EFFICIENCY OF FOLIAGE IN HORIZONTAL INTERCEPTION

By

W. B. Fowler[1] and H. W. Berndt[2]

Introduction

If we examine the role and impact of rime and hoarfrost in our western winters, we find these forms of precipitation viewed quite differently. To the hydrologist, rime and hoarfrost appear as supplementary sources of winter precipitation. Depending on local climate, amounts of moisture may significantly contribute to the winter water balance. In portions of central Washington, up to 10 percent of the total yearly moisture input is from these sources (1). This precipitation is common at higher elevations in cold, snowy forest types (boreal) and has been described by a number of writers, e.g., Molchanov (6).

Alternate viewpoints suggest that rime and hoarfrost are detrimental. Damage to the forest from ice and wind plus heavy static snow loads can contribute to poor growth forms. Indication of this direct silvical importance of atmospheric moisture is given by Oosting (7).

McKay and Thompson (5) have described the physical impact of ice and frost on utility operations.

For some purposes, knowledge of number of days of occurrence and expected rates of accumulation and/or total amounts would be sufficient for a local hazard forecast. If, however, we desire eventually to manipulate the accumulation processes to enhance or minimize amounts received, additional facts are required. Within our area of watershed management interest, where improvement of water yield is desirable, certain immediate questions can be posed: Are certain species of high elevation stands more efficient collectors due to their branch morphology? More specifically, would the open foliar structure of the pine species be preferred over a more closed canopy of spruces and firs; or might species selection maximize horizontal interception and minimize vertical interception? Is the accumulation process self-limiting, or are limits due only to duration of proper weather conditions? Alternately stated, does the efficiency of the accumulation process change such that there is a maximum expected amount of moisture within a given stand for given conditions?

The question of the variable efficiency of foliar elements in horizontal precipitation is of immediate concern because it is a basic concept which underlies possible interspecies differences suggested above. Our continuing research into this aspect of the accumulation process has produced some tentative conclusions.

Earlier Evidence of Variable Foliar Efficiency in Rime and Hoarfrost Accumulation

In our earliest study of rime and hoarfrost in upper slope forests (1), we found enough similarity in daily rime accumulation totals to suggest that a "rime day" delivered a moisture equivalent of about 0.05 to 0.06 in. of water to our study stand. Although the daily film record of weather conditions showed most riming conditions were of 1 to 2 days duration, a sequence producing 5 rime days was monitored on site. Samples of rime accumulation following the fourth day indicated a total of approximately 0.28 in. water equivalent had been collected in the stand--about equal to four normal "rime days". However, the fifth day sample showed little change over the fourth day, suggesting that although riming conditions persisted, accumulation had decreased markedly. The efficiency of the accumulation process, apparently near maximum at the initiation of the rime sequence, had become essentially zero during the final 24 hr (fifth day). The possibility exists that the 0.28 in. moisture equivalent represented an upper limit to total rime accumulation under the existing conditions.

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[1] Meteorologist, Pacific Northwest Forest and Range Experiment Station, USDA Forest Service, Wenatchee, Washington.

[2] Supervisory Research Forester, Pacific Northwest Forest and Range Experiment Station, USDA Forest Service, Wenatchee, Washington.

Direct Measurement of Changing Foliar Efficiency in Rime and Hoarfrost Accumulation

During the winter of 1969-70, a preliminary investigation of hourly rates of accumulation of hoarfrost and rime on simple test objects[3] (cylinders) and more complex foliar elements was made at our Table Mountain, Washington, site. Separate events, one where hoarfrost was the primary deposit and another where rime accumulation predominated, were analyzed.

Cylinders approximately 250 mm long and ranging in diameter from 3 to 59 mm were suspended in the unobstructed air stream at 1.5-m height. Four samples each of five different diameters were exposed along with single samples of foliage from lodgepole pine and alpine fir. A rotating framework provided equal exposure of all objects. Rotation was at 1/2 rpm, too slow (less than 1/2 m sec^{-1}) to provide appreciable velocity above ambient wind levels. A 7-ft lodgepole pine, used as a control, was continuously weighed with a recording proving ring.

All test objects were weighed to the nearest 0.01 mg on an analytical balance at intervals as frequently as each hour during times of major accumulation. All 22 samples were measured in about 10 min. Air temperature, dewpoint, and cumulative wind run were monitored on an hourly basis.

Surface area of sample objects within each class was initially equalized by adjustment of length. Since within sample variation was generally less than 0.1 g, accumulation data were combined into hourly means by size groups. Record of the continuously weighed tree was analyzed to provide comparable hourly moisture increments.

