Transport of Intercepted Snow from Trees During Snow Storms

David H. Miller

U. S. FOREST SERVICE RESEARCH PAPER PSW-33

Pacific Southwest
Forest and Range Experiment Station
Berkeley, California

1966

Forest Service - U. S. Department of Agriculture

Foreword

The West looks to winter snowfall for much of its water, and there is a good deal of evidence from Forest Service and other research that management of mountain lands for wood, forage and recreational amenities can affect the accumulation of snow into a long-lasting pack. Studies of the physical processes that influence this accumulation, however, have lagged behind empirical studies.

To help research workers interested in planning future basic studies, Dr. Miller has reviewed past research related to the basic processes by which intercepted snow is transported from tree branches during periods of snowfall—the second step in a complex chain of events that affect the accumulation and melting of snow.

This paper is the second of several reporting results of his investigation. The study was part of the cooperative snow research program of the Forest Service and the State of California Department of Water Resources. Valued aid has also come from the University of California at Berkeley, and from the U. S. Army Cold Regions Research and Engineering Laboratory.

—JOHN R. McGUIRE, *Director*

Miller, David H.
1966. **Transport of intercepted snow from trees during snow storms.** Berkeley, Calif., Pacific SW. Forest & Range Exp. Sta. 30 pp. (U.S. Forest Serv. Res. Paper PSW-33)

Five principal processes by which intercepted snow in trees is removed during snow storms are described and evaluated as far as data permit: vapor flux from melt water, vapor flux from bodies of snow, stem flow and dripping of melt water, sliding of bodies of intercepted snow from branches, and wind erosion and transport of intercepted snow. Further research is suggested to evaluate each mass-transport process and to determine how it is affected by atmospheric and forest conditions.

116.11:111.784

Miller, David H.
1966. **Transport of intercepted snow from trees during snow storms.** Berkeley, Calif., Pacific SW. Forest & Range Exp. Sta. 30 pp. (U.S. Forest Serv. Res. Paper PSW-33)

Five principal processes by which intercepted snow in trees is removed during snow storms are described and evaluated as far as data permit: vapor flux from melt water, vapor flux from bodies of snow, stem flow and dripping of melt water, sliding of bodies of intercepted snow from branches, and wind erosion and transport of intercepted snow. Further research is suggested to evaluate each mass-transport process and to determine how it is affected by atmospheric and forest conditions.

116.11:111.784

Miller, David H.
1966. **Transport of intercepted snow from trees during snow storms.** Berkeley, Calif., Pacific SW. Forest & Range Exp. Sta. 30 pp. (U.S. Forest Serv. Res. Paper PSW-33)

Five principal processes by which intercepted snow in trees is removed during snow storms are described and evaluated as far as data permit: vapor flux from melt water, vapor flux from bodies of snow, stem flow and dripping of melt water, sliding of bodies of intercepted snow from branches, and wind erosion and transport of intercepted snow. Further research is suggested to evaluate each mass-transport process and to determine how it is affected by atmospheric and forest conditions.

116.11:111.784

Miller, David H.
1966. **Transport of intercepted snow from trees during snow storms.** Berkeley, Calif., Pacific SW. Forest & Range Exp. Sta. 30 pp. (U.S. Forest Serv. Res. Paper PSW-33)

Five principal processes by which intercepted snow in trees is removed during snow storms are described and evaluated as far as data permit: vapor flux from melt water, vapor flux from bodies of snow, stem flow and dripping of melt water, sliding of bodies of intercepted snow from branches, and wind erosion and transport of intercepted snow. Further research is suggested to evaluate each mass-transport process and to determine how it is affected by atmospheric and forest conditions.

116.11:111.784

Contents

Acknowledgments

I wish to acknowledge the help of Professor S. Ogihara with interpretation of the study by the Meguro Forest Experiment Station, and of Clark E. Holscher, Kenneth R. Knoerr, Arnold Court, Henry W. Anderson, Nellie Beetham Stark, A. J. West, Lloyd Gay, B. C. Goodell, Marvin D. Hoover, and others who took the time to review and criticize earlier stages of this study.

The Author

DAVID H. MILLER has been studying problems in snow hydrology and meteorology for more than 20 years—in operations work of the U.S. Army Corps of Engineers (1941–43) and in research with its snow studies (1946–53), and with the U.S. Forest Service (1953–64). He earned bachelor's (1939) and master's (1944) degrees in geography and meteorology at the University of California at Los Angeles, and a doctorate (1953) at the University of California. Dr. Miller is now on the faculty of the Department of Geography, University of Wisconsin, Milwaukee.

Forest covers much of that portion of the earth that receives some of its precipitation in the form of snowfall. Yet many questions about the amount of snowfall that penetrates forests to reach the soil surface remain unanswered. In some places, as Seppänen (1961) points out, more snow accumulates in forest than on open locations, and in other places less; the relation differs in different years. The diversity of forms taken by tree groups, the diversity of forms of snowfall and of conditions in which it is delivered to forest, and the inadequacy of sampling and measuring techniques make it impracticable to settle the questions by direct measurement. However, it has proved difficult to find simple but universally applicable relations between snowfall in forested and unforested places that might serve purposes of prediction. This failure leads us to suspect that the action by which forest receives, intercepts, holds, and disposes of snowfall is not a simple, unitary phenomenon but rather a series of events or processes, which require individual study.

In this belief, I have in an earlier report (Miller 1964) examined processes involved in the delivery of snowfall to forest, and continue in this paper by examining five basic processes by which this intercepted snow is transported from the branches during periods of snowfall. My aim has been to determine the general magnitude and hydrologic significance of each process, and its response to conditions of weather, vegetation, and site.

Snowflakes deposited in the crowns of trees form aggregations of all shapes and sizes, depending on the streamlining action of the wind and the characteristics of the supporting surfaces. Changes do not end with deposition; snow on the ground experiences many changes in physical properties, and it is likely that accelerated changes are experienced by small bodies of snow suspended in a moving air stream, freely exposed to a continuing exchange of mass and energy with it and with surrounding surfaces. The bodies of snow lose mass by attrition of the various media of transport, which act through such mechanical forces as wind pressure and gravity and such thermodynamic forces as radiative and convective heat exchange. Wind pressure tears a cohesive snow body apart and distributes its fragments far downwind. Thermodynamic forces facilitate the transport of intercepted snow by changing it to a more mobile physical state—to melt water or to vapor.

Partial melting of snow that releases its hold on the branches and lets it slide off works faster than does melting that goes to completion, with concurrent removal of the melt water by stem flow or dripping from branch tips. Removal by evaporation requires still more heat than melting, but confers added mobility; vapor diffuses downward or upward from the zone of the tree crowns, depending on the gradient of vapor pressure and the intensity of turbulent mixing in the air stream. And vapor is carried farther from the original body of intercepted snow than is melt water or partly-melted masses of snow that slide to the ground.

Investigation of the processes of mass transport of water applies the principles of continuity (the water budget) and of conservation of energy in a system (the heat budget). These principles constitute two frameworks in which we can examine the complicated events involved in the transport of intercepted snow from tree crowns when snow is still falling.

This paper also discusses other kinds of data that fall outside the principles of continuity and conservation of energy, for the sake of the indirect information they can provide about the sizes of the mass-transport processes and the factors that influence them. There is, as Goodell (1959) states, a deficiency in "basic data to test hypotheses" and of suitable instruments. The data discussed here include measured or estimated weights of intercepted snow at the end of storms, reports of snow breakage and probable amounts of critical snow loads, and calculations of the difference in accretion to the snow mantle at sites in and near forest, involving certain errors inherent in such calculated differences. However, emphasis has been put on events occurring during single snow storms, rather than upon seasonal or yearly summing of end-products or other resultant effects. A wide range of research in peripheral fields of inquiry has been drawn upon in order to evaluate the mass-transport processes.

Wind Erosion

Air movement during snowstorms exerts mechanical forces upon intercepted snow by shaking its supports, eroding the masses of snow, blowing them off their supports, and transporting the fragments downwind. Snow masses are usually built up relatively slowly, but torn apart and blown away abruptly. Hirata (1929) notes that one reason for interception processes to differ between snow and rain is that snow readily falls off the branches. Assessment of the falling and blowing processes has, however, seldom been carried out in the field. Nor has it ever been done in wind tunnels, although the processes lend themselves to experimentation in controlled environments and might be understood by an extension of existing theory on snow transport by drifting.

Wind forces that act directly on snow masses in tree crowns are set in operation by large-scale and meso-scale motion systems in the atmosphere. This momentum is transmitted downward to the canopy and through it as a succession of micrometeorological flows and forces within the space occupied by tree crowns. However, it is not yet clear how existing knowledge of the spectrum of turbulent eddies in the air stream can be used to reconstruct the field of forces within the forest, nor how information about the drag of forest on air stream can be converted, with the aid of data on aerodynamic and mechanical properties of trees, into information about vibration as a factor in the removing of intercepted snow from the branches. Wellington (1950) shows that snow bodies in deciduous trees are often less affected by direct action of the wind than by its indirect action in shaking the tree crowns, which occurs with gust periods of the appropriate length. Eddies of somewhat greater length cause wind speed to alternate between quiet periods when snow accumulates and gusts that blow it away.

Salamin (1959, 1960) describes, with excellent photographs, intercepted snow in various shapes. He points out that if snow is held by conifers in form of cushions or balls, it falls less easily than does snow held by deciduous trees. If loose snow occurs in firs, it falls gently when it blows off the trees, and is more likely to be carried into an opening. He feels that most intercepted snow falls or blows off tree branches.

Heikinheimo (1920) refers to the fact that trees below the cloud base receive snow unmixed with rime, and are easily blown clear. Sakharov (1949) describes snow blowing from a spruce upper story but not from spruce reproduction. Goodell (1959) found that only a third of the fresh, cold, dry snow intercepted by a spruce tree could be shaken out of it, or about the same fraction of rain that Grah and Wilson (1944) could shake off a small pine. Pruitt (1958) reports that a windstorm had only minor effect on cohesive intercepted snow. Although we have no quantitative information either on cohesion of snow bodies or the erosion power of wind on them, it should not be difficult to get experimental data to extend existing theory of erosion of a snow cover.

Cionco's (1965) model for air flow in vegetation has an attenuation coefficient of the wind speed profile down into the canopy that is related to drag of the top surface. His model could provide a means of formulating the eroding power of the wind on snow masses at different levels in the canopy. This coefficient, however, depends on leaf type, density, and rigidity—properties not yet quantified for many kinds of forest.

A counterpart of wind action in plastering sticky snow onto tree foliage is found in its transport of intercepted snow, a phenomenon often remarked and seldom measured. Snow masses cohere in winds below a threshold speed, then may blow off as clumps that do not completely disintegrate during the time they are airborne. Snow that develops strong cohesion can accumulate in masses large enough to catch the wind; Morey (1942) observed that heavy accumulations are more likely to blow off than light. Cramer (1960) made similar observations in a study of helicopter effects. Strong adhesion of snow to foliage resists blowing, and is affected by snow temperature.

From the only available data on wind effects (Govt. Forest Exp. Sta., Japan 1952), a critical speed for snow on an isolated tree in a relatively warm storm is reported as about 3 m./sec. This force removes the more vulnerable snow, about half the total load. When wind rises to this speed during a storm, it blows intercepted snow off, as is illustrated in the storm of February 19–22 (fig.

3 in Govt. Forest Exp. Sta., Japan 1952), in which wind speed increased to 3 m./sec. between midnight and 0400 on February 20, and snow load decreased from 10 kg. to 5 kg. When lighter winds followed, snow load increased to 21 kg. by 1000. Higher wind speed near the end of the storm resulted in another decrease in load. Blowing of intercepted snow out of the experimental tree in 11 storms is shown (fig. 10 in Govt. Forest Exp. Sta., Japan 1952) by a trend line from zero loss at a wind of 1 m./sec., to loss of half the intercepted snow at 3 m./sec.

Takahashi (1953) notes that intercepted snow on the sloping branches of Cryptomeria does not accumulate at wind speeds higher than 3.5 m./sec. If snow falls into a layer of quiet air near the surface, interception may be larger than in a mountain region that projects up into the moving stream of air. A peak that projects into the cloud level, however, is in a region of riming and exposed trees become heavily loaded—though not with snow alone.

