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Spatial and temporal variations in precipitation and cloud interception in the Sierra Nevada of central California

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ABSTRACT

Spatial and temporal variations in patterns of precipitation and cloud interception were studied for a period of 14 months in the Sierra Nevada of central California. 14 fully automated sampling stations, located at elevations from 800 to 2400 m, were utilized in the study. Both precipitation and cloud interception were observed to increase with elevation. Cloudwater deposition increased at higher elevations due both to a greater frequency of cloud interception and higher wind speeds. Cloudwater deposition, caused primarily by the interception of clouds associated with cold fronts approaching from the north or northwest, is most important at elevations above 1500 m; however, the interception of highly polluted winter "Tule" fogs, lifting above the floor of the San Joaquin Valley, appears to be an important mechanism for cloudwater deposition at lower elevation sites. Observed and estimated hydrological and chemical inputs to the passive cloudwater collectors used in the study were substantial, suggesting that cloud interception may contribute significantly to the same inputs for exposed conifers in the region.

1. Introduction

Interception of fog and clouds by forests has been shown to remove significant quantities of water, nutrients, and pollutants from the atmosphere. This is particularly true for forests growing near the ocean, or on mountain slopes which are frequently immersed in fog or clouds. Kerfoot (1968) and Schemenauer (1986) have reviewed several studies undertaken to examine this phenomenon. In some cases, intercepted cloudwater has been estimated to deposit as much water as rainfall. Kerfoot (1968) cites several instances where interception of cloudwater is believed to supply the water necessary for the survival of certain plant varieties in otherwise inhospitable habitats.

The rate of cloudwater deposition strongly on four factors: (1) the liquid water content (LWC) of the fog or cloud, (2) the droplet size distribution, (3) the structure of the forest canopy, and (4) the ambient wind speed (Lovett and Reiners, 1986). Cumulative deposition over a specified period of time also depends on the frequency and duration of fog or cloud interception in that interval.

The quantity of cloudwater deposited to the forest on a mountain slope may vary significantly with elevation, due to variations in the parameters governing the deposition process. Cloudwater deposition may increase with elevation, due to increases in average wind speeds and higher liquid water contents. The most important factor determining the elevational dependence of cloudwater deposition, however, is the elevational pattern of cloud interception. Different meteorological conditions may tend to favor cloud interception at different elevations. The upper boundary of coastal stratus clouds, for example, may be limited to 500 to 1000 m elevation by the presence of a strong temperature inversion. Cloud interception in this environment will occur at elevations at or below the predominant inversion height. Alternatively, clouds associated with frontal systems often have base elevations exceeding 1500 m; thus, these clouds will be intercepted most frequently at higher elevations. Schemenauer et al. (1987) found that deposition rates of cloudwater to passive cloudwater collectors located on a coastal mountain in Chile were maximal at 700 m and decreased at higher elevations. While this pattern presumably reflects a prevalence of cloud interception at 700 m elevation, their monitoring system did not actually collect information regarding the frequency or duration of interception, which could support or refute this hypothesis.

In the southern and central Sierra Nevada Mountains of California, interception of cloudwater by the forest canopy is believed to contribute significantly to regional deposition budgets for water, nutrients, and pollutants (Collett et al., 1989, 1990). Three mechanisms are thought to lead to the interception of fog and clouds in the region: (1) the passage of frontal systems, which often leads to interception of clouds by the mountain slopes; (2) local formation of fog due to the rapid cooling of moist air produced during snow melt on sunny days; and (3) the lifting of dense "Tule" fogs previously trapped near the floor of the San Joaquin Valley (Jacob et al., 1986), due to a reduction in atmospheric stability over the valley. In conjunction with a study of the chemical composition of intercepted cloudwater in the Sierra (Collett et al., 1990), a field program was initiated to evaluate the frequency and duration of cloudwater interception, as a function of elevation, in Sequoia and Yosemite National Parks. The results of this investigation, which are essential for determining which elevations in the Sierra are likely to be affected by the deposition of cloudwater, are described below.

2. Experimental procedure

2.1. Monitoring sites

14 sites were selected to serve as cloudwater monitoring stations throughout the course of the study, which lasted from September 1987 until November 1988. 8 of the sites, referred to as SQ1 through SQ8, were located in Sequoia National Park (Fig. 1); 6, YO1 through YO6, were located in Yosemite National Park (Fig. 2). The chemical composition of intercepted cloudwater was monitored at sites SQ5 and YO3. Most of the sites were located in open areas where ambient clouds could intercept the site directly, although two stations (SQ4 and YO1) were situated in sparse woodland. The sites were selected so that an elevational gradient was represented in each Park. While an attempt was made to locate sites at similar elevations in the two Parks, several factors prevented the selection of entirely comparable sites. Sites were not permitted to be highly visible to Park visitors, could not be located in designated wilderness areas, and had to be accessible by foot. The elevational gradient represented in Sequoia National Park ranged from 820 to 2360 m; site elevations in Yosemite National Park ranged from 1220 to 2300 m Individual site elevations are listed in Table 1.