Surface areas of the test cylinders, small branch samples, and the 7-ft tree are given in Table 1. Leaf surface of all foliage elements was calculated from needle dimensions and counts on a branch-by-branch basis. The 7-ft tree was comprised of 63,192 needles, with a combined surface area of 223,000 cm^2. Stem and the 60 first order branches of this tree had an additional surface area of 30,800 cm^2, which is not included in this analysis. These large diameter elements will be shown relatively ineffective in accumulation.

TABLE 1.--CHARACTERISTICS OF TEST OBJECTS

Type of object	Diameter in millimeters	Number of surface elements	Surface area in square centimeters
Cylinder 1	3	1	110
2	7	1	230
3	19	1	501
4	28	1	931
5	59	1	2,165
Alpine fir needles (branch)	[a] 2.0	928	826
Lodgepole pine needles (branch)	[a] 1.5	185	940
Lodgepole pine needles (tree)	[a] 1.5	63,192	223,000

[a] Mean diameter

Accumulation rates per square centimeter of surface of the test cylinders at various times on March 4 and March 5 are shown in Figs. 1 and 2.

Rime

The plot for March 5 (Fig. 1) indicates a major disparity between the accumulation rates on the different diameter cylinders when rime was predominant. The smallest diameter cylinder was most efficient in accumulation in all cases on a unit surface area basis.

Theoretical consideration of this accumulation process initially applied to rime accumulation on aircraft wings by Langmuir and Blodgett (4) produced equations not only

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[3] Light gage, plastic cylinder, hollow except for solid 3-mm diameter.

capable of describing the efficiency of accumulation but relevant to the self-limiting phenomena as well. A critical dimension for growth cessation expected under constant conditions of droplet size and wind flow can be specified (2) as:

$$R_c = 1.03 \times 10^4 Vr^2$$

where

V = wind velocity ($m\text{-}sec^{-1}$)

r = droplet radius (μ)

R_c = critical radius (cm)

In this instance the 59-mm diameter cylinder appears to approach the critical radius under these conditions in all except the 0710 sample. The reason for increased efficiency of the larger cylinders at this 0710 sample time cannot be determined. This is a 6 hour average, and a record of wind velocity on the hourly basis is not available during this period. Slightly increased accumulation appears for the 59-mm diameter at 2255 hr, which is also unexplained.

With these data from the test cylinders, it is possible to estimate how a cylinder equivalent to a 2-mm diameter needle element would have accumulated rime for comparison with performance of actual foliage. Table 2 presents measured accumulation rates for the pine branch, pine tree, fir branch (columns 4, 5, and 6, respectively) and an estimated rate for a 2-mm needle element (column 7). From these data and weight increments of the sample tree (column 8), effective surface of the tree (column 9) and its accumulation efficiency (column 10) can be calculated.

For the first sample period to 2225 hr, the sample tree appears to be exhibiting an effective surface nearly equal to the measured surface area of 223,000 cm^2. The next sample period to 2325 indicates an effective surface area almost twice this amount--555,000 cm^2. This is likely due to the 2-mm diameter element overestimating the actual needle diameter. (Most needle diameters measured on this tree did not exceed 1.5mm). Most important, however, are the next three periods during which the effective surface dropped to about one-fifth of the initial rate. This dramatic reduction in effective surface indicates the rapidity with which the aerodynamic profile of the foliar elements changes with accumulation. The efficiency of the rime accumulation process decreased to roughly 10 percent of the maximum exhibited by the 2325-hr sample.

All natural foliage elements show similar trends in accumulation rate (columns 4-6) during this period, suggesting that the diminution of collection efficiency was taking place in all three samples.

In a similar situation where matched sample trees were compared in a snow-covered versus a snow-free state, the reduction in efficiency in rime accumulation by prior snow cover was to about 15 percent of the snow-free sample. It therefore appears that any prior accumulation of snow or rime reduces the ability of the foliage to accumulate additional rime. Both the radial enlargement of needles and a more aerodynamic profile to the impinging airflow effectively modify the process.

Hoarfrost

Growth of hoarfrost on objects occurs in a manner quite in contrast to rime accumulation. Hoarfrost appears as crystalline growth from a near saturated atmosphere at temperatures below freezing. Quite frequently temperatures are lower than those common to rime. On the March 4 sample day, hoarfrost predominated in the study area--clear skies and low windspeeds aided foliar radiative loss at the ambient temperature near -12° C.