From the Fort Valley studies, Pearson (1913) describes the large deposits of snow in crowns of ponderosa pine, especially in still air and when snowfall was moist. He found that the bulk of it blows off into the openings, less of it melting and evaporating; he ascribes deeper snow in the openings to this effect. Amplifying this, Jaenicke and Foerster (1915) mention occasional heavy deposits in the crowns that mostly blow off into openings, but report that there was no accurate measure of them.

In stands with high crowns, such as the virgin pines at Fort Valley, the wind profile often displays a secondary maximum in the trunk space, where large quantities of snow could be carried. In forest types with many openings, a large downward transport of momentum would support rapid low-level wind speed and snow transport. In stands where a dense, continuous canopy separates the trunk space from the free air, light air movement and slow transport of snow can be expected. Sakharov (1949) estimates that 25 to 30 per cent more snow reaches the ground under a single-storied spruce stand subject to wind action than under a two-storied stand in which the under-story is not shaken or exposed to wind action.

Snow blown out of tree branches differs from the original snowflakes because it has undergone changes caused by close contact. But the length of stay of snow in the branches and the changes occurring during this time are not known.

Effects of Wind on Snow Loads

Some reports on snow-broken trees after heavy storms indicate the total effects of wind on snow loads as a composite of wind delivery to trees and transport of intercepted snow from them in particular topographic sites. Suominen (1963) made a study of a forest in southern Finland devastated in the winter of 1958–59 by snow loads that must have exceeded 30 mm over wide areas. Damage was determined by surveys made a few days afterward (Seppänen 1959). Suominen notes that trees at the edges of fields or lakes suffered less damage than those on lee edges or within forest bodies. In the belt from the edge to 25 m. within the forest, 41 percent of the stands escaped damage, but only 15 to 17 percent escaped in stands farther than 50 m. within the forest. Suominen's conclusion that silvicultural management had only a minor effect on the distribution of damage confirms the importance of exposure to wind. In stands exposed to a free sweep of wind, much of the intercepted snow was blown out of the crowns before it broke the trees. Exposure of windward-edge trees to additional impaction of snow was less important than exposure to the power of the wind to move snow from the crowns. This finding indicates perhaps, that in this storm a relatively minor role was played by adhesion of snow to branch surfaces.

Damage by snow breakage in a storm on the east shore of the Sea of Japan in December 1960 (Sugiyama and Saeki 1963) was heaviest to stands on lee slopes, especially if they were sides of valleys; less damage occurred to forest on plains, and still less to those on windward slopes. Trees on exposed edges of stands, mostly plantations, similarly incurred less damage than did trees on the lee sides and around openings. Although snow in this storm was of moderate density—0.10 to 0.12—and fell in "mild" winds at temperatures slightly below the freezing point, adhesion of snow on branches apparently was a minor factor in comparison with the effect of wind in removing excess snow load. Similar heavy damage on steep lee slopes was reported by Hirata and Hotta (1951) from a storm on the opposite side of Honshu, Japan.

Falling speeds and surface/volume ratios of the clumps of blowing snow determine how far the clumps will be carried in the air stream. Field research on wind during storms should provide a pattern for wind-tunnel simulations. Mesometeorological phenomena include long-period pulsations, which permit snow to accumulate and become cohesive in the quiet periods, and be carried away in the gusts, if cohesion does not become too strong. Pulsations of a period of several minutes are determined by the movement of storm cells in which kinetic energy is transmitted downward.

Wind in the trunk space, however it may be related to wind above the tree crowns, is the vehicle for transporting snow detached from the bodies of snow in the branches. Its turbulence affects how much snow it can carry as suspended load. The volume of solid particles in the air during blizzards on the plains is measured by drift meters near the ground, and this method is applicable to forest sites. Measures also can be made of such relevant properties as density, aggregation, and cohesion of the blowing clumps of snow. The transport of single snowflakes in the air stream above the forest canopy might be compared with the slower flow of larger particles in the stream below the canopy, for wind-tunnel modeling.

The height from which intercepted snow is blown affects its movement. High crowns give it a longer period of travel while falling and allow higher wind speeds, as is suggested by the notes on snow blowing made by foresters in the Fort Valley observations among virgin ponderosa pine (Jaenicke and Foerster 1915, Pearson 1913). Gay[1] notes a similar effect of canopy height in Australia, in studies of tall mature mountain ash *(Eucalyptus delegatensis),* immature ash, and low snowgum *(E. niphophylla).*

The duration of airborne transport of a snow fragment has a bearing on its evaporation while in this vulnerable situation. Diunin's (1961) experiments on evaporation of drifting snow particles may serve as models for work with blowing fragments. The larger particles have the advantage of greater effective size and a shorter period in suspension to reduce their potential evaporation.

Field observation of suspended snow particles suggests to me that a considerable amount of gravity flow takes place on slopes during snowstorms, and redistributes snowflakes as well as fragments of intercepted snow blown from branches. West's (1961) measurements of snow cover that was deeper (by 80 to 300 mm. more water equivalent) in downslope than in upslope sectors of small openings in forest, which he interprets on a thermodynamic basis, seem to me also to be explainable as gravity flow of the density-current type.

Mass transport in mosaic landscapes of tree groups and openings present a difficult problem in measurement. To the practical questions of performance and locating of precipitation gages as well as to a physical understanding of snow transport by wind, such measurements are basic. The air stream receives snow fed into it intermittently from above, but deposits snow more or less continuously beneath it, where—as Diunin (1961) shows—it evaporates only very slowly. The process is similar to that of a liquid current traversing a region of alternating sources and sinks of heat. This process might be useful in laboratory modeling of the situation.

Role of Forest Canopy

The role of forest canopy when snow is delivered to or blows out of it may resemble that of shelterbelts or screens of crop-plant stalks used to manage the winter-time distribution of snow drifted by the wind. If screens 60 to 80 cm. high and 3 to 4 meters apart increase snow depth to 50 to 60 cm. and provide the most uniform cover, would tree belts 3 to 4 meters high, 20 to 30 meters apart, be most appropriate for accumulating snow in depths of 300 cm.—representative of depths in many western ranges? Diunin's (1961) discussion of spacing of shelter belts and other results of experiments with drifting snow on the steppes also has implications for management of mountain lands. It may be possible to influence, by changes during wind transport, not only the gross pattern of deposition of snow but also such properties as its grain size, density, thermal conductivity, and albedo.

The influence of forest on land outside the direct shade of its canopy is exerted through the snow-transporting process as well as by movement of heat and vapor; both forest and open areas have to be included in a research site. As land managers tend to move away from great acreages in pure stands of one species to meet such other objectives as developing wildlife habitat, forage, and recreational amenity, or to accommodate harvesting methods that create small openings for regeneration, the question of the transport of blowing snow in mosaic patterns of

[1] Gay, L. W. *The influence of vegetation upon the accumulation and persistence of snow in the Australian Alps.* 1958. (Unpublished thesis on file at Australian Forestry School, Canberra.)

tree groups and openings becomes increasingly vital.

Snow that blows into openings in the forest or into bordering fields (Baldwin 1957 and Morey 1942, among many authors), increases the advantage of these places in collecting snow. Since phenomena measured in openings have come under the influence of forest, they do not form a true basis for comparison of forested and open areas. In forest stands with openings, blowing of intercepted snow means that less snow falls to the forest floor. Hoover (1960) has asked, "How much of the snow in the openings was blown off the foliage of surrounding trees?" and from this he questions the "conventional emphasis" on snowfall interception in Rocky Mountain hydrology.

The finding that eddies smaller than 100 m. are the prevailing size in a snowstorm (Rogers and Tripp 1964) suggests a critical dimension for openings receiving excess snowfall. This is in general agreement with the findings of Costin, *et al.* (1961). Exploratory work with a dense network of wind sensors, including bi-vanes, in and above trees of reproducible dimensions and patterns, would provide the fundamental background against which can be studied the processes of snow transport themselves.

In studying the distribution of snow, it is necessary to study the whole forest. Tree groups and openings are interdependent members of the whole; interception in tree groups is affected by air circulation in nearby openings, just as interception in openings is a function of the bordering trees. Snow that fell on tree branches may in the passing of the next eddy be blown away; snow that fell in openings is sheltered from the wind, and is less subject to being shifted around. In this exchange, the openings are not the losers.

Snow board measurements of snowfall were made after each of five storms in the Beaver Creek basin, Arizona by Ffolliott, Hansen, and Zander (1965). In openings to the lee of a stand of uneven-aged ponderosa pine of 40-ft. height, the excess deposit of snow within 100 ft. of the edge was about 15 cu. ft. of water equivalent in a foot-wide cross-section extending outward from the edge of the forest. This mass represents more than an inch of water equivalent transported from the nearest 150 ft. of pine stand, and is a sizable fraction of the snowfall intercepted by the pines.

Research on snow drifting as a function of wind speed, turbulence, and surface roughness is applicable to the blowing of intercepted snow from the tree crowns. Wind-tunnel and water-flume (cf. Theakston 1963) studies that have been successful in determining the effects of shelter belts, fences, and structures on snow transport near the ground required correct simulation in the laboratory of particle size and density, turbulence-element sizes, and roughness factors. These studies also have determined the correct reproduction of the distribution of drifting snow with height, shelter belt or fence height, and permeability.

The study by Shiotani and Arai (1954) appears especially relevant to the problem of blowing of intercepted snow because they considered crown height, depth, width and other dimensions of the trees. Drifting snow differs from wind transport of intercepted snow in vertical concentration of the solid component, in particle size and density, in the manner of introduction of the solid flow into the air, and in the role of turbulent eddies in keeping particles in suspension rather than detaching and lifting them from the ground. However, with valid scaling, laboratory experiments will make it possible to develop an adequate theory of wind transport of intercepted snow from which could be determined not only the redistribution it produces in the water budget, but also the lengths of paths of blown fragments and the probability of their evaporating and undergoing other changes while airborne.

Intercepted Snow Sliding from Tree Branches

Intercepted snow may slide off tree branches without wind intervention if the branches provide an unstable or slanting support. Bodies of snow balanced on the ends of branches bend them into steeply sloping surfaces or produce elastic deformation. Because both situations are unstable, the branches tend to release potential energy and return to normal when disturbed. The triggering action may be the impact of snow falling from a higher branch, or the rebound of a lower branch that was suddenly unloaded, or rapid melting of the bonds holding snow on the sloping surface.

These events release an instability that becomes greater the more heavily the branch is loaded with snow, and the farther the snow is balanced away from the trunk of the tree. The resulting readjustment of the intercepted snow in a forest crown is continuous throughout a storm; bodies of snow are continually being built up and producing local instabilities that, almost at random, are released. At times, the snow on many elastically stressed branches all through the forest may be set off all at once by a gust of wind. But the most widespread releases of snow masses are caused by the simultaneous melting of the frictional bonds holding them on the branches. This transport process is important in heavy snow storms, but measurements of it are scanty.

Where snow falls from warm maritime air masses—as in Japan, Western Europe, and Western North America—it often falls through a layer of air that has a temperature above the freezing point. Experiments on intercepted snow in Japan (Govt. Forest Exp. Sta., Japan 1952; Watanabe and Ôzeki 1964) took place at air temperature up to +2 or +3 C; Ratzel (1889) and Aniol (1951), report that about 40 percent of snow in Germany falls at air temperatures above freezing; in the crest region of the Sierra Nevada in California, snow is reported at air temperatures to about 35° F., and a third of it falls at temperatures above freezing (Miller 1955, p. 25).

A snowflake survives its fall through the warm layer of air if it reaches the relative safety of the cold snow mantle soon enough. Its chances of survival are poorer when it remains in the warm layer of air, as it does when intercepted by tree foliage. For a time, heavy snowfalls accumulate faster than they melt, but a slight rise in temperature starts the melting of the accumulated masses, particularly at places where they are most vulnerable—the points of attachment to their supports.

Melting in the warm air at the level of the tree crowns may be increased by solar radiation, which is not always low during snowstorms. In the Sierra Nevada, daily amounts during storms often exceed 50 langleys (Miller 1955, p. 25), about one-sixth of the clear-day amount in winter, and enough to compensate for net loss of heat from the snow by long-wave radiation. Heat supplied by warm air and solar radiation during a storm is usually less obvious in complete melting of snow masses than in partial melting that lets them slide off the branches. The large decreases in snow load (Govt. Forest Exp. Sta., Japan 1952) that occur after the supply of relatively small amounts of heat indicate the sliding of partly-melted snow masses off the branches. In one storm, the snow loads decreased by 10 mm. in a few hours, in response to increased air temperature or solar radiation. Average decreases usually are smaller.