2.2. Equipment

Intercepted cloudwater was collected at each site using a passive cloudwater monitoring system, described in detail elsewhere (Collett, 1989; Hoffmann et al., 1989). This system includes a cylindrical cloudwater collector, which utilizes ambient winds to collect cloudwater droplets by inertial impaction. The collection surface is comprised of two concentric rows of 180 Teflon strands, 508 μm in diameter. The outer diameter of the collector is 0.155 m. The height of the collection region is 0.37 m. The collector, which has omni-directional collection characteristics, collects most cloudwater droplets efficiently when wind speeds exceed 1 m s^{-1} (Collett, 1989; Hoffmann et al., 1989). Use of a passive collector, rather than an active collector, served to minimize power requirements (all power had to be supplied from batteries carried in to each site), and to provide a record of only those interception periods when ambient winds were high enough to produce

Table 1. *Elevations of monitoring sites*

Site	Elevation (m)
SQ1	820
SQ2	1070
SQ3	1510
SQ4	1780
SQ5	1860
SQ6	2010
SQ7	2360
SQ8	2180
YO1	2300
YO2	1490
YO3	1590
YO4	1220
YO5	1370
YO6	2020

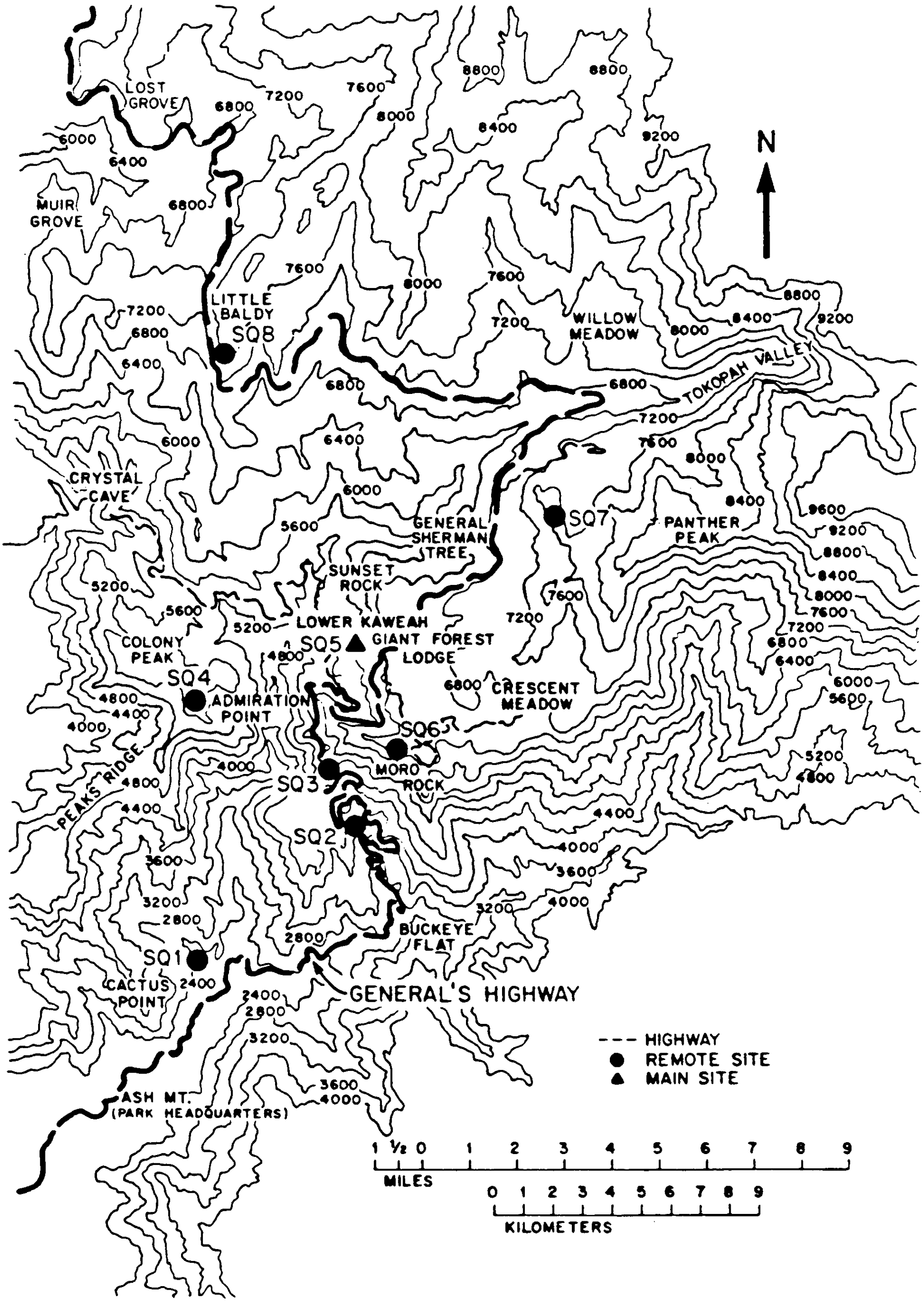

Fig. 1. Map of Sequoia National Park indicating the locations of the cloudwater monitoring sites, labeled as remote and main sites. SQ5, labeled as a main site, also was utilized to collect cloudwater samples for chemical analysis. Contours are labeled in feet (ft) where 1 ft = 0.3048 m).