Though smaller cylinders were slightly more efficient, observed hoarfrost accumulation rates (Fig. 2) were relatively constant over the range of cylinder diameters.

The rates on the test cylinders are in general higher than during the rime event except for the smallest diameter. If a collection rate equivalent to that of a 2-mm cylinder for these sample times is assumed, calculation of the effective surface of the sample tree can also be made (Table 2). This was found to be severely limited. Only one-tenth to

TABLE 2.—MEASURED ACCUMULATION RATES; CALCULATION OF EFFECTIVE SURFACE AND PERCENTAGE EFFICIENCY OF WHOLE TREE (BASED ON ESTIMATED 2-MM DIAMETER CYLINDER)

			Accumulation rate, g cm^{-2} hr^{-1} x 10^{-4}						
Precipitation (1)	Date (2)	Time (3)	Pine branch (4)	Pine tree (5)	Fir branch (6)	2 mm needle element (estimate) (7)	Weight increment (tree) g hr^{-1} (8)	Effective surface cm^2 (9)	Percentage efficiency (10)
Rime	March 5	2125							
	"	2225	8.50	8.96	11.25	7.5	199.8	266,400	119
	"	2325	9.08	18.66	10.89	7.5	416.2	555,000	248
	March 6	0025	3.93	5.97	4.23	20.0	133.2	66,600	30
	"	0125	-5.10	-1.49	-3.51	---	-33.2	---	---
	"	0710	21.75*	13.19*	23.20*	55.0*	294.1*	53,500	24
	"	0810	9.86	14.93	9.56	60.0	333.0	55,500	25
Hoarfrost	March 4	1855							
	"	1955	3.08	0.29	3.02	19.5	6.6	3,400	1
	"	2055	4.78	2.08	4.47	21.0	46.6	22,200	10
	"	2155	5.33	3.58	4.60	24.0	79.9	33,300	14
	"	2255	5.76	2.68	5.81	18.2	59.9	32,900	15
	"	2355	5.10	3.28	5.20	20.5	73.2	35,700	16
	March 5	0055	4.36	0.89	4.35	14.0	19.9	14,300	6
	"	0155	4.57	1.79	4.84	20.0	39.9	20,000	9
	"	0755	3.29*	0.79*	3.02*	20.0*	17.6*	8,900	4

* Mean for six hr.

---Not calculated, melting on all samples.

(9) Calculated as (8)/(7).

(10) Calculated as (9)/223,000 (actual surface area).

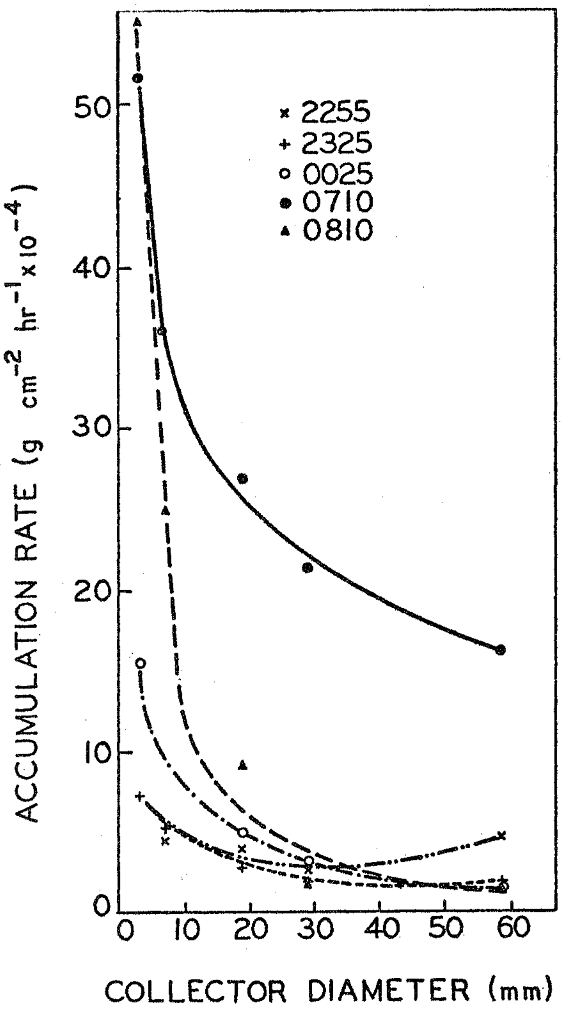

Figure 1--Rime accumulation rates on cylinders of different diameters, March 5, 1970.