Though rapid, removal of intercepted snow by sliding is not instantaneous because it takes time to melt the bonds of adhesion holding the snow mass to the pendant branches, or to produce enough free water to lubricate the zone of frictional contact. The cumulative effect is shown by the fact in some experiments that, although the total load subject to sliding decreased for several hours, the hourly weight of snow released remained nearly uniform. This transport process did not display an exponential decrease.

Heat Requirements

Sliding of partly melted masses requires relatively little heat, considering how much snow is transported. If it is assumed that melting of 20 percent of the intercepted snow releases the hold of the rest on the branches, hourly rates of decrease of snow load of 1 to 2 mm. represent a heat requirement, strategically applied, of 2 to 3 ly/hr. By using potential energy stored when snow lies on sloping branches or imposes elastic loading on them, this mode of mass transport requires only a small amount of thermal energy.

In one storm (shown in fig. 11 in Govt. Forest Sta., Japan 1952), during a day on which snow fell with light wind through the daylight hours and air temperature rose from −2 C to +1 C, the snow load on the Cryptomeria tree being weighed, expressed in mm. of water equivalent, decreased from about 25 mm. at 1000 hours to 2 mm. at 1500 hours. The rate of decrease was linear, not exponential with time. In an average of several storms that continued from night into the daylight hours, an average load of 8 mm. that had persisted from 0400 to 0800 decreased after sunrise at an hourly rate of about 20 percent of the load still on the tree. Running between 1 and 2 mm./hr., this high rate of transport probably reflects the influences of both insolation and warm air.

Decrease in intercepted snow on the tree during daytime is related to insolation, which supplies some heat even while more snow is falling. Percentage loss of load in 13 storms plotted against insolation gives a graph (fig. 9 in Govt. Forest

Exp. Sta., Japan 1952) in which no storm falls below an envelope line extending from the origin upward at a slope of 0.9 percent loss of snow for each langley of insolation. This relation can be applied to estimate the ratio of heat supply to mass transported. With low radiation, the rate of loss of intercepted snow may be slow or fast, presumably depending on air temperature; with high radiation, it is always fast. (Air temperature was close below freezing in all experiments.) If the tree had, on the average, an initial burden of 8 mm. of intercepted snow and continued to receive new snow at a rate of 1 mm./hr., an hourly rate of net loss of 9 percent load corresponds, by the relation cited, to diffuse insolation incident at the rate of 10 ly./hr. Assuming absorption of 0.25 of the short-wave radiation and equilibrium in long-wave radiation, the cost of mass transport in radiative energy is calculated as 1.5 ly. for the release of 1 mm. water equivalent. This ratio between transport and insolation, with convective heat fluxes assumed to have no differential effect among storms, confirms the statement postulated earlier that release of intercepted snow occurs after about 20 percent of it has melted. Bodies of snow in unstable positions on branches may be released after less melting has occurred; those on stable supports may remain and melt in place for a longer time.

When air temperature is slightly above freezing, the joint effect of air temperature and insolation can be approximated by examining the hourly loss rate of 20 percent of an 8-mm. load of intercepted snow, cited earlier in this section, and estimating new snowfall at 1 mm./hr. The total loss of snow is then equal to 2.6 mm./hr. and its release by 20 percent melting requires 4.2 ly/hr. If 2.5 ly./hr. represents the contribution of insolation absorbed by the snow-covered tree, 1.7 ly./hr. represents the amount by which sensible-heat flux from air to snow exceeds latent-heat flux away from the snow.

In the storm of February 19–22 (fig. 3, in Govt. Forest Exp. Sta., Japan 1952), the load of intercepted snow on the tree remained constant at 12 mm. from 0800 February 20 through the rest of the day, while snow continued to fall and temperature rose nearly to the melting point. After midnight, the air became cooler, and the load of snow slowly increased until daylight, when air temperature rose to the melting point. In the ensuing 6 hours, while light snow continued to fall, 14 mm. of intercepted snow came off the tree—a rate of transport of nearly 3 mm./hr. Final disappearance of snow was associated with further warming to +4 C.

The effect of sensible-heat flux from warm air on disposition of intercepted snow is exerted jointly with that of latent-heat flux and condensation of vapor on the snow. High air temperature produces a steep temperature gradient from air to snow and a rapid flow of sensible heat. This heat is divided between melting and evaporating snow in dependence on vapor pressure, in accordance with the psychrometric relation. Since melting usually predominates over evaporation in this division of energy, and since it is more likely than evaporation to break the adhesion between snow mass and foliage, high air temperature usually favors the loosening and sliding of snow bodies. The study in Japan (Govt. Forest Exp. Sta., Japan 1952, p. 143) shows the role of temperature in rapid decreases of snow load during storms. In one storm, when air temperature suddenly rose 1 C.° above freezing, the loss of weight was 3 mm./hr. The decrease of weight, at first slow, then fast, suggests that a couple of hours of melting are needed before the snow masses begin to lose their attachments to the pendant branches of the tree. Takahashi (1953) reports that all intercepted snow drops off a tree with steeply sloping branches at air temperatures higher than +0.4 C., though not instantaneously.

Tree crowns are good media of heat exchange. Gates, Tibbals, and Kreith (1965) have derived coefficients of convective heat transfer from irradiated needles to air from wind-tunnel experiments, which show the effectiveness of this heat exchange. Similar experiments with broad leaves by Knoerr and Gay (1965) show that wind speed has a small effect on heat transfer, since the leaf-air temperature gradient changes in compensation. This compensation does not occur between air and snow.

As among the several processes of mass transport, the falling or sliding of interecepted snow is more likely to happen than removal by wind if air temperature is high. Blowing of snow is favored by low air temperatures, until the snow becomes cohesive or cemented to branches by refreezing after a brief warm period. Sliding of intercepted snow seems more closely associated with melting than with evaporation, which is slow to remove ice bonding the snow mass to the tree. Because melting is halted by low air temperature, the removal of snow by sliding is also reduced by low air temperature.

Heavy amounts of intercepted snow are likely to slide off conifers, according to Horton (1919), who compared conditions in winter and summer. Baldwin (1957) says that if accumulations are so heavy that they force spruce and hemlock branches to droop, the snow slides off. From his measurements in white pine, however, "the greater the fall of snow in any one storm, the higher the percentage intercepted." Branch stiffness of pine seemed to account for this difference.

The importance of transport of intercepted snow by partial melting and sliding from the branches is attested to by many studies. The species or varieties of trees that silviculturists believe to be well adapted to sites receiving heavy falls of wet snow and their meteorological corollary (rises of air temperature above freezing) are those with branch form that favors sliding. The Kammfichte—a variety of spruce—has a pendant habit, whereas the Plattenfichte—with stubby branches that support ice in glaze storms—is vulnerable to snow breaking (Anon., 1954). Watanabe and Ôzeki (1964) report smaller snow loads on *kumasugi*, a variety of Cryptomeria with branches that under load are depressed 20° or 30° below the horizontal, than on a variety with stiffer branches. Baldwin (1957) differentiates species that have stiff branches from those that droop enough to let snow slide off; pendant branches of a fir in the Rockies are termed an accommodation to heavy snow loads (Butters 1932). It is notable that these ascriptions refer not to a strengthening of the tree against snow but to a device by which potential energy can be easily released; the heavier the load has grown, the more easily it is released.

Sources of Heat

Heat supplied to intercepted snow during periods of snowfall comes primarily by convection, secondarily by radiation, and to a small degree by conduction. Convective heat flow is assured whenever air temperature lies above freezing, a frequent situation in many snow storms. At a temperature differential of 1°C., I calculate from wind-tunnel experiments on needles that provide data on the Reynolds and Nusselt numbers (Gates, Tibbals, and Kreith 1965) that a snow mass 1 cm. in diameter will receive a convective heat flow of about 5 ly./hr. If air filled with melting snowflakes can maintain a temperature of +1°C., this rate of heat supply will melt 0.8 mm. water equivalent per hour. The flux to larger bodies of snow is slower; otherwise, snow would melt faster than it accumulates on the ground in warm storms of mean snowfall intensity of 1 to 2 mm. water equivalent per hour. To the snow-shrouded tree of the experiments in Japan, the rate of heat supply by convection and condensation that I calculated earlier from the data on weight loss, 1.7 ly./hr., of which +3 might be sensible heat and −1 latent, is consistent with the few data we have on convective heat fluxes to and from an isolated tree.

Heat flux to intercepted snow by long-wave radiation during periods of snowfall is probably about the same as that emitted by the snow. In the short-wave lengths, winter measurements in the Sierra Nevada at latitude 39°N show that insolation on stormy days is about 50 ly. and midday intensities are 6 to 8 ly./hr. With an albedo of 0.67, newly intercepted snow in the tree crowns would have a net surplus of whole-spectrum radiation of 2 to 3 ly./hr., corresponding to a melting rate of 0.25 to 0.35 mm. water equivalent per hour.

Heat flow by conduction from the tree to intercepted snow occurs only if air temperature falls suddenly. If a cold snow storm following warm weather brings a temperature drop of 5°C., cooling of the biomass yields about 2 langleys, which would melt the first quarter millimeter of snow to be deposited. As cold snow continues to fall, the film of melt-water freezes and bonds the intercepted snow to the branches (cf. Heikinheimo 1920).

Advective components of the heat supply to snow have, like the radiative components, been included in research on melting of the snow cover, but mostly as residuals or in formulas with such empirical coefficients as those for film heat transfer. These coefficients cannot easily be transferred to snow masses, with their small, irregular surface areas. Advective heat transfer can be measured only by experimental instruments that are more appropriate to large meadows than small snow masses. Instruments in engineering wind-tunnel research on heat transfer may be useful in questions of heat exchange between the solid surfaces of a permeable medium and the moving air stream. Heat transfer by condensation of vapor on the snow presents more complicated instrumentation problems.

Stem Flow and Dripping of Melt Water

Melting of intercepted snow and subsequent removal of melt water during periods of snowfall by dripping off branch tips and flowing down the stems is minor in some forests and climates, large in others. If drainage through the branch system is adequate, the flow of melt water down the stems bypasses the snow mantle and enters the soil and perhaps directly into ground water; it enters a different hydrologic storage than the snow mantle represents—a storage from which there is less delay and more winter-time outflow into the streams than from melting at the surface of the snow cover.

The hydrologic implications of stem flow were recognized as early as the 1890's by Ney (1894, p. 18), who noted that drip of water from spruce branches corresponds areally to the shallow root plate, and that stem flow down a pine trunk can follow the tap root down to the absorbing roots. Melt water dripping from the ends of branches also has as much mobility as stem flow and may penetrate the snow mantle to reach the soil. Whether dripping or flowing occurs depends on branch form and attitude. Both forms at times represent important media of transport of water.

Measuring Stem Flow

Stem flow of intercepted rain is most commonly measured in summer, when heat is available to evaporate it as it moves along the drainage network of the tree. Consequently, the observed rates of flow near the ground may not indicate the amounts of flow generated in the crowns and may not correctly reflect winter conditions. Leyton and Carlisle (1959) stress the need for valid measurements of stem flow "during fog and winters with snow." Stem flow and dripping of melt water from intercepted snow are favored by humid, cloudy weather just above the freezing point. These same conditions favor melting over evaporation and also represent weather in which much snowfall is intercepted. In some climates, such weather is frequent in winter; Delfs (1954) speaks of long periods in the uplands of northwestern Germany when crowns of spruce remain wet and melt water easily becomes stem flow in measurable quantities, and his later report (1958) over several years' work confirms this. Eidmann (1959) reports stem flow in spruce as something less than 1 percent of precipitation. In relatively mild temperatures, Rowe and Hendrix (1951) found stem flow in pine to be about 3 percent of snowfall. In snow storms of six winters, stem flow averaged 1.5 mm. per storm. The heat required to produce this much melt water is 12 ly. per storm.