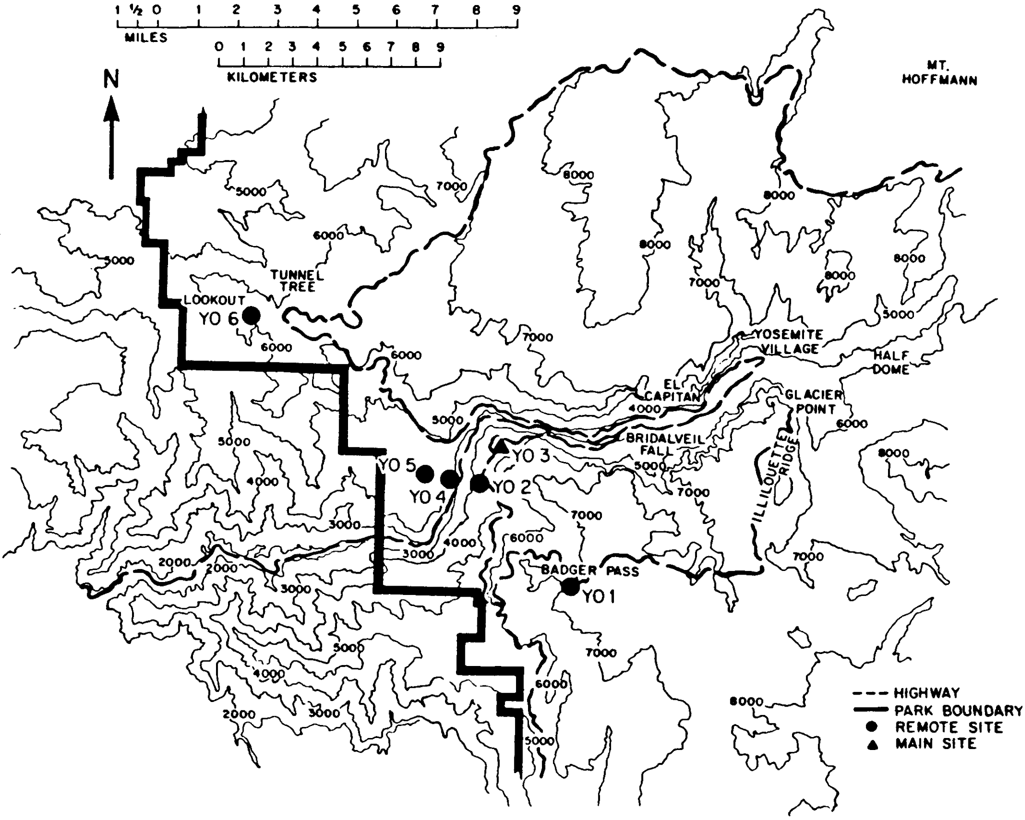

Fig. 2. Map of Yosemite National Park indicating the locations of the cloudwater monitoring sites, labeled as remote and main sites. YO3, labeled as a main site, also was utilized to collect cloudwater samples for chemical analysis. Contours are labeled in feet (ft) where 1 ft = 0.3048 m).

significant rates of cloudwater deposition to the forest canopy. The monitoring system also included a tipping cup gauge which measured the volume of cloudwater collected, an anemometer which measured ambient wind speeds during interception, a tipping cup rain gauge (orifice diameter of 0.209 m) which measured rainfall at the site, a data-logging system, and two 6 V batteries which supplied all power used at the site.

Sites were serviced monthly. Data was transferred from the data-logger to a portable computer carried to each site. After transferring the data, the monitoring system was checked to make sure that the equipment was functioning properly, and the batteries were replaced. In the event of damage to the equipment or equipment malfunction, an attempt was made to remedy the problem at the site. When this was not possible, due to extensive damage or an unanticipated malfunction, site operations had to be curtailed until the next visit. The most common problems encountered were failure of components in the data-logging system, problems in the data-logging software, and equipment damage by curious black bears.

The tipping cup gauges (Weathermeasure #6011 – A) used to measure collected volumes of rainfall and intercepted cloudwater were identical. Each gauge tips every time 8.7 ml of water are collected, corresponding to 0.25 mm of rainfall for the rain gauge and 0.46 mm of intercepted cloudwater for the passive cloudwater collector. Predicting actual rates of cloudwater deposition to the nearby forest canopy, based on observed rates of deposition to the passive cloudwater collector, is difficult because the structure of the canopy and the profile of the wind velocity is largely unknown.