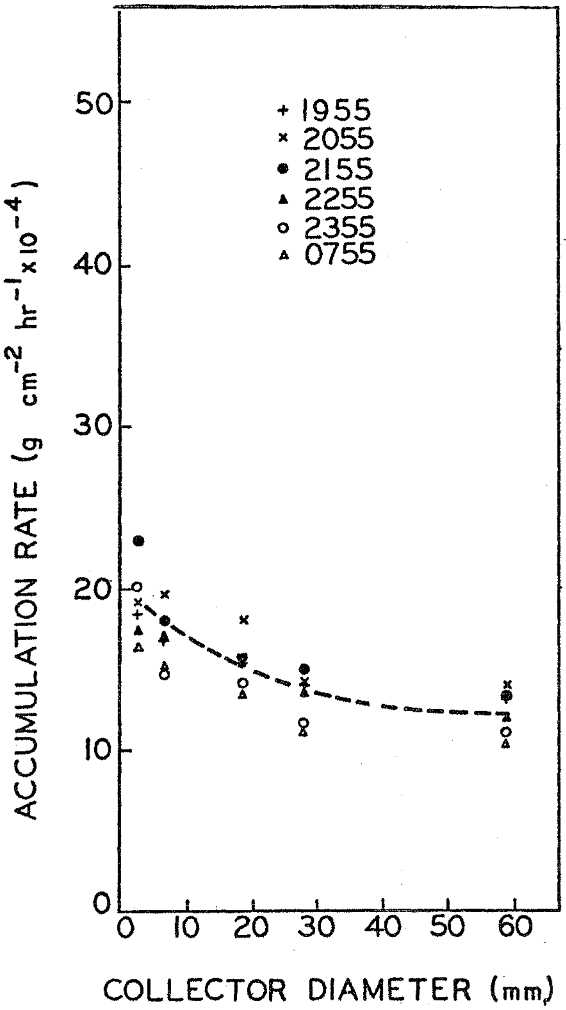

Figure 2--Hoarfrost accumulation rates on cylinders of different diameters, March 4, 1970.

one-twentieth of the actual surface of the tree would be sufficient to produce these weight increments predicted on the basis of isolated samples. The efficiency of the tree remained relatively constant and low throughout the night.

A key difference between the tree and the test cylinders is the isolation of the latter. Heat loss from the interior surface of the needle fascicles and branches is restricted by progressive depth into the tree canopy. Only the outermost surfaces are capable of continued heat loss to fall below ambient dewpoint. Sublimation releases additional heat which must also be dissipated. Even the test cylinders, though similar in their accumulation rates, show the effect of improved heat transfer in the smallest sizes.

Heat transfer theory indicates that heat loss in cases of forced convection on cylindrical elements is approximately inverse to the square root of their diameter (3). Though this provides an explanation for the different accumulation rates on the test cylinders and offers some insight to the poor collection performance by the tree canopy, foliage systems are too complicated to treat rigorously at this time.

Though reasonably similar accumulation rates on the natural elements were observed for rime, Table 2 (columns 4, 5, and 6) indicates a contrasting pattern developed in the hoarfrost event. The smaller elements (branches) exhibited similar accumulation rates, but at roughly twice the full tree rate. Mutual interaction of the needles is occurring, but to a lesser degree than on the full tree.

Summary and Conclusions

Simplification of form, and consequent modification of the air stream with continuing accumulation, accounts for rapid changes in the efficiency of rime accumulation on the foliage samples. This process is repeated within each successive rime event if trees are cleaned between events by melt or mechanical action. Apparently maximum amounts of rime are limited both by foliage characteristics, including size and spatial arrangement, and by elements of the impinging airstream such as windspeed and droplet size. Previously intercepted snow greatly reduces accumulation of rime by reducing the collection efficiency of the branch elements.

Within the initial 12 hr of these collections, a distinct difference between tree species did not appear, based on the small branch sample. Although the fir has a more compact needle mass, the narrow needle apparently compensated for decreased throughflow of moisture laden air.

Efficient hoarfrost accumulation requires continual heat loss by exposed elements for their temperature maintenance below the dewpoint of the surrounds. This process is most favorable to the smaller branch elements. Small branch samples of both species were several times more efficient per unit surface area in accumulating hoarfrost than the whole tree.

A number of aspects of these accumulation processes remain to be investigated. Among them are the role of ventilation of interior canopy elements, dissipation of heat of fusion and sublimation, and changing heat transfer rates with changing shape, size, and orientation of branch elements.

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