud-only periods with winds from the west-northwest through southwest at 5–15 m s^{-1}. The regression lines for the ASRC data are shown to emphasize the change in linearity of fit among the data obtained above-canopy and amid-canopy.

4. Concluding remarks

Cloud or fog water collected by forest canopies could represent significant sources of moisture and nutrients for forest ecosystems and water for human consumption. It may also serve as an alternative source of water for agriculture and domestic use. The physical characteristics of fogs and other clouds have been well studied above-canopy or within canopy clearings but rarely amid the canopy. Concurrent above-canopy and amid-canopy water information can be useful to water balance or canopy–cloud interaction model verification and to calibration or training of satellite-borne sensors to recognize atmospheric attributes, such as optical thickness, albedo, and cloud properties.

This "first-of-a-kind" amid-canopy and concurrent above-canopy cloud water study in the Mt. Mitchell State Park, NC, unquestionably indicates a physical interaction between the canopy and the cloud. The data from this study, although limited in quantity, indicated that this canopy removed about half the water and half the droplets from the cloud. The canopy probably loads with water (perhaps from 4- to 7-μm drops for the sake of discussion), and there could be some ionic exchange between this captured water and the canopy. This water may be subsequently shed during the course of a cloud event. Further study is worthwhile. This could lead to a more complete understanding of canopy–cloud interactions, which will then allow for more accurate models for a variety of applications, for example, for predicting and monitoring the amount of fog water as an alternative water source for agricultural use and human consumption.

Two particularly noteworthy first-of-a-kind physical characteristics of the clouds amid the trees within the Mt. Mitchell State Park between 13 June and 22 June 1993 are as follows.

- A droplet number concentration with a mean value of 250 ($\pm$ 65) drops cm^{-3}, a diameter with a mean value of 9.5 ($\pm$ 2.9) μm, and a liquid water content with a mean value of 0.11 ($\pm$ 0.08) g m^{-3}. The cloud droplets exhibited a bimodal distribution with modes at about 2.0 and 8.0 μm and a mean diameter of 5.3 μm during precipitation-free periods, whereas the concurrent above-canopy cloud droplets had a unimodal distribution with a mode near 6 μm and a mean diameter of 6 μm.
- The horizontal cloud water flux is nonlinearly related to the rate of collection onto that surface amid the trees, especially for the ASRC sampling device, whereas it is linear using the FSSP data. Theory predicts that the horizontal cloud water flux to a surface is linearly related to the rate of collection onto that surface.

These characteristics suggest that statements about the effects clouds have on surfaces they intercept, which are based on above-canopy or canopy-clearing data can be misleading, if not erroneous. Similarly, caution is needed when reporting how much water and the water quality available from cloud water collection technology.

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References

Baumgardner, D., 1983. An analysis and comparison of five water droplet measuring instruments. J. Clim. Appl. Meteorol. 22, 891–910.

Beswick, K.M., Hargreaves, K., Gallagher, M.W., Choularton, T.W., Fowler, D., 1991. Size-resolved measurements of cloud droplet deposition velocity to a forest canopy using an eddy correlation technique. Q. J. R. Meteorol. Soc. 117, 623–645.

Cahalan, R.F., Oreopoulos, L., Tsay, T.-S., Wen, G., DeFelice, T.P., 2001. Cloud characterization and clear sky correction from Landsat 7. Remote Sens. Environ. 78, 83–98.

Cereceda, P., Schemenauer, R.S., 1998. Fog water collection at El Tofo, Chile and other coastal sites in South America and Arabia. In: Schemenauer, R.S. (Ed.), Proceedings 1st International conference on Fog, Vancouver, BC. Toronto Univ. Press, Toronto, pp. 409–411.

Choularton, T.W., Consterdine, D., Gardner, I., Gay, B., Hill, M., Latham, J., Stromberg, I., 1986. Field studies of the optical and microphysical characteristics of clouds enveloping Great Dunn Fell. Q. J. R. Meterol. Soc. 112, 131–148.

Collett Jr., J.L., Daube Jr., B.C., Hoffmann, M.R., 1990. The chemical composition of intercepted cloud water in the Sierra Nevada. Atmos. Environ. 24A, 959–972.

DeFelice, T.P., 1997. Investigation of wet acidic deposition episodes capable of damaging Red Spruce in the Mt. Mitchell State Park. Atmos. Res. 43, 325–344.

DeFelice, T.P., 1998a. Physical and chemical aspects of within canopy clouds and their application to current physical/chemical models of cloud–canopy interactions. 1st Inter. Conf. on Fog and Fog Collection, Vancouver, Canada, 19–24 July, 317–320.

DeFelice, T.P., 1998b. Introduction to Meteorological Instrumentation and Measurement. Prentice-Hall, New Jersey, 229 pp.

DeFelice, T.P., Saxena, V.K., 1990a. Temporal and vertical distribution of acidity and ionic composition in clouds—comparison between modeling results and observations. J. Atmos. Sci. 47, 1117–1126.

DeFelice, T.P., Saxena, V.K., 1990b. Mechanisms for the operation of three cloud water collectors: results from mountain top tests. Atmos. Res. 25, 277–292.

DeFelice, T.P., Saxena, V.K., 1991. Characterization of extreme episodes of wet and dry deposition of air pollutants deposition on an above cloudbase forest during its growing season. J. Appl. Meteorol. 30, 1548–1561.

DeFelice, T.P., Saxena, V.K., 1994. On the variation of cloud condensation nuclei in association with cloud systems at a mountain-top location. Atmos. Res. 31, 13–39.

Dye, J.E., Baumgardner, D., 1984. Evaluation of the forward scattering spectrometer probe: Part I—electronic and optical studies. J. Atmos. Ocean. Technol. 1, 329–344.