Furthermore, the canopy structure varies considerably from one location to another. Dasch (1988) and Lovett (1984) modeled cloudwater deposition to two eastern U.S. fir stands with total surface area indexes (SAI) of 6 and 7, respectively (SAI is defined as the ratio of the total surface area of a canopy component to the corresponding plan area). Trees studied in both areas were approximately 10 m high. Taller trees in the Sierra probably have greater values of SAI, perhaps comparable to that of the passive cloudwater collector, 11.3. Actual collection rates by the cloudwater collector and nearby conifers are not directly comparable, however, because of differences in the dimensions, orientation, and mutual aerodynamic shielding effects of the impaction surfaces between the trees and the collector.

2.3. Data processing

The data record from each site includes a log of the number of tips recorded by each tipping cup counter (rain and cloudwater) during the monitoring period, and the time at which each tip occurred. 5-min average values of the measured wind speeds were also recorded during all periods of precipitation or cloud interception. The design of the data-logging system limited observations to a single output at a time (tipping cup gauges or anemometer). In order to accommodate this restriction, the data-logger program contains a loop which alternately monitors the status of each input. The time required to execute this loop is dependent on the wind speed, since a wind speed measurement subroutine in the loop monitors one full period of the sinusoidal output of the anemometer, the length of which is inversely proportional to the anemometer's rotational velocity. If the length of the period exceeds a predetermined time, corresponding to a wind speed of approximately $0.5 \mathrm{~m~s^{-1}}$, execution of the subroutine is terminated. In order not to miss any pulses generated by tips of the rain or cloudwater gauges, which might occur while the wind speed subroutine is executed, the data logging circuitry lengthens the duration of the incoming pulses. Initially the pulses were lengthened to approximately 1 s. Longer pulses were not used to minimize the chance of obtaining overlapping responses from the two gauges. At low wind speeds ($\leqslant 1 \mathrm{~m~s^{-1}}$), however, execution of the wind speed subroutine requires slightly longer than one second, consequently, rain or cloudwater tips occurring right at the beginning of the subroutine go undetected under these conditions. We estimate, based on field experiments, that the percentage of tips missed during periods of low wind speed is approximately 10% using this system. Because of the prevalence of low wind speeds observed during cloud interception and rainfall during the fall of 1987, the system was modified for the spring sampling period by lengthening the pulse duration. While this modification resulted in a few cases of overlapping responses from the two gauges, it eliminated the problem of underestimating rainfall and cloud interception at low wind speeds.

Since the passive cloudwater collector is an efficient collector of rain as well as intercepted cloudwater, the tips of the cloudwater gauge had to be partitioned into two groups: those due to rainfall and those due to cloudwater. Partitioning was possible only because of the simultaneous collection of rainfall data at each site. Experiments designed to compare the relative responses to rainfall exhibited by the cloudwater collector and the rain gauge indicated essentially equivalent responses at wind speeds between 1.5 and $3 \mathrm{~m~s^{-1}}$; however, preferential collection of rainfall by the rain gauge was observed at lower wind speeds (Collett, 1989; Hoffmann et al., 1989). Similar patterns were observed in Sierra field data during periods of rainfall without simultaneous cloud interception; consequently, tips of the cloudwater gauge, observed during rainfall, were removed from the Sierra site records, on a one-to-one correspondence with observed tips of the rain gauge. This method of eliminating the rain response of the cloudwater gauge provides a slightly conservative estimate of the overall quantity of intercepted cloudwater. The relative responses of the rain gauge and the cloudwater collector at wind speeds $> 3 \mathrm{~m~s^{-1}}$ were not determined.

3. Results and discussion

Cloudwater interception was monitored at the fourteen monitoring stations from September, 1987 through October, 1988, although some of the sites were not in use during the entire period. Approximately half of the sites were removed during the winter months because freezing of the intercepted cloudwater on the collection strands of the passive cloudwater collector would prevent measurement of the volume collected. Snowfall collected by both the rain gauge and the cloudwater collector also creates data interpretation difficulties. Some of the lower elevation sites were left in place through the winter, however, to test winter operation of the system and to obtain a record of cloud interception at lower elevations during this period. Equipment at one of the sites in Yosemite, YO1, was seriously damaged in November 1987. In addition to the equipment damage, data collected by this station during late October and early November was lost as well. This site was not used following this incident. Selected data from the network are presented and discussed below. The remaining data from the program have been presented in detail elsewhere (Collett, 1989; Hoffmann et al., 1989).

A typical profile of the elevational gradient observed in precipitation and cloudwater deposition is depicted in Fig. 3, which illustrates the records from sites SQ1, SQ3, and SQ6 during the fall of 1987. The ordinate in each plot depicts the number of tips by each gauge at the given site; the abscissa represents time. Precipitation contributions to the cloudwater collector record have already been subtracted. Little activity in the way of precipitation or cloud interception was observed before late October, but late October and early November comprised the most active period of cloud interception observed during the study. Rainfall amounts during the period increased substantially between 800 and 1100 m elevation, but only slightly above that elevation. Periods of rainfall were generally observed simultaneously at all Sequoia monitoring sites.