In deciduous trees, intercepted snow already lies *in* the drainage net, like rain that has fallen into stream channels; in conifers, it lies *on* foliage that slopes at many angles and may not connect with the central drainage network. Other hydraulic characteristics are the smooth bark of some hardwoods, such as beech. This indicates that only small amounts of channel storage are to be filled, and that channel roughness is small. However, Leonard (1961) reports that stem flow from northern hardwoods was negligible during snowfall periods.

In winter, stem flow is less likely to be measured than visually estimated at random, and often is assessed as negligible. But when air temperature lies near freezing and humidity may be so high that the melt water that corresponds to channel storage—the wetting value (Benetzungswerte) of branches and bark—is not evaporated quickly, then appreciable amounts of water may reach the ground by stem flow and dripping. The careful observations of stem flow by Hamilton and Rowe (1949) in chaparral during rain storms in which snowfall was occasionally intermingled led them to conclude that "snowfall appeared to decrease stemflow" during the storm. Because the periods of snowfall were usually "followed by intervals of rain in the same storm," they could not separate stem flow caused by melting of intercepted snow. However, since stem flow from rain was large, averaging 6 mm. per storm, the "decrease" mentioned might still indicate several mm. of stem flow in a snow storm and the succeeding rain.

Stem flow appears to be greater in marine climates, with large values of snowfall, heat supply, and humidity favoring the melting of intercepted snow. When heat is supplied to snow in the presence of high vapor pressure, evaporation is suppressed in favor of melting. Stem flow varies from winter to winter because of its dependence on storm temperatures and humidities, that is, the variable marine component in the climate. Rowe and Hendrix (1951) report that stem flow in pine varied from less than 1 percent of snowfall in one winter to almost 6 percent in another. No data are reported for individual storms, but the standard deviation of stem flow in the six winters was 1.8

percent. Stem flow varies over so large a range, from year to year, and from visual reports of "negligible" in some investigations, to measured values of several percent of moderately heavy amounts of precipitation in others, that estimates should be made with caution. There is need for more winter-time measurement of this transporting and distributing process.

Observing Drip

Dripping of melt water, like stem flow, is more often mentioned from casual observation than it is measured; subjective reports seem to be in conflict with the measurements that have been made. Is this a transport that by reason of its nuisance to field men is reported beyond its hydrologic magnitude? Or is it truly a means by which appreciable amounts of water move? The methods of measuring drip have been subjective and the sampling density required by the highly variable nature of the process is not known.

Drip observations should be accompanied by data on air temperature, humidity, and radiation; such information determines the relative roles of dripping, evaporation, and blowing in the disposition of intercepted snow. Methods of measuring stem flow are well known, although low temperature creates a problem. However, visual observation may not be adequate for deciding whether or not to set up stem-flow measurements, because stem flow is intermittent and may go unobserved.

Films of melt water on foliage are affected by its roughness, wetting coefficient, and geometrical pattern. These are parameters that have been considered qualitatively by students of rainfall interception. The subject of water films on foliage and bark might well be reopened where Horton (1919) left it, and in particular by use of such measurements as those Grah and Wilson (1944) made by weighing sprinkled plants. For example, their calculated depth of 0.08 mm. of water averaged over the total surface area of the foliage of young plants of *Pinus radiata,* when compared with similar measurements for other conifers, could be related to hydrophobic or hydrophilic properties of the surfaces; their laboratory determinations of removal by dripping and shaking are relevant to such questions of the disposition of melt water as: How thick is the film of melt water? How extensive is it, and how much water is stored in it? How does depth affect its movement, and how well does its movement correspond to overland flow, as related to detention storage on a drainage basin? How important are the surges in flow that some observers have noted, and how do they depend on bed friction? O'Loughlin's (1966) conclusion that evaporation from an entire draining film is independent of the rate of evaporation per unit area makes it important to record the recession of water flow in films following each surge.

Study of mass transport by dripping of melt water requires observations of water collecting into drops on needles, clusters of needles, and branches. Therefore, the relevant parameters of foliage and branches in this collecting process need to be identified and quantitatively expressed because the atmospheric factors that favor melting probably do not have much to do with the way melt water is partitioned between stem flow and dripping. The geometry of foliage—pattern, roughness, and occurrence of such blind alleys as drip points—is more important. Although laboratory experiments with foliage cannot be made as rigorously analytic as those dealing with well-measured atmospheric conditions, studies of individual trees or species will be inadequate unless each factor is quantified as well as possible. Bark roughness, for instance, should be amenable to methods for measuring roughness of machined surfaces or skin friction of pipes. The suggestion that Horton's indexes of stream-network dimensions might apply to tree crowns may provide a key to describing the characteristics of branch patterns that determine water collection and stem flow.

Perhaps it would be instructive to establish the conditions for maximum stem flow, that is, when most of the intercepted snow melts and when most of the melt water flows down the trunk. The effect of wind in shaking water loose before it can run to the trunk should be examined in terms of thickness of the melt-water film, with reference to such studies on rain interception as that by Grah and Wilson (1944). In the absence of wind, stem flow might be analyzed by unit-hydrograph methods, simulating values for water input, surface and channel storage in the drainage network, and outflow.

Examination of melting snow in place and the movement of melt water from it might be supplemented by surveys on the ground beneath, recording drip marks on the snow mantle, and collecting drops by the flour method to determine sizes and volume. In sampling with pans, drops would be separated from clumps of unmelted snow and snowflakes; in addition, the erratic areal distribution of dripping melt water requires a high sampling density.

Questions of mass transport in liquid state include determining the rate at which the film of melt water in tree crowns is generated, how thick and extensive it is, how it is directed into dripping or stemflow, and how these phenomena are related to heat supply, wind speed, and the properties of a tree crown as a collecting and concentrating network. Laboratory experiments do not appear complicated, and much information from research on the disposition of intercepted rain water may be transferable to this problem.

Vapor Transport from Melt Water

Observations of evaporation during storms of the film of melt water derived from intercepted snow are generally lacking. This fact derives from the lack of observations in tree crowns and also from the infrequent development of the phenomenon itself.

The conditions for evaporation of melt water during snow storms are unusual: generation of water from the snow, and heating it enough to produce a vapor pressure higher than that of the air, which, in the circumstances that favor melting, is likely to be high. Evaporation requires much heat, which is not easily obtained while snow is falling. The whole-spectrum radiation-flux resultant is close to equilibrium. And convective heat flux is limited by an air temperature unlikely to exceed +3 C. during snowfall and a wet-bulb temperature that cannot exceed 0 C. in air coexisting with snowflakes. Vapor pressure of the air is then 5.7 mb., only slightly less than that of a film of water at 0 C. (6.1 mb.); accordingly, while evaporation would occur, supported by sensible-heat flux from air to water, neither the sensible-heat nor the latent-heat flux between air and melt-water would be larger than those between the air and adjacent bodies of unmelted snow. Unless appreciable amounts of radiative heat, more greatly absorbed by the water than by the snow are received, melt water and its generating snow bodies evaporate equally slowly, both being restrained by the limit set to convective fluxes by the psychrometric relation.

However, an advantage of the melt-water film over the snow as to evaporation may lie in its greater surface area; many observers, including Delfs (1954), have stressed the extensive areas of wetted surface. But large areas may result not only from the mobility of water flowing from many well distributed bodies of snow, but also from slowness of the rate of evaporation from it. It seems clear that laboratory comparisons of evaporation of melt water with its movement as a liquid need to be made in a few typical conditions of air temperature and vapor pressure, under typical values of insolation up to 10 ly./hr. Increasing amounts of radiant energy widen the gap between snow bodies and melt water as to evaporation, but presence of the storm clouds sets upper limits to the role that radiation can play.

Area of the melt-water film and shape factors representing its complex form and distribution may be determined by study of data on evaporation of intercepted rain that are being developed in the revival of research on interception in England (Rutter 1963). The possibility that evaporation of melt water, which is usually a small mass-transport factor, might become important in special conditions of weather and tree form, warrants the separate discussion it has received here. The briefness of the discussion indicates the present lack of information from field or laboratory.

Vapor Transport from Intercepted Snow

Evaporation directly from intercepted snow into the atmosphere while snow is falling[2] has not to my knowledge been measured or observed. Evaporation is hard to measure in any situation; in tree crowns the problems are multiplied. Methods of estimating evaporation are adequate in only few situations, least of all in forest, where there is "need for a more direct method of measuring the

[2] The occurrence of evaporation after a storm or in breaks between periods of snowfall represents a different meteorological situation from that considered here, and will be considered in a later publication.

losses in vapor form from intercepted snow," because snow can leave the canopy in different ways, among which "it is extremely difficult to isolate the loss caused by vaporization" (Goodell 1963). Wind-tunnel experiments on this process apparently never have been undertaken, nor has the vapor flux upward from a snow-bearing, as distinguished from a rain-wet or transpiring forest canopy been measured. However, a review of some facts about evaporation from other surfaces and in other environments may be helpful in discussing factors that influence evaporation from intercepted snow.

The low vapor pressure of snow does not promote a large vapor flux from it, particularly when the vapor pressure in the air is nearly as large as that of the snow surface, as is true during storms. Insolation penetrating the storm clouds is likely to be absorbed by the falling snowflakes and provide energy for their evaporation, that will humidify the air below the cloud close to saturation. The intercepted snow has neither a special radiative or convective heat source strong enough to raise its surface temperature and vapor pressure much higher than air temperature and vapor pressure.

Cold, humid air does not provide a large supply of sensible heat for the evaporation of intercepted snow, and air full of falling snowflakes cannot be other than cold and humid; both conductive and radiative heat sources are small.Diunin (1961), in the most complete study to date on the evaporation of snow, reports experimental findings that can be related to intercepted snow, although his primary concern was with evaporation of blowing snow during blizzards. The reason that less snow accumulates in forest than is removed from open areas of west Siberia is that some evaporates during transport by wind. Diunin formulated this condition in terms of the psychrometric relation, including measurements of the diffusion layer and form coefficients, and made extensive experiments in controlled-environment chambers on snow surfaces, blocks, hemispheres, and particles of many shapes, as well as in wind tunnels on snow surfaces. In quiet air, evaporation in a month was measured as 1 to 2 mm. per mb. deficit in vapor pressure of the air. (A saturation deficit of about one-half mb. is typical of most snow storms.) From Diunin's wind-tunnel experiments on snow surfaces, I estimate that at a wind speed of 4 m./sec., measured 5 cm. above a snow mass, the quiet-air value of evaporation is increased about 20 times; daily evaporation during a snow storm, if the saturation deficit remained 0.5 mb., would be 0.7 mm.

Particles blown from the trees and carried in the wind stream experience only slight motion relative to the air, but their small size favors evaporation, until they come to rest on a surface again. Diunin concludes that evaporation of suspended snow particles is common enough that some lands should be reforested in order to shorten the paths of drifting, reduce evaporation of drifting snow, and restore regional water budgets.

Diunin's experiments on evaporation were conducted in blizzard conditions in which dry air from higher levels of the atmosphere can replace air that has become saturated from evaporation of the drifting snow. The experiments do not take the place of measurements in snow storms, when a deep layer of air is near saturation and the snow-bearing forest canopy is not the sole source of vapor. They do, however, form the basis for a tentative conclusion that vaporization of intercepted snow during periods of snowfall is not large.