Gallagher, M.W., Beswick, K.M., Choularton, T.W., Coe, H., Fowler, D., Hargreaves, K., 1992. Measurements and modeling of cloud water deposition to moorland and forests. Environ. Pollut. 75, 97–107.

Joslin, J.D., McDuffie, C., Brewer, P.F., 1988. Acidic cloud water and cation loss from red spruce foliage. Water, Air, Soil Pollut. 39, 355–363.

Joslin, J.D., Mueller, S.F., Wolfe, M.H., 1990. Tests of models of cloud water deposition to forest canopies using artificial and living collectors. Atmos. Environ. 24A, 3007–3019.

Kidder, S.Q., Vonder Haar, T.H., 1995. Satellite Meteorology: An Introduction. Academic Press, New York, 466 pp.

Kulp, J.L., Herrick, C.N., 1987. NAPAP (National Acid Precipitation Assessment Program) Interim Assessment: the causes and Effects of Acid Deposition, vol. 1. U.S. Gov. Printing Office, Washington, DC, pp. 1–53.
Lindberg, S.E., Lovett, G.M., Richter, D.D., Johnson, D.W., 1986. Atmospheric deposition and canopy interactions of major ions in a forest. Science 231, 141–145.
Lindberg, S.E., Bredemeier, M., Schaefer, D.A., Qi, L., 1990. Atmospheric concentrations and deposition of nitrogen and major ions in conifer forests in the United States and Federal Republic of Germany. Atmos. Environ. 24A, 2207–2220.
Lovett, G.M., 1984. Rates and mechanisms of cloud water deposition to a subalpine balsam fir forest. Atmos. Environ. 18, 361–371.
McLaren, S., Kadlecek, J., Kadlecek, A., Spencer, J., Conway, C., 1985. Field intercomparison of cloud water collectors at Whiteface Mountain. Report from the Whiteface Mountain Field Station, ASRC, Wilmington, NY 12997, 66 pp.
Menon, S., Saxena, V.K., 1998. Role of sulfates in regional cloud–climate interactions. Atmos. Res. 47–48, 299–315.
Mueller, S.F., Imhoff, R.E., 1989. Infering cloud deposition to a forest canopy using a passive cloudwater collector. Geophys. Res. Lett. 16(7), 683–686.
Mueller, S.F., Joslin Jr., J.D., Wolfe, M.H., 1991. Estimating cloud water deposition to subalpine spruce–fir forests—II. Model testing. Atmos. Environ. 25A, 1105–1122.
Olivier, J., 1998. A high elevation fog water collection experiment in South Africa. In: Schemenauer, R.S. (Ed.), Proceedings 1st International Conference on Fog, Vancouver, BC. Toronto Univ. Press, Toronto, pp. 441–443.
Rao, P.S.P., Momin, G.A., Safai, P.D., Pillai, A.G., Khemani, L.T., 1995. Atmos. Environ. 29, 1029–2025.
Raupach, M.R., Thom, A.S., 1981. Turbulence in and above plant canopies. Annu. Rev. Fluid Mech. 13, 97–129.
Reinking, R.F., 1995. An approach to remote sensing and numerical modeling of orographic clouds and precipitation for climatic water resources assessment. Atmos. Res. 35, 349–367.
Sabino, A.A., Moreno, J., 1998. Fog water collection in Cape Verde Islands: an alternative source of water for agriculture and domestic use. In: Schemenauer, R.S. (Ed.), Proceedings 1st International Conference on Fog, Vancouver, BC. Toronto Univ. Press, Toronto, pp. 445–448.
Saxena, V.K., Lin, N.-H., 1990. Cloud chemistry measurements and estimates of acidic deposition on an above cloudbase coniferous forest. Atmos. Environ. 24A, 329–352.
Saxena, V.K., Durkee, P.A., Menon, S., Anderson, J., Burns, K.L., Nelson, K.E., 1996. Physico-chemical measurements to investigate regional cloud–climate feedback mechanisms. Atmos. Res. 30, 1573–1579.
Saxena, V.K., Stogner, R.E., Hendler, A.H., DeFelice, T.P., Lin, N.-H., Yeh, R.J.-Y., 1989. Monitoring the chemical climate of the Mt. Mitchell State Park for evaluating its impact on forest decline. Tellus 41B, 92–109.
Schemenauer, R.S. (Ed.), 1998. Proceedings 1st International Conference on Fog. Toronto Univ. Press, Toronto, p. 300.
Snedecor, G.W., Cochran, W.G., 1980. Statistical Methods, 7th ed. The Iowa State Univ. Press, Ames, IA, pp. 54–59, 139, 143, 146, 469.
Stogner, R.E., Saxena, V.K., 1988. Acidic cloud–forest canopy interactions at Mt. Mitchell North Carolina. Environ. Pollut. 53, 456–458.
Vong, R.J., Kowalski, A.S., 1995. Eddy correlation measurements of size-dependent cloud droplet turbulent fluxes to complex terrain. Tellus 47B, 331–352.
Wallace, J.M., Hobbs, P.V., 1977. Atmospheric Science an Introductory Survey. Academic Press, New York, 467 pp.
Walmsley, J.L., Schemenauer, R.S., Bridgman, H.A., 1996. A method for estimating the hydrologic input from fog in mountainous terrain. J. Appl. Meteorol. 35, 2237–2249.
Wetzel, M.A., Borys, R.D., Xu, L.E., 1996. Satellite microphysical retrievals for land-based fog with validation by balloon profiling. J. Appl. Meteorol. 35, 810–829.
Winters, W., Hogan, A., Mohnen, V., Barnard, S., 1979 May. ASRC Airborne cloud water collection system. ASRC SUNYA Publ. 728 (50 pp.).