A comparison of the cloudwater interception records reveals that cloud interception events, in contrast to rainfall, often occurred only at the higher elevation sites. This is a reflection of the fact that most of the intercepted clouds were associated with frontal systems approaching from the north or northwest, with cloud bases often located at or above 1500 m elevation. Due to their association with frontal systems, periods of cloud interception were often accompanied by precipitation, although this was not always the case. During the passage of strong cold fronts, wind speeds as high as 10 m s^{-1} were recorded during cloud interception, although wind speeds were normally much lower. At SQ5 (elev. 1860 m), for example, typical wind speeds during cloud interception were on the order of 3 m s^{-1}. The highest wind speeds were generally observed at those sites with the greatest degree of exposure.

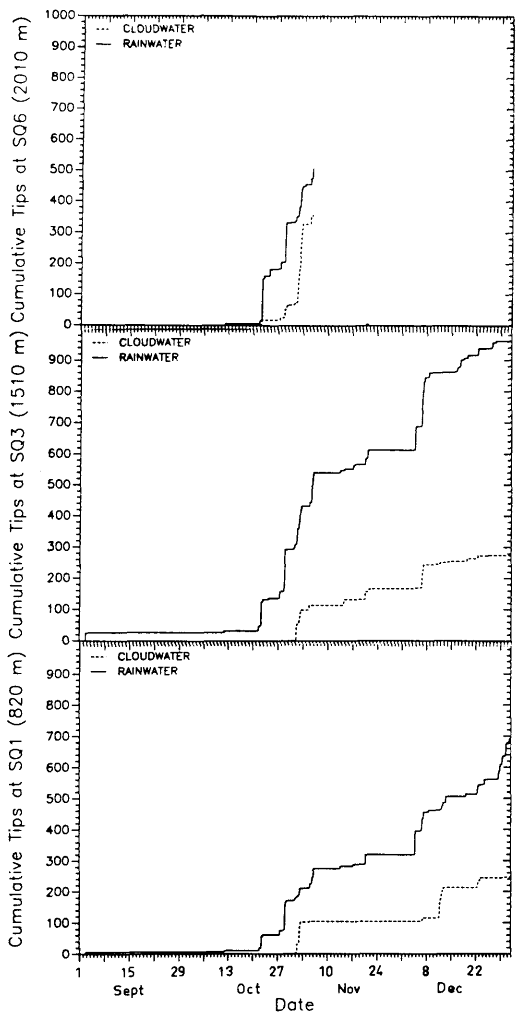

Fig. 3. Precipitation and cloudwater deposition at SQ1, SQ3, and SQ6 during the fall of 1987. Each tip of the rain gauge corresponds to 0.25 mm of precipitation; each tip of the cloudwater gauge corresponds to 0.46 mm of deposited cloudwater.

Rainfall collected at the Sequoia sites exceeded the amount of cloudwater deposited to the passive collector, on an absolute basis, during the fall of 1987. Typically, the ratio of rainfall collected to cloudwater collected was on the order of three or four during this period, although at SQ6 the ratio was only slightly higher than one. SQ6 (elev. 2010 m) is located on a fairly open ridge-top and at least part of the increased cloudwater deposition at this site is attributable to higher wind speeds observed during cloud interception. Higher wind speeds increase the efficiency with which small cloud droplets are collected as well as increase the total volume of air sampled within a given time period.

We also can compare the hydrological inputs of rainfall and cloud interception per square meter of surface area covered by each collector. Recalling that each tip of the rain gauge corresponds to 0.25 mm of rainfall, while each tip of the cloudwater gauge corresponds to nearly twice as much deposited cloudwater (0.46 mm), it is clear that cloudwater interception may play an important role in the deposition of both water and ions at these sites.

Deposition rates during the fall of 1987 typically were observed to be the largest at SQ6. During a 2.5-h period on the evening of 28 October 1987, cloudwater was deposited to the collector at SQ6 at an average rate of 4.0 mm h^{-1}; a rate of 1.2 mm h^{-1} was observed during a four hour period the following day. Cloudwater deposition rates at SQ6, during an extended interception event on 1 November, averaged 4.3 mm h^{-1} over an 11-h period. Wind speeds ranged from 1 to 3 m s^{-1} during this period. High deposition rates also were observed at other monitoring stations. During an overlapping 7-h period on 1 November, cloudwater deposition to the collector at SQ3 (1510 m) averaged 3.1 mm h^{-1}. These deposition rates are somewhat greater than reported for deposition to an exposed redwood in northern California (1.6 mm h^{-1}; Azevedo and Morgan, 1974), and much higher than reported for cloudwater deposition to a single exposed 10 m fir tree on the summit of Clingmans Peak in North Carolina (0.3 mm h^{-1}; Dasch, 1988).

Cloudwater concentrations of NO_3^- and NH_4^+ are typically an order of magnitude or more higher in Sequoia National Park (SNP) than SNP precipitation concentrations of these same species (Collett et al., 1990). Therefore, it is likely that the deposition of these species to the cloudwater collectors located at the higher elevation sites, via cloud interception, exceeded that due to precipitation during the fall of 1987; deposition of SO_4^{2-} probably also was dominated by cloudwater interception, at least at SQ6, since SO_4^{2-} concentrations average more than three times higher in SNP cloudwater than in SNP precipitation (Collett et al., 1990). Although we are unable to quantitatively relate deposition to the passive collectors to that experienced by similarly situated exposed conifers, it seems clear that inputs of these species to such trees via cloud interception also were important for this period. Cloudwater deposition rates to trees located in closed canopies in the region are probably significantly lower than the rates suggested here for the cloudwater collectors, because of reduced wind speeds within the canopy and the removal of droplets by trees located upwind.