Further work on this problem may also follow the lines of Nordon's (1963) study of convective transfer of water in a permeable medium, and of forest research by Denmead (1964) and Anderson (1964) on the penetration of convective and radiative energy into forest as a porous medium. For example, Denmead measured downward sensible-heat flux into a plantation of 5.5-meter *Pinus radiata* near Canberra, Australia, under conditions of a slight inversion on an afternoon in May when the net surplus of whole-spectrum radiation at the canopy top was 5 ly./hr., and found it to be about 2 ly./hr. His calculations of the vertical distribution of the latent-heat source in the stand of trees, which corresponded in his study to transpiration but in a snow-bearing stand would correspond to evaporation and melting, show that its maximum rate, located about 1 meter below the forest top, was 4×10^{-2} cal/cm.^{3} hr. If the branches hold bodies of snow of density 0.2 that occupied 0.1 of the stand volume, one body weighing 1 gram would be found in each 50 cm.^{3} of the crown volume, and would yield 1.8 cal./hr. of latent heat, equivalent to evaporation of $1.8/600 = 0.003$ g. of mass in an hour. If the whole-spectrum radiation surplus were taken as 2 ly./hr. for storm conditions and the sensible-heat flux the same as in the situation where Denmead measured it, the latent-heat source through the stand would average 0.8×10^{-2} cal./cm.^{3} hr. through the 5-meter depth of the pine crowns, and the rate of evaporation from a body of one gram of snow would be 0.0006 g./hr. In a column of 1 cm.^{2} cross-sectional area through the stand, 4 ly./hr. would be available to melt or evaporate snow. Assuming that the air is dry enough to permit evaporation, 0.007 g. of water equivalent would evaporate in an hour, that is, 0.07 mm. from the entire snow-laden forest canopy. The 24-hour average would be less than these figures, because the radiation surplus would be zero or negative at night; total evaporation in a day would approximate 1 mm., considerably less than the estimates I made some years ago (Miller 1961) on the basis of less complete information about the fluxes of sensible heat and radiation into forest. These estimates of evaporation of intercepted snow on the basis of heat supply would also apply to evaporation of melt water. They do not deal, however, with the problem of partition of heat between evaporation and melting. As in the deductions from Diunin's results, there remains a question whether or not the air would continue dry enough to permit evaporation to continue throughout the storm.

Vapor flux upward from a snow-laden canopy is similar to that from a transpiring forest or crop. The forest in a snowstorm, however, has a far smaller surplus of radiation, and the upward flux of latent heat depends more than it does in most crops upon the downward flux of sensible heat. The recently perfected "evapotron" (Dyer and Maher 1965) should prove valuable in field observations of vapor flux from forest stands of uniform roughness that are extensive enough to provide suitably long fetches of the air stream.

Vapor flowing from intercepted snow is both mixed upward into the free air and condensed on the snow surface on the ground of forest and adjacent open areas. The exact division is not known but could be determined by analysis of the fields of temperature, vapor pressure, radiation, sensible-heat and latent-heat flux above, in, and below the forest canopy. Vapor pressure is critical in determining the equilibrium between melting and evaporation of a body of snow acting as a wet bulb, and should be precisely measured at various levels in the crowns while the storm is in progress.

Diunin (1961) emphasized the vital need for "experimental, laboratory, and field" investigations into snow evaporation in general, and his recommendations apply to this particular problem. Micro-meteorological measurements in laboratory models and in large areas of uniform forest crowns during snow storms are essential to this perplexing problem.

Mass Transport Processes and Their Residues

The snow load on trees results from continuous delivery of snow to the branches and continuous removal by the media of transport (table 1). Data on size or weight of the residual snow load conveys no unique information about the separate processes of delivery or removal. But determining snow load under conditions that minimize some of the transport processes may give useful indirect knowledge of the others. As an illustration, the measurements of weight of a snow-loaded tree during storms (Govt. Forest Exp. Sta., Japan 1952) show abrupt decreases that can hardly be due to evaporation, or to stem flow or drip of melt water, and at the recorded wind speeds probably not to blowing of snow; they were no doubt caused by sliding of snow from the pendant branches, and their association with rises in air temperature shows the bearing of temperature on adhesion.

The difference between buildup of intercepted snow and its removal from the tree crowns is altered during nights when temperature is around freezing and air is calmer than in the daytime. These circumstances, according to Shidei (1954), favor "remarkable" growth of the snow load, especially after the snow has bridged gaps between the small branches and coalesced into a single sheet that envelopes the tree. Delays in this bridging action account for irregularities in the trace when weight of load, as recorded by spring tension on a deflected branch (Kataoka 1954), is plotted against accumulated snowfall. From lapsed-time photographs of white pine, Lull and Rushmore (1961) found that "snow accumulated on the needles, beginning at the bases of several needle fascicles, and later bending them over to form a platform."

Some indications regarding the amounts of snow in trees at the end of a storm are given by

Table 1.--*Processes of transport from intercepted snow during storms*[1]

Weather element	Transport by-- Falling or blowing of dry snow	Sliding or falling of partly-melted bodies of snow	Dripping or flowing of melt water	Vapor flux from melt-water film	Vapor flux from snow
Wind speed	++ a	+ b	+ b, c	+ d	+ d
Air temperature		++ c	+ c	+ d	+ d
Vapor pressure		+	++	-	- -
Insolation		++	+	+	+ d

[1]+ indicates an element of storm weather that favors a mode of transport from the crowns; ++ indicates strongly favors; - indicates an element of storm weather that discourages a mode of transport from the crowns; -- indicates strongly discourages.

a = Effect of wind is conditioned by the rate at which masses of intercepted snow are streamlined and wind packed, or develop internal cohesion.
b = Conditional on air temperature being above 0°C.
c = Conditional on air being near saturation.
d = Conditional on low vapor pressure in air.

Table 2.--*Snow deposits on wood dowels at end of several snow storms, near Fairbanks, Alaska*[1]

Date	Snowfall	Width of dowel	Length covered	Depth
	Cm.	*Inches*		*Cm.*
Nov. 21	16	11/16 and larger	full	4
Dec. 5	6	3/16 and larger	full	3
		2/16 and 1/16	quarter	1
Dec. 19	10	9/16 and larger	full	3
		8/16 to 3/16	full	2
		2/16 and 1/16	quarter	1
Dec. 26	0.2	14/16 and larger	full	1
		13/16 to 9/16	quarter	1

[1]Data scaled from graph in Pruitt (1958).

Pruitt's (1958) measurements of depth and lengths of deposited snow on dowels of different sizes (table 2). Depths of 3 to 4 cm. far exceed the widths of the deposits; appreciable depths of snow were found on supports as narrow as 0.3 cm.

Maximum depths of snow on branches of several species of conifer (Lull and Rushmore 1961), presumably occurring at the ends of storms, were 10 to 11 cm. on balsam fir, spruce, and hemlock, and 16 cm. on white pine. Goodell (1959) weighed a 4-meter spruce tree after a snow storm of 10- to 11-mm. water equivalent and found a load of 16 kg., which corresponds to 5 mm. water equivalent if the crown projectional area of the tree is taken as 3 $m.^2$ Higher loads are reported in wet snow storms, such as 25 mm. (Costin, *et al.* 1961) in *Eucalyptus dalrympleana*. Some silvicultural studies of snow breakage report the weights of snow that caused the damage, but the method of measurement is seldom stated and the rounding of values suggests that they are estimates; however, even estimates are valuable if they refer to critical values (Bühler 1886, Rosenfeld 1944).

Information on snow loads at any given time in a storm usually can be obtained by shaking snow off small trees or blowing it off by a helicopter onto plastic sheets and perhaps melting it by a heater to permit measuring it in tanks. More basic data, however, would be gained if the bodies of snow in tree crowns were to be observed as entities to be enumerated in order to determine distribution by size, and dispersion through the crown space. Particular attention would be given to exterior or interior location, in analogy to the sun and shade leaves in studies of transpiration and its distribution through the crowns.

Snow Breakage of Trees and Their Responses

If intercepted snow is removed slowly, the accumulation in the branches during a storm may put excessive stress on a tree, especially as multiplied by the lever effect of a crown on a tall stem and the increase in sail area of the crown. Some factors in interception, unfortunately, are ambivalent; high winds, for example, may remove snow as fast as they deliver it, or, in other circumstances may produce heavy loading of the crown if the snowflakes adhere to sloping surfaces. For this reason, information on snow damage to trees does not have direct value in studying interception processes; such indirect value as it may have, however, should be used.

The weight of snow critical for a tree of a particular species, age, and growth form is not easily determined because silvicultural reports of snow breakage do not usually include information that can be interpreted in terms of amounts of intercepted snow. For example, Naegler's (1940) report of heavy breakage in a storm with 50-mm. precipitation gives only a general upper limit of interception; it does not tell how much of the snowfall remained in the tree crowns, or whether, in fact, the trees may have incurred additional loading from horizontally-driven snow not recorded by the precipitation gage.

In a critical analysis of many reports of snow breakage in forests of western Honshu, Saeki and Sugiyama (1965) developed three conditions for heavy snow damage: (a) snowfall at a rate of more than 20 cm. depth per day; (b) air temperature varying between —3°C. and +3°C. between night and day, which ensures high density and strong adhesion of the snowflakes; and (c) a relatively small value of mean maximum depth of snow on the ground in the region, expressing the premise that tree strength where deep snow is unusual is likely to be small. Frequency of critical loading per decade was mapped, showing extensive areas of three occurrences per decade, and small areas of lee slopes presenting still higher hazards. These conditions of heavy interception embody a high rate of delivery and absence of blowing or sliding to remove intercepted snow. At high rates of delivery, evaporation can have only a minor effect; if air temperature drops below freezing at night, melt water will not accumulate in amounts large enough that transport by stem flow, dripping, or evaporation would remove much of the snow load. In the weighing experiments carried out by other investigators in Japan on single trees, some snow-removal process usually intervened before a damaging load was reached; but in a closed forest these transport processes do not operate so effectively—especially on lee slopes.

Delfs (1958) reported that snow breakage—although apparently not to a catastrophic degree—occurred in the spruce stands he studied when a loading of 20 to 30 mm. water equivalent was reached with wet snow. More commonly, he reports depth of snow on the branches as 8 to 10 cm., suggesting that the snow load did not usually exceed 10 to 12 mm. water equivalent. More damage occurred on exposed edges than inside the stands, as reported for thinned jack pine by Godman and Olmstead (1962). This finding suggests an augmentation of the measured 30-mm. water equivalent of the snowfall by horizontal precipitation of the type described by Slatyer (1965) at edges of groves of trees.

Attempts to deduce information about intercepted snow from reports of its effects on trees cannot be pushed very far because silviculturists cannot draw reasonable conclusions even about tree factors from snow-breakage reports unless they know the history and management of the stand and the concurrent weather (Hoffmann 1964). These data usually are not available to the hydrologist either. If complete data were at hand on all conditions surrounding a significant snow breakage event, they could be analyzed from an engineering standpoint to obtain information about intercepted snow, by using such concepts as those of Doerner (1965), who described deflection of a conical tree in terms of vertical loading on the trunk and lateral force on the crown. Both factors would be increased by intercepted snow; conversely, data on the moment of inertia and modulus of elasticity of a trunk that had broken under a snow load, and on crown area and weather, would permit calculating the loading critical for a given tree and, hence, the upper limit of interception. The probability of such an extreme event could be evaluated from weather data by methods like those of Saeki and Sugiyama (1965).

The effect of the weight of intercepted snow on trees is indicated in Hoover's (1962) comment about factors that tend to increase the size of the snow load: the leaf area, rigidity, and arrangement of the receiving surfaces. Said he: "Trees with dense stiff foliage, horizontal or upturned stiff branchlets, considerable vertical spacing between branches, and closely crowded together, hold a maximum of snow in their crowns. The fact that trees of that type suffer greatly from snow breakage indicates their efficiency in holding snow."

Trees that are often heavily loaded are thought to develop evasive forms, such as pendant branches that let snow slide off if it is heavy enough to bend them down (Delfs 1955; Iashina 1960). Trees in a region with deep snowfalls propagate from these pendant lower branches (Takahashi 1962). Rusanov (1938) states that winds accompanying the rare snowfalls in the deserts of central Asia prevent snow breakage of saxaul (*Haloxylon ammodendron*) shrubs and permit profuse branching; Watts[3] believes that snowfall is a limiting factor in the unusual areal distribution in California of digger pine (*Pinus sabiniana*), a tree with open foliage but a broad crown and forked branching. Similar comments are often found in the literature, but are not detailed enough to outline the critical frequency-loading relation that produces a particular response in a tree. Although a tree may tend to adjust to a certain frequency of snow loading, many do incur snow breakage. Is it the occurrence of several heavy snow storms per winter, or the extreme fall once in several decades, that affects genetic selection of tree form? Without such information, form alone cannot serve as a very precise index to either frequency or amount of interception. Because evidence from tree form is inconclusive, the question of evaluating the processes of transport of snow must be resolved by measurement in the laboratory and in the field.