Rainfall and cloudwater interception data for the fall of 1987 are presented for three Yosemite National Park (YNP) sites (YO2, YO3, and YO6) in Fig. 4; data from YO4 closely resemble those for YO2 during this period. Rainfall at YO2, YO4, and YO6 was comparable to that observed at the higher elevation SNP sites during the period ending in mid-November. Data for YO3 is missing for much of this period because of data-logger failure. Cloudwater deposition at YO2 (1490 m) and YO4 (1220 m) was fairly low during this period, somewhat less than was observed at the lowest elevation SNP site: SQ1 (820 m). YO2 and YO4 are situated on opposing slopes of the Merced River canyon. The canyon, which has a north-south orientation in this region, is relatively narrow, preventing most frontal system clouds, advancing from the west or northwest, from dropping into the canyon interior where these two sites are located. Alternatively, cloudwater deposition at YO6 (2020 m) was greater than that observed at all but one of the Sequoia sites: SQ6. The timing of the interception events at YO6 also agreed quite closely with that at both SQ6 and SQ8, which are located at 2010 m and 2180 m, respectively. YO6 is situated just below the summit of a fairly open hillside, and, like SQ6 and SQ8, has good exposure to the west.

A closer examination of the cloud interception record from YO6 illustrates some of the patterns in cloud interception observed at this elevation. During the fall monitoring period at YO6 (18 September–24 November 1987), 13 cloud interception events were observed. (For purposes of this analysis, an event was defined as a period

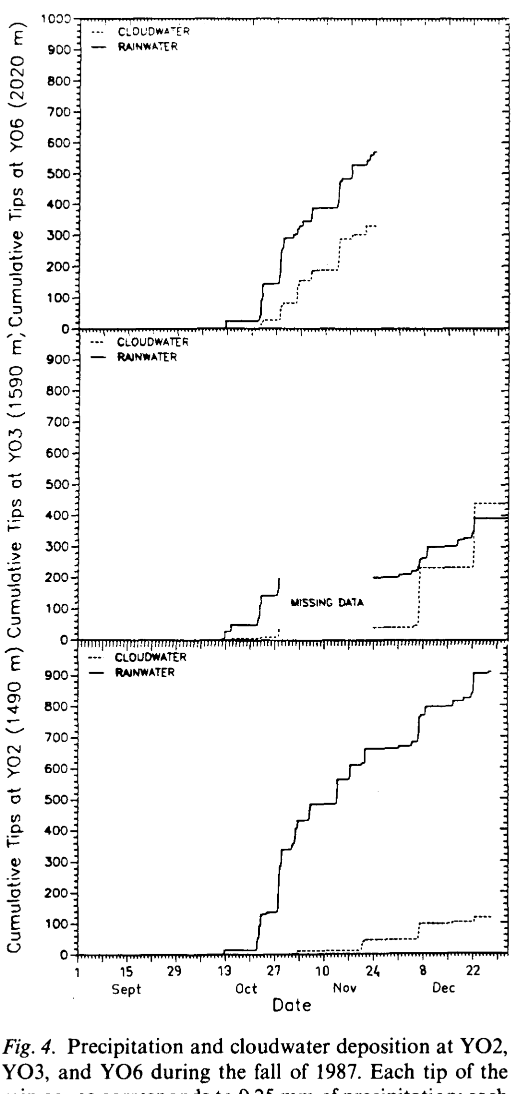

Fig. 4. Precipitation and cloudwater deposition at YO2, YO3, and YO6 during the fall of 1987. Each tip of the rain gauge corresponds to 0.25 mm of precipitation; each tip of the cloudwater gauge corresponds to 0.46 mm of deposited cloudwater.

where multiple tips of the cloudwater gauge were observed. A period longer than 1.25 h between successive tips was considered to define the end of an event.) All of these events, which were distributed evenly between day and night, were observed during a one-month period between 22 October and 21 November. Of the 13 events, 5 were observed to last between 0 and 2 h, 3 lasted between 2 and 5 h, 4 lasted between 5 and 10 h, and 1 exceeded 10 h duration. Cloud interception during this period totaled approximately 56 h. This is significantly less than the 114 h of interception observed at SQ5 (1860 m) in SNP during October and November (Collett et al., 1990). Much of the difference is due to substantially longer periods of cloud interception in SNP during two events in early November. Part of the difference may be further accounted for by a difference in the monitoring techniques. Collett et al. (1990) report data for SQ5 based on measurements made with an active cloudwater collection system, whereas the YO6 data are based on the passive cloudwater collector measurements. When ambient winds are insufficient to provide significant deposition to the passive collector, cloud interception is not recorded.

The correlation between periods of cloud interception and precipitation may also be illustrated with the YO6 data record. Of the 13 fall cloud interception events, 6 periods produced rainfall amounts exceeding the amount of cloudwater captured. During 2 of the events, no precipitation was observed, while during the remaining 5 periods precipitation amounts were less than the amount of cloudwater deposition. The association between cloud interception and precipitation is significant, because large amounts of precipitation may serve to rinse deposited cloudwater, which tends to be substantially more polluted than precipitation in this region (Collett et al., 1990), off plant surfaces.

Several cold fronts crossed the Sierra Nevada Mountains during the month of December, depositing a substantial amount of snow. Nevertheless, there were several cloud interception events at lower elevations that we were able to successfully monitor during this period. Data collected at sites SQ1 and SQ3, from late November through the end of 1987, are depicted in Fig. 3. Rainfall during this period represents the sum of actual rainfall and snowmelt in the rain gauge. While cloudwater interception events during this period generally were recorded simultaneously at both sites, the volume of cloudwater collected differed significantly between the two sites for a given event. Cloudwater interception on the late morning of 22 December, for example, was much greater at SQ1 (820 m) than at SQ3 (1510 m). This interception event followed a period of dense fog in the southern San Joaquin Valley, which had persisted throughout most of 21 December and into the morning of 22 December (NOAA, 1987). Since much greater interception activity was observed at the lower site (SQ1) on 22 December, it seems likely that the cloud interception was the result of lifting of the fog layer previously trapped near the valley floor. This observation indicates a need to investigate the chemical composition of cloudwater during the winter at lower elevation sites (500 to 1000 m) in SNP, since southern San Joaquin Valley fogs have been shown to be heavily polluted (Jacob et al., 1986).

Fig. 4 displays the observations made at sites YO2 and YO3 from late November through the end of December 1987. Approximately 80 mm of rain and melted snow was measured at both YO2 and YO4 during this period; 50% more rain was measured at YO3. Cloudwater deposition at YO3 was 3 × the levels observed at YO2 and YO4, despite the close proximity of these three sites (see Fig. 2). Wind speeds at YO3 typically were observed to be much higher than at YO2 and YO4, providing a more conducive environment for high rates of cloudwater deposition. In addition, YO3 is situated on top of a granite dome, and is completely exposed to clouds approaching from almost any direction, whereas YO2 and YO4 are shielded somewhat by the walls of the Merced River canyon.

Major events involving both rainfall and cloudwater impaction were observed in both Parks on 6 December and 22 December 1987. In fact, there appears to be a high degree of correlation between periods of cloud interception and precipitation in the two Parks. In several cases, correlations between deposition rates at a given elevation in SNP and those at a similar elevation in YNP are much stronger than those between sites at different elevations within a single Park. This is not too surprising, given that much of the cloudwater deposition is due to interception of clouds associated with the passage of frontal systems across the Sierra. Often the cloud base in such systems lies above the elevations of several of the lower sampling sites, as observed previously, but the horizontal extent of the system may reach for several hundred kilometers, easily covering the 150 km between the two Parks. Nevertheless, there are many occasions when clouds are observed at one Park, but not at the other, particularly when the passing frontal system is centered in extreme northern or extreme southern California.

Data collection during the winter was greatly complicated by the presence of snow and rime ice. Since no temperature record was available at the sites, it is difficult to ascertain whether tips of the two gauges during this period were due to cloud interception, rain, hail, or melting snow. In addition, several problems were experienced with the data-loggers during this period. For this reason, only those data collected in December have been presented from the winter sampling period; however, as indicated elsewhere (Collett et al., 1990), relatively little cloud interception activity was observed during January, February, or March.

Data collected at the 13 Sierra cloudwater monitoring sites (SQ1 through SQ8 and YO2 through YO6) in use between early may and early November 1988 revealed several rain events over the course of the spring and summer, but only two major cloud interception events. These occurred on 17 and 28 May, and were observed at almost all of the monitoring stations. Amounts of cloudwater deposited during these two events generally were greater at the higher elevation sites, as observed during most of the previous interception events. Total cloudwater deposition at SNP, during the two events, was dominated by contributions on 17 May, while cloudwater deposition at YNP was generally greater during the 28 May event. Volumes of cloudwater collected at several of the sites during these two events were relatively large compared to the seasonal total precipitation. At YO3, in fact, the volume of cloudwater collected on 28 May exceeded the total volume of precipitation collected between early May and the end of October (see Fig. 5), underscoring the importance of cloudwater deposition in the Sierra. Rates of cloudwater deposition to the collector during a 5-h period on the evening of 28 May, driven by wind speeds of $10\ \mathrm{m\ s^{-1}}$, averaged more than $24\ \mathrm{mm\ h^{-1}}$. A cloudwater deposition rate of $13.4\ \mathrm{mm\ h^{-1}}$ also was observed at YO6, during an overlapping 3-h period on the same evening. Wind speeds at YO6 averaged $4–5\ \mathrm{m\ s^{-1}}$ during the period. These cloudwater deposition rates are substantially higher than have been reported elsewhere. It should be noted that precipitation was falling at both sites during this period. Since evaluations be noted that precipitation was falling at both sites during this period. Since evaluations of the relative responses of the cloudwater collector and the rain gauge to precipitation were not