Differences in Accretion to the Snow Mantle

An indirect means of estimating intercepted snow in a forest canopy at the end of a snow storm has been the comparison of accretion to the snow mantle produced by the storm in and near the forest. This method encounters the difficult problem of securing accurate measurements of any atmospheric or atmospherically-carried property above or in forest that are not influenced by the proximity of openings, or near forest stands that are not influenced by their proximity. Until these problems are solved, the interpretation of data on accretion to the snow mantle is biased

[3] Watts, D. *Human occupance as a factor in the distribution of the California digger pine.* 1959. (Master's thesis on file at Dep. Geog., Univ. Calif., Berkeley.)

to an unknown extent by the wind field and other conditions during snowfall. However, it is desirable to examine some of the available data to see what indirect information can be deduced about qualitative characteristics of the interception processes.

Rauner (1963) concluded that a forest stand narrower than 2 or 3 km. does not have a climate independent of its surroundings. Observations of snow transport by wind suggest to us that separating the dichotomy, forest vs. open, is as difficult in the case of snow as with heat or vapor in the air. Rainfall is more easily measured than snowfall, yet Bleasdale (1959) questions the validity of measurements of it made in forest openings, where additional turbulence in the air stream is evidenced by prevalence of damage at forest edges. Leyton and Carlisle (1959), recommend against ground-level measurements in forest openings, saying that

> . . . true interception can only be defined in terms of precipitation incident on the canopy. It is well known that this may be very different from precipitation in the open at ground level, especially if one includes snow and ice.

With specific reference to snowfall in a mosaic of forest bodies and openings, Hoover (1962, p. 36) points out that

> The great difficulty of obtaining exact values for incoming snow hampers comparison of snow accumulation between kinds and arrangement of tree cover as well as comparisons of open with tree-covered areas. There are no snow gauges unaffected by wind and, to date, no way of accurately measuring incoming snow when wind velocities exceed a few miles per hour. Comparisons based on the amount of snow on the ground almost invariably show more snow in openings than under the crowns but leave unanswered the following questions:
> 1. Is the excess in the opening a result of evaporation of snow from tree crowns?
> 2. Was intercepted snow merely blown, or shaken off, into the opening?
> 3. Did the wind eddies due to the surrounding tree crowns cause excess snow deposition in the opening?

Processes Producing Differences

Measurements of differential accretion to the snow mantle in and near forest beg the question of evaluating the physical processes of mass transport that produces the difference, and remain inconclusive, in particular as long as the input of snowfall to the forest remains unknown. Furthermore, if snow gages are considered inaccurate instruments, or, in Wilson's words (1954) "the deficiency in catch due to interception by the forest canopy is small compared with that due to wind," then elevating a snowfall gage to the upper surface of the tree crowns may not provide a better measure of actual delivery of snow. For this reason the validity of comparisons between accretion to the snow cover in forest and that to the snow cover in adjacent open areas, here called $\triangle A$ for brevity, fluctuates with exposure of the forest body and the floor of the opening to winds changing during the progress of a storm. It also fluctuates with other factors influencing the trajectories of snowflakes nearing the ground; a smaller fault, mentioned by Costin, *et al.* (1961) is that the melt-water going into the ground is not detected.

After it became clear to early investigators that a single sample cannot give an accurate estimate of accretion of snow to the forest floor, more samples were used to improve the estimate, and in some studies also to indicate variation from place to place. Some measurements of accretion at each sampling site have been found related to crown coverage immediately above; vertical transport processes such as drip off the branch ends are then dominant over horizontal transport. In other investigations, such as by Rowe and Hendrix (1951), the small sector of canopy directly above each catchment site had little specific relation to accretion, although the yearly sum varied from 700 mm. to 1440 mm. Kittredge (1953) found crown coverage above each sampling site closely related to accretion in only one type of forest—the cut-over mixed conifer stand, although cover provided a useful means of stratifying the measurements in all stands he studied.

A heavily replicated sampling program in the Soviet Union (Luchshev 1940), which used gages, illustrates variations of snowfall in pure spruce 18 m. tall (50 gages) and in aspen with a 10-m. spruce understory (30 gages). The variations were expressed as the average difference from the mean in each stand (table 3). The average error among gages under the canopy is several percent of storm precipitation, and is larger when snow is wet than dry.

From Leonard's (1961) means and coefficients of variation of catches in five gages in each of three plots of northern hardwoods, in nine snow storms exceeding 8 mm. and averaging about

Table 3.--*Average difference, in mm., of individual snow sampling gages from the mean, by type of forest stand and size of storm, in mm.*

Stand	Precipitation as dry snow			Precipitation as wet snow		
	2-5	10-15	15-20	2-5	15-20	> 20
Spruce	0.1	0.2	0.4	0.1	0.4	0.5
Aspen/spruce	0.2	0.6	0.6	0.1	1.0	0.9

Source: Luchshev, 1940.

15 mm., the standard deviations can be calculated as about 2 mm. Leonard ascribes some of the variation to the circumstance that large accumulations of snow in the branches might or might not fall on a sampling site in a given storm.

Several kinds of water substance reach the ground in and near forest. Snowflakes fall directly from the atmosphere, small agglomerations of loosely-cohering snow drop from nearby branches, fragments of snow bodies of more coherent structure are blown from distant branches, chunks of snow melted at planes of adhesion to a branch slide off, melt water drops to the ground, and crystals condense from vapor. Snow that has descended directly from the clouds is, unless driven by wind, the same wherever it lights, but snow that has rested on tree branches has experienced more or less radical changes during its arboreal phase. It may have been consolidated by wind action, or partly melted, or otherwise metamorphosed. To understand the hydrologic significance of accretion to the snow mantle, the different qualities of snow transported in each fashion need to be separately measured and related to storm weather. Comparisons of kinds of accretion in different winters and regions might indicate the relative importance of the major processes of snow transport during storms, and elucidate the roles of wind and temperature.

Forest Types Producing Differences

A few paired measurements of snowfall accretion in and near forest stands in individual storms may be cited to indicate the general level of $\triangle$A, in mm. of water equivalent. These data do not group themselves well by species, age, or other putative biological factor in interception. And they are accompanied by too little information about physical dimensions of the measurement sites to make a logical grouping possible.

Bühler (1918) cites differences in snow depth after a major storm in 1884. Assuming a snow density of 0.1, his findings show $\triangle$A values of 25, 23, 29, 20, and 15 mm. in stands of spruce of ages 15, 25, 40, 50, and 90 years, respectively. This storm broke many trees, as the large values suggest. Bühler did not consider the values precise, since he states that snow may be carried long distances by the wind into a gage.

Measurements in virgin ponderosa pine of northern Arizona, made by silviculturists at the Fort Valley experimental forest, Arizona, more than 50 years ago, record values of $\triangle$A in several years. Mattoon (1909) reports greater deposits of new snowfall in forest than in the open "parks" or treeless tracts, $\triangle$A being —2 mm. in one storm. Pearson (1913) sums up the storms of four winters, reporting $\triangle$A larger in midwinter than in spring. Jaenicke and Foerster (1915) report individual storms of two winters. In 1910–11, $\triangle$A in 13 storms averaged 0.7 mm., nearly half of the storms having zero or negative values. In 1912–13, $\triangle$A in 30 storms averaged 0.03 mm., 26 storms having zero or negative values. The authors grouped their forest stations according to shelter afforded by the groups of pines. Mean values of comparison between accretions to snow cover in forest and to adjacent open areas were as follows:

	1910–11 13 storms	1912–13 30 storms
	----(mm.)----	
Forest site:		
"No crown protection"	—0.8	—0.4
Slight protection	0	—0.4
Protected	+0.4	+0.3
Well-protected	+0.9	+0.5
Surrounded by tree crowns	+2.3	+1.4

In well-protected and surrounded locations $\triangle$A averaged 1 to 2 mm. in each storm; less protected sites received more snow than the open park.

Burger (1934) reports measurements after a storm in the selection forest of the experimental Sperbel- and Rappengraben studied by Swiss hydrologists. In beech, $\triangle$A was 2 mm.; in 40-year-old heavily thinned spruce and fir, it was 4 mm.; in dense 50-year-old fir, 10 mm.; in a natural fir group in the selection forest, 15; and in old fir with undergrowth it was 17 mm.

During a study of rainfall interception (Ovington 1954) in quarter-acre plots of 20-year-old introduced and native species in Kent, one small snow storm occurred. Assuming a snow density of 0.1, △A in *Quercus* was 1 mm.; in *Larix* and *Nothofagus* 2 mm.; in *Pseudotsuga, Thuja,* and *Pinus negra,* it was 2.7 mm., and equaled the amount of precipitation.

Maule (1934) measured snow deposited on the ground by six storms in New Haven, Connecticut, and reported mean values after each storm in stands of hemlock and northern hardwoods of uneven ages and in 6- by 6-ft. plantations of red and white pine and Norway spruce. The means and standard deviations of △A, in mm. in each stand are as follows:

	In individual storms	Mean ΔA	Std. dev.
	-------(mm.)-----		
Forest stand:			
Northern hardwoods, unevenaged	0 0 0 0 2 1	0.5	0.8
Hemlock 50–70 ft. tall	1 2 6 0 3 5	2.8	2.3
Red pine 24 ft. tall, 16 years	1 2 7 0 2 5	2.8	2.7
White pine 26 ft. tall, 10 years	1 2 7 0 3 3	2.7	2.4
Norway spruce 30 ft. tall, 19 years	2 2 9 2 4 8	4.5	3.2

Mean values of △A in the hemlock and pines were about 3 mm., and standard deviations among storms are nearly as large. In the spruce, △A was large, with only moderate variation, and in hardwoods only 0.5 mm.

From figures 1–14 in Kittredge's (1953) report on his study of several aspects of snow cover in the Sierra Nevada of California, observations of accretion of snow can be selected that probably correspond to single continuous storms without long breaks but storms that deposited enough snow to load the trees well. Only those storms for which precipitation in the open site was between 1 and 2 inches are selected. In nine sites where accretion was measured by snow-boards or gages (the larger of the two readings being accepted), from 2 to 45 storms were available. Values of △A can be seen in different topographic sites and forest stands, accepting a variable sample of storms. Table 4 presents information about each stand, with means and standard deviations of △A in the number of storms indicated, at measurement stations beneath tree crowns and beneath gaps in the canopy.

Considering sampling points located beneath tree branches, △A varies from 3 to 17 mm., with large values of standard deviation reflecting large differences among storms.

Sampling points under gaps in the canopies of mature white fir and cut-over mixed conifers had low values of △A and large standard deviations. Those in the immature white fir had the largest value of △A. Furthermore Delfs (1958) found large values of △A in openings in a pole stand of spruce, about the same size as at points under the canopy. Stålfelt (1963) found that winter precipitation "screened off from the gages by the crowns" of spruce in Sweden totaled as much as 0.8 of the value of △A under well-developed spruce crowns that reached nearly to the ground. In the fir openings in the Sierra Nevada, more snowfall seems to reach the ground than in spruce openings in Europe. Plotting values of △A at points under gaps in the canopy against crown coverage within 20 ft. of the point or averaged for the whole stand revealed no relation. If both species and crown coverage of the whole stand are considered, △A is largest in the pines and the pine-dominated mixed conifers; it was smallest in the fir and the cut-over mixed conifer stand, in which many fir trees remained.

In the mature stands of pine and white fir, sampling points under the canopy and under its gaps have about the same values of △A. The two classes of sampling points differ the most in the cutover stand of mixed conifers. This striking difference in behavior between tree groups and openings may possibly be related to earlier selective logging of the sugar pines, the tallest trees of the mixed-conifer stand. While the large openings in the mature pine stand presumably developed naturally, with foliage covering most of the vertical extent of their borders, those in the logged stand might have porous open borders that afford little opportunity for snow to be caught, and would favor transport of snow into the openings. Artificial openings may thus affect mass transport processes much differently than openings bordered by snow-catching foliage reported by Delfs (1958) and Stålfelt (1963).

At sites near 1600 m., △A averaged 6 mm., and at the higher sites 9 mm. Sites with northwest aspects averaged higher than the two of southeast aspect, but the distinction is not clear cut. The large differences in △A among sites are a matter of interest even if not explicable on the basis of available information.

Table 4.--*Site characteristics and ΔA in the Sierra Nevada, California*[1]

Forest type			Site characteristics			Crown coverage			Record	Number of storms		ΔA, mm.[2]	
Species	Age	Height	Elevation	Aspect	Slope steepness	C[3]	O[3]	Whole stand		C[3]	O[3]	C[3]	O[3]
		Feet	*Feet*		*Percent*				*Years*				
Ponderosa pine, mature	all ages	120	5,200	SE	15	35	9	21	7	37	42	3±9	5±6
Ponderosa pine reproduction	28	15	5,220	SE	10	40	-	79	5	13	-	7±13	-
Mixed conifers, virgin (Sugar pine, ponderosa pine, white fir, incense cedar)	all ages	140	5,580	NW	3	62	29	35	5	18	10	12±10	7±7
Mixed conifers, cut-over	all ages	110	5,550	NW	35	55	27	37	7	32	40	17±11	1±7
White fir, mature	140	100	5,200	N	31	51	41	41	7	45	14	3±14	2±8
White fir, immature (pole size)	70	80	5,280	NW	16	70	58	68	5	27	7	15±11	8±2
Red fir	200	120	6,260	N	21	75	2	52	7	3	2	10±8	7
Open logged area[4] (15 acres)			5,200	NW	13	0	0	0	7	(5/)		(4/)	
Open screened area[6]			5,250	NW	1	0	0	0	5	-	21	-	1±17

[1]Source: Various tables and graphs in Kittredge (1953).
[2]Presented as Mean ± Standard Deviation.
[3]C = Stations under canopy; O = Stations under gaps in canopy. Crown coverage taken within 20 ft. of the station; of the entire stand also in percentage.
[4]Taken as the base station for comparison.
[5]All storms.
[6]Near edge of fir forest.

Also in the Sierra Nevada, but at a lower elevation (1000 m.) and in second-growth ponderosa pine, Rowe and Hendrix (1951) carried out measurements over 6 years, during which 11 snow storms of 1 to 2 inches water equivalent occurred. Scaling $\triangle A$ in these storms from their figure 2 yields values from 5 to 7 mm. Stem flow of melt water from intercepted snow was 0 to 2 mm. in these storms. From the brief published report on this long thorough study, it is hard to estimate such other transport processes as blowing of snow, although with records of wind pulsations it should be possible to evaluate the buildup of snow on the branches and its subsequent blowing off into the near-by openings, which were considerably larger than the 40- by 55-ft. study plot in the forest. Storms with low total wind movement would provide the most reliable measurements of accretion, as West and Knoerr (1959) comment in discussing their measurements in and near a tree group at a site at 2,100 m. elevation in the Sierra Nevada. However, even without meteorological observations, the findings of Rowe and Hendrix require a re-examination of exaggerated ideas of $\triangle A$, and their measuring of stem flow calls attention to other transport processes.

Some investigations using paired sampling sites in and near forest publish only monthly or seasonal sums of accretion. Such limited information does not permit separation of the transport processes during storms from those after storm, which may act quite differently. Empirical relations between accretion at paired stations might have local use, in places with the same regimes of snow storms, wind, advection of heat, and radiation as those at the site studied. The comparisons have been determined to have little generality—a warning issued, in fact, by the first scientist to make such readings; Krutzsch (1864) stated that his observations were good only for the site (near Tharandt) where he made them. He felt that elsewhere they indicated only that intercepted precipitation might make a valuable contribution to the moisture content of the atmosphere.

When data on $\triangle A$ are presented only in terms of a ratio to precipitation, they should not be interpreted as indicating either (a) the amount of intercepted snow, or (b) the rate of vapor flux from it. Interpretation (a) implies that snowfall continuing without limit can increase the weight of snow that can be held by trees. Interpretation (b) implies that continued snowfall confers energy upon the intercepted snow to expedite its evaporation at rates equivalent to 15 to 25 langleys per hour. These are very large rates of heat flux in a situation more commonly considered one of radiative equilibrium and an isothermal field of temperature. Any validity in the empirical relation $\triangle A = a + bP$ (in which P is snowfall, and a and b are calculated coefficients) might rather be sought in the hypothesis that heavier snowfall produces larger bodies of snow in the branches that are more susceptible to wind transport into the opening, thereby increasing $\triangle A$ by biasing the "open" catch upward. The coefficients a and b give no information about the processes by which snow, water, and vapor are transported from intercepted snow in the branches. As Delfs (1955) states, they have limited predictive value in forests that vary in species, habit, foliage density, or stand structure. Calculation of $\triangle A$ does not provide a measure of intercepted snow or its removal from trees. Although calculating it from snow-board measurements avoids the problems of gage defects, there remain unknown differences in aerodynamic characteristics and snow deposition between the tops of tree groups and the bottoms of openings in forest.

Calculation of $\triangle A$ by comparing gage readings cannot be recommended as a practical approach to questions of interception of snowfall and its transport during snow storms until accurate measurements of snow movement—resolved into vertical and horizontal components—can be made above, within, and beneath the zone of tree crowns. Furthermore, measurements of the wind field in terms of its ability to suspend and transport snowflakes must be included. Sampling profiles through the foliage zone have proved effective in determining the flux of radiative energy into and through the active layers of trees and crop plants, and are currently being used in research on the turbulent flux of heat and vapor. Until similarly aerodynamically adequate meters to measure the flux of snow in the atmosphere are developed, the practice of comparing amounts of snow caught in and near forest in the kind of sites customarily employed can provide little knowledge of the processes of interception of falling snow by foliage or of transport of intercepted snow from foliage during snow storms.

Research Approaches

This discussion of the ways in which intercepted snow is transported from tree crowns during snow storms indicates a great need for quantitative determination of each transport in its relation to the varying conditions of storms and forest stands. The means of acquiring these data and improving our capabilities for measuring the fluxes vary in difficulty, precision required, and urgency; fortunately, the modes of transport that are probably most important during snow storms do not seem to be the most difficult to measure, and should receive priority in further research.

Studies of Transport Processes

The transport processes are not equally understood. Stem flow has, perhaps, been the most successfully measured, where measurement has been attempted, although in other situations it has often been overlooked. The solid-state flux of snow in the air stream has been least successfully measured, in spite of the existence of methods that could be modified for the purpose. Failure to measure this horizontal transport has resulted not only in a lack of information about the influence of forest on adjacent land, but also in an inability to evaluate and possibly to correct the errors inherent in the technique of paired sampling points in and near forest.

Of all the transport processes, the evaporation of intercepted snow and the flux of vapor from forest into the free air is, although much alluded to, perhaps the hardest to measure. The practice of estimating vapor flux as a function of rate of snowfall is without physical justification. Considering it a residual does not suffice if other modes of mass transport are unmeasured. The snow that remains in the branches when a storm ends has seldom been measured; it has only been estimated from reports of snow breakage of trees, and from observations made at ground level without the meteorological data that would permit us to separate the usable measurements of snow accretion in and near forest from those biased by differential action of the mass transport agencies. These indirect methods give inadequate information about the intercepted snow and the transport processes that affect it. It is almost impossible to generalize this information or use it as a predictor; it is necessary to study the individual mass transports as independent natural phenomena.

One of the most important of these processes, especially in view of its capability for lateral transport, is the solid flux of snow dropping and blowing from the tree branches and carried with the wind. This transport presents problems of sampling more than of sensing, because it is visible and the particles can be caught and weighed. Methods of measuring the solid flux in an air stream also might be applied to determine the delivery of snow to the forest top. They could be developed from practices for measuring drifting snow, and consider differences in particle size and aggregation, density, sinking speed, and source relative to the transporting air stream. Installations of drift meters and bi-vane and vertical-direction anemometers, in profiles from the ground to several meters above the forest canopy would, in a relatively few storms, secure a good sampling of the downward transmission of momentum in eddies of the sizes that determine the building and destruction of bodies of intercepted snow and on the horizontal component of suspended particles moving into the air stream. Moreover, these methods would easily be extended to the special cases of trees at the edge of a forest body, trees bordering openings in forest, forested slopes that might produce density currents, and trees being weighed, as in the study in Japan (Govt. Forest Exp. Sta., Japan 1952), to determine how much snow is delivered and removed.

Profiles of wind speed would provide a basis for wind-tunnel modeling, and thus permit the generalized application of information on blowing snow to many kinds of forest. There is sound reason for combining the recommendation for use of drift meters with that for determining the vertical and horizontal components of the field of motion of the air, with its eddies and pulsations in and below the forest canopy. Each set of measurements will aid interpretation of the other. Erosion by gusts of bodies of intercepted snow supplies suspended material for horizontal transport; the efficiency of horizontal transport depends on the prevalence of upward motion in the turbulent air stream. Furthermore, the flows of snow and air are themselves intricately interrelated, since snow particles have little inertia. The likelihood that large amounts of snow are redistributed by this mode of transport gives priority to this research.

The release of partly-melted snow bodies to fall or slide from the branches involves both atmospheric conditions and properties of the branches themselves—slope, friction, strength, deformation under load, and ease of being triggered to release potential energy stored as they are bent. Watanabe and Ôzeki (1964), in particular, have demonstrated that many relevant characteristics of trees are measurable in the field; other characteristics are measurable in the laboratory. Wind-tunnel studies would seem ideal for evaluating the variables of support and adhesion of snow to branches, because the variables of heat supply could also be introduced into the experiments. It then could be determined what fraction of the intercepted snow in trees of different growth forms and species melts before the rest is released from its support.

Whether atmospheric heat causes a body of snow to melt partially and slide off the branches or to melt completely in place depends on support and adhesion characteristics. In laboratory experiments these characteristics can be varied with different values of foliage friction and branch inclination. And, laboratory methods can determine the conditions that favor heat supply at the lower, supporting surface of a snow mass rather than its sides and top. They can also measure initial cohesive and frictional forces to determine how much melting takes place before mechanical bonds give way and sliding starts. Such laboratory studies would form a transition to field work on small trees of known foliage friction and other properties, under atmospheric conditions observed in detail, with surveys of the snow mantle beneath trees to identify fallen chunks of intercepted snow and to measure their size, density, and wetness. Drip pans might be used if there were a means of separating blown from fallen snow, perhaps on a basis of density or aggregation.

It would be worthwhile, for example, to see whether the estimate reached on page .... that the melting of 20 percent of the intercepted snow on an isolated tree coincides with gravity movement of the remainder will hold true for trees of different branch form than the cryptomeria described in this paper. Lastly, extending the tentative calculations of heat flux reported in this paper, trees with intercepted snow could be weighed under different conditions of radiative and turbulent heat flux to determine the fraction of the total mass transport that takes place by sliding and falling of partially-melted bodies of snow.

Movement of melt water from intercepted snow is visible and easily collected if it moves as stem flow, but with more difficulty if it moves as drip. It is important to determine the frequency of each of these movements and their typical rates of flow during storms of different types. There are two basic questions: (a) determination of the rate of melting as a function of supply of energy, which is a function of atmospheric variables that involves the division of heat between melting and evaporation; and (b) partition of melt water between stem flow, dripping, and possibly evaporation, which is a function of foliage attitude and branch structure, and of the hydraulics of a branching film of water clinging to the leaves and bark. Basic research on the disposition of intercepted rain may throw light on these two questions of snowfall interception.

Thorough melting of snow in place in tree crowns involves heat transfer to securely held bodies of snow over long periods, without localization of heat at such critical points as the zone of adhesion. Convection and condensation of vapor are important during storms, and some heat is added by short-wave radiation; the net flux of long-wave radiation is not likely to produce a deficit as large as in clear weather. Laboratory experiments can reproduce all avenues of heat flow in various combinations. Combined at the same time with measurements of melting of suspended bodies of snow and of snow on the wind-tunnel floor, they would make it possible to establish at least empirical relations between mass and energy transfer at a cold boundary overlain by stable air in contrast with that at surfaces distributed throughout the medium. As a result, turbulence theory could be used to transfer the extensive knowledge about melting snow on the ground and on glaciers to the special situation of tree crowns. The flow of melt water through suspended bodies of snow might also differ from that in a snow cover.

Controlled-environment chambers seem useful for studies of heat supply, melting, and flow or drip of melt water on small trees of different forms and species, offering the possibility of comparison with melt rates of a plane snow surface in the same environment. Successful transfer of such studies into the field would require quantitative description of the tree variables as well as the atmospheric ones, although the pattern of occurrence of melt water seems to display a predominance in marine climates.

Vaporization of melt water and intercepted snow produces an invisible flux of great mobility, which can be measured only with difficulty, even in geometrically simple situations. The film of melt water on foliage and branchwood of a tree is not geometrically simple, and so it seems likely that empirical laboratory studies of branches or small trees of different degrees of wetting should take priority, but without neglecting efforts to conceptualize and describe numerically the shape and area of the film.

Evaporation of bodies of intercepted snow can also begin in the laboratory, along the lines shown by Diunin's (1961) work in the framework of the psychrometric relation. However, due regard should be given to the size of the snow agglomerations moving in the air stream and the greater size of the bodies of snow held in mid-air by the branches. These larger bodies need to be enumerated and located by some kind of census of a typical snow-laden tree before wind-tunnel experiments are designed. Attempts made in other disciplines to estimate evaporation as a residual of changes in mass of water require extreme precision in measurement that is probably not feasible for the dispersed bodies of snow *in situ,* but perhaps may be feasible for individual bodies held in a moving air stream. Quite a different approach is to measure the vapor flux emanating from a forest canopy of sufficient uniformity and area to warrant measurement by the evapotron or other device from agricultural meteorology.

The fraction of the total vapor flux from intercepted snow that diffuses downward to condense on the snow mantle presents difficult sampling problems, and is probably smaller than the upward flux from the snow-bearing canopy as a whole, at least during snow storms. Neither flux of vapor may be large under these conditions, because it is difficult to conceive of a steep vapor-pressure gradient from the forest canopy either up into the clouds or down to the snow mantle. However, the return of intercepted water to the major flux of the atmospheric circulation that supports further precipitation downwind has interesting hydrometeorological implications, noted by such forest scientists as Krutzsch (1864) and Eitingen (1953).

Much effort in forest climatology has been limited to the human level, that is, within the trunk space, although it has long been known that the level of greatest activity, physical and biological, is the upper canopy. The classical picture of the dark cool forest climate reflects this limitation in scale; the concentration of effort on measuring accretion to the snow mantle on the ground has drawn research attention away from the place where interception phenomena occur with full intensity—in the tree crowns. For this reason, it has been possible only to sketch the processes by which snow particles, melt water, and vapor are transported from the tree crowns; few measurements have been made. It is highly desirable that future research shift its focus from the quiet inactive zone of the trunk space to the active zone of the tree crowns, and study their interaction with radiation and the atmosphere, with its solid suspensions, i.e., snowflakes.

In estimating interception by comparing accretion to the snow mantle in and near forest, the investigator faces aerodynamic questions of delivery of snowfall to the top of a forest body and the depths of a forest opening, and of mass transports that confound the sought-for distinction between accretion in forest and near it. An unfortunate parallel was drawn in the past with the processes that operate during rain storms. These processes can be measured with ordinary instruments because vertical transports predominate over horizontal ones. But the processes in snow storms are quite different; horizontal transports are so great as to make uncertain the measurement of snowfall in any situation whatever. Detailed rainfall studies such as those by Kittredge, *et al.* (1941), Hamilton and Rowe (1949), Luchshev (1940), and many others, were made not simply to plug a gap in a local water budget but to examine fundamental hydrologic processes. Their studies had a degree of detail in sampling and meteorological data not matched in studies of snowfall.

Even long programs of observations of accretion to the snow mantle are hard to interpret in terms of mass transport from snow intercepted in the tree branches, especially in the absence of meteorological data. Satterlund and Eschner (1965) feel that studies of snow on the ground "have probably passed the point of diminishing returns under most forest conditions. Snow losses should be studied where they occur—in the trees themselves." While these authors are referring primarily to post-storm conditions, their recommendation applies with equal force to conditions during storms.

Applying the differential-accretion, or $\triangle$A method, to observations from precipitation gages in and near forest introduces the familiar defects of such gages as scientific instruments. The use of troughs on the forest floor, instead of gages, as has been reported by Delfs (1958a), Grunow (1965), and others, is helpful there. But this use does not eliminate, as Grunow notes, the problem of gages in openings, nor of mass exchange between openings and surrounding forest. Proper use of the $\triangle$A method awaits development of measuring instruments that are aerodynamically correct, arrayed in replicated patterns above, in, and beneath the canopy, and accompanied by measures of horizontal and vertical wind speed. Such a study need not depend on the openings in forest as places to make measurements, but can concentrate upon the canopy itself.

Micrometeorological methods of measuring heat transfer to bodies of intercepted snow in tree crowns and vapor flux away from them should start with profiles measured near individual bodies of snow under controlled heat supply, as, for example, in a wind tunnel. Results of these experiments can be extended, at increasing scales, first to several bodies of snow on a tree branch or in a small tree standing in a climatic chamber, using branches and small trees that provide a sample of different growth forms and different species; then to a snow-laden tree in a well-measured field site; and finally to the crown space of a tree group considered as a porous volume of finite depth and semi-infinite extent, generating vapor that diffuses out of its lower and upper boundary surfaces.

The forest crown as an environment for bodies of intercepted snow is a medium not easily described in quantitative terms; yet, without numerical expression of its attributes, the laboratory experimenter cannot know how to build a model that will adequately simulate natural phenomena nor how to simplify the problem with minimal distortion. Neither can the analyst of the atmospheric processes that act upon intercepted snow set up hypotheses for testing with assurance that he is approximating the true situation in a drainage basin. Because such categories as age, closure, and even species do not index those geometrical and mechanical properties of forest that are relevant to the phenomena of snow interception, new forest parameters need to be recorded.

Among the data required on vegetation are totalizing measurements, like biomass, in cm^3 volume or grams per cm^2 of stand area. Surface area of foliage, crown depth and volume, lengths of branchwood of various diameters, are other measures that have proved their utility in scattered studies, and should have general use in preference to such indexes as closure, stocking, basal area, or stem density, which have uncertain relations with physical phenomena in the crown space.[4] For the measurement of other attributes of forest stands, however (for example, branching pattern and crown structure), no methods exist at present.

Laboratory data on the changes in individual bodies of snow has to be related to the universe of snow bodies in tree crowns in the field. The first step might be to take a census of snow masses, by size, shape, location, and type of support. Next, instrumental measurements of density, cohesion, wetness, and other physical properties should be made on representative snow bodies, in order to determine internal structure, crusts, adhesion zones, liquid-water content, permeability to air and water, and manner of draining of these bodies. Changes in these qualities indicate the action of radiative and atmospheric forces and define the individual transport processes.

Weighing experiments following the thorough Japanese example might be undertaken in representative sites within a forest stand and at windward and leeward edges. The measurements would be accompanied by a census of snow bodies and a sampling of their properties. In this site should be made measurements of wind speed and gustiness, air temperature, humidity, fluxes of shortwave and long-wave radiation, and fluxes of snow particles and vapor as extensions of earlier laboratory and controlled-environment experiments. As a result of these observations of mass and distribution of intercepted snow and of atmospheric conditions, simultaneous visual observations of blowing, dripping, melting, sliding, and stem flow could be associated with specific quantities of snow carried in each transport process. Such field measurements of the bodies of snow, their arboreal environment, the wind forces and heat fluxes acting on them, and the fluxes of snow, water, and vapor to which they give rise would provide—if carried out in a few snow storms of different synoptic types—ample data for developing and testing a comprehensive theory of the mass transport of intercepted snow from the crown of a forest.

Mechanical strength of foliage, fine branches, large branches, and trunks—all measurable by

[4] The measurement of branch angle and lengths by Watanabe and Ôzeki (1964) demonstrate the value of this kind of numerical data in interception work.

standard engineering techniques—have not yet been used in interception studies but are needed in studying the vibration of tree crowns, deformation under wind stress, and bending under snow load. Some of these attributes are commonly associated with species, and these relations need to be given quantitative support by determining the general level and dispersion of each attribute of a species by measurement in a wind tunnel and a mechanical-engineering laboratory. The recommendation in the *Allgemeine Forstzeitschrift* (Anonymous 1954) for research on growth form and breaking strength, in order to develop means of reducing damage by snow breakage, is equally relevant to the general problems of snow interception.

The crown space of a tree group is a porous medium through which air, vapor, momentum and radiation flow, and throughout which are distributed many small bodies of snow that are sinks of heat and momentum and sources of water in all three physical states. Recent models and experiments with flow in porous media may be helpful in formulating concepts of this system that will be aerodynamically and thermodynamically valid. The forest mosaic, as a complex of tree groups and of interstices, whether "natural" or made by strip, patch, or group-selection cutting, influences the distribution of radiation and particularly the movement and advected properties of the air stream, hence the processes by which snow is transported. To extend findings about transport processes in single trees and in tree groups to drainage basins covered by mosaic systems of forest and openings will require some means of characterizing the mosaic. The means might come from current work in image recognition of remotely-sensed data or from quantitative geography and ecology.

Obtaining the required measurements of mass transfers in the complex forest mosaic environment will require intensive and well-planned sampling on a micrometeorological scale within this porous medium, and on a larger scale at its boundaries, particularly the upper surface. However, if the processes that transport energy and water have been individually analyzed and relevant factors identified, relatively short records in the laboratory and during selected field periods should suffice to establish the limits and variation in each process. Elements requiring observation over long periods are those for which standard instruments are generally available and in which great detail is not important.

This is the trend in many lines of geophysical research: brief studies of high observational intensity with continuous records of many fluxes in a dense sampling network, in order to determine how the transport processes can be predicted as functions of more commonly observed factors. The more that can be done in controlled environments, the more simple can be the field experiments, and the more generally applicable will be the results. If all relevant conditions are recorded, accurate relations between them and the mass transports can be established; once these are known, short cuts can be taken with confidence, and a few key factors in any forest site can become the basis for successful application of the universal relations between the mass transports of water from intercepted snow and the sources of energy and momentum that cause them.

Summary of Recommendations

Suggestions for promising research may be summed up as follows:

- Each mass-transport process should be regarded as separately influenced by conditions of storm weather, tree geometry, and characteristics of the bodies of intercepted snow.
- Measure one or two mass-transport processes selected as significant in a particular region with respect to their action in carrying snow, water, or vapor; measure the wind fields and energy flows associated with them in the tree crowns; and measure the relevant characteristics of the tree crowns and bodies of intercepted snow.
- So little research has been done with snow in controlled environments that almost any laboratory experiment would be useful, as long as its modeling simulates field conditions properly and will permit transfer to field sites; intensive experiments, adequately instrumented in controlled wind fields and heat fluxes, with typical tree crowns bearing bodies of snow will shorten subsequent field work. Use laboratory work to save field time.
- The mass-transport processes that move intercepted snow from tree branches to other resting places in or near forests can be understood and their magnitude determined if their physical nature is kept in mind. Snow is eroded and transported by mechanical forces, such as wind, and its physical state is changed by thermodynamic phenomena that release it from supporting branches, melt it, or evaporate it. Investigation of these processes, therefore, requires measurement of the wind field

and the fluxes of energy, as they occur in the special environment of tree crowns, as well as of the transported snow, water, and vapor. Simulation of simplified aspects of this environment in climatic chambers offers the opportunity to witness the effects of varying wind speed, snow adhesion, branch attitude, radiant energy fluxes and convection. Finally, these experiments would provide basic relations for productive measurements in the field that will evaluate the transports and verify techniques for predicting them in forest sites and weather of every kind.

Selected References

Anderson, Margaret C.
1964. **Light relations of terrestrial plant communities and their measurement.** Biol. Rev. 39: 425–486.

Aniol, R.
1951. **Uber die Lufttemperatur bei fallendem Niederschlag.** Meteorol. Rdsch. 4: 147–149.

Anonymous
1954. **Natürliche Auslese in Schneebruchlagen.** Allg. Forstz. 9(1):10; 9(2):30.

Baldwin, H. I.
1957. **The effect of forest on snow cover.** Proc. Eastern Snow Conf. 4: 17–24.

Bleasdale, A.
1959. **Water and woodlands: Investigations in the United Kingdom into the water relationships of woodlands, and the problem of measuring rainfall over woods.** Int. Ass. Sci. Hydrol. Publ. 48: 87–91.

Bühler, A.
1886. **Untersuchungen über Schneebruchschaden.** Forstwissensch. Centralbl. 8: 485–506.

Bühler, A.
1918. **Der Waldbau nach wissenschaftlicher Forschung und praktischer Erfahrung. I. Band.** Stuttgart: E. Ulmer 662 pp. illus.

Burger, H.
1934. **Der Wasserhaushalt im Sperbel