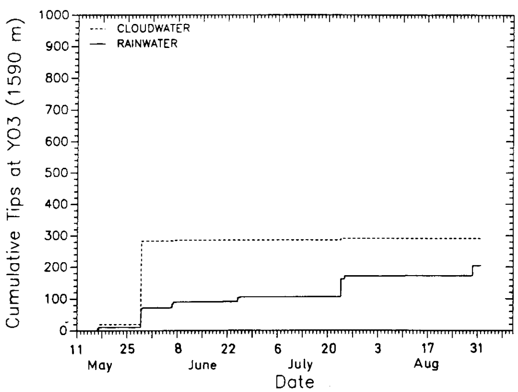

Fig. 5. Precipitation and cloudwater deposition at YO3 during the spring and summer of 1988. Each tip of the rain gauge corresponds to 0.25 mm of precipitation; each tip of the cloudwater gauge corresponds to 0.46 mm of deposited cloudwater.

carried out at such high wind speeds, cloudwater deposition rates for this event should be considered as approximate.

The passage of the cloud mass, associated with a strong Pacific cold front approaching the Sierra Nevada from the northwest, on 28 May is documented by the cloud interception records at YO3 and YO6. Cloudwater interception began at YO6 approximately half an hour before interception was observed at YO3. This pattern is consistent with the direction of approach of the storm, since YO6 is located several kilometers northwest of YO3. Cloud interception at YO3 was observed to continue for approximately two hours after it had ceased at YO6. Total cloudwater deposition at YO3 was approximately 2.5 times that observed at YO6, consistent with the higher wind speeds and greater interception time observed at YO3.

Volume-weighted average YO3 cloudwater concentrations of NO_3^-, SO_4^{2-}, NH_4^+, and H^+ were observed to be 20, 14, 34, and 9.4 μN, respectively, during the 28 May cloud interception event (Collett et al., 1990); cloudwater deposition to the passive cloudwater collector at YO3 was approximately 118 mm during this period. Chemical deposition to the collector during this event, therefore, can be estimated as 150 mg m^{-2} of NO_3^-, 81 mg m^{-2} of SO_4^{2-}, 72 mg m^{-2} of NH_4^+, and 1.1 mg m^{-2} of H^+. By comparison, the average annual quantities of NO_3^-, SO_4^{2-}, NH_4^+, and H^+ deposited in YNP precipitation in 1983 and 1984 were 550, 495, 145, and 5.3 mg m^{-2}, respectively (NADP/NTN, 1985, 1986), suggesting that cloudwater deposition of these ions to the passive collector, on 28 May 1988 alone, probably equaled a substantial fraction of their total annual deposition, wet plus dry at the site. By extension, cloudwater deposition of these ions to exposed conifers at the site was undoubtedly substantial as well, although a lack of information regarding relative rates of deposition to the passive collector and exposed conifers precludes quantifying this amount. We hope to explore this relationship in more detail in future investigations.

4. Conclusions

The spatial and temporal variations exhibited in patterns of precipitation and cloud interception were investigated at 14 sites in the Sierra Nevada Mountains of California. The sites, located in Sequoia and Yosemite National Parks, were selected to represent an elevational gradient in each Park, ranging from approximately 800 to 2400 m. The study began in September 1987 and continued through October 1988. A new monitoring system, which incorporated a passive cloudwater collector, was developed and built for this study. The system also included a data-logger, a rain gauge, and an anemometer. The data-logger maintained a time-resolved record of activity by the cloudwater collector, the rain gauge, and the anemometer.

Data collected during the program illustrates that cloud interception may make important contributions to the total deposition budgets of water and pollutants in the Sierra; however, further work is required to relate cloudwater deposition rates measured by the passive cloudwater collector to deposition rates for similarly situated exposed conifers. Rates of cloudwater deposition to the passive collectors were observed to frequently exceed 1.0 mm h^{-1} at several sites, and surpassed 20 mm h^{-1} at one site in Yosemite National Park during passage of a strong Pacific cold front.

Most Sierra cloud interception events are believed to result from the interception of clouds associated with frontal activity; however, there is some evidence to suggest that dense winter "Tule" fogs, formed near the floor of the San Joaquin Valley, may intercept lower elevation sites in Sequoia National Park, when the atmosphere over the valley is destabilized. Due to the association of cloud interception with frontal passage, cloudwater deposition is frequently associated with periods of precipitation. Interception of clouds is observed most frequently at sites above 1500 m elevation. Ridge-top sites, which often experienced the highest wind speeds, usually receive the greatest hydrological deposition fluxes from impacting cloudwater. Cloud deposition within valleys oriented perpendicularly to the direction of frontal passage tends to be lower than is observed at other locations with similar elevations, but better exposure to the west. Correlations of cloudwater deposition between sites in Sequoia National Park and similarly elevated and exposed sites in Yosemite National Park are often stronger than those between sites with differing elevations in a single Park.

5. Acknowledgments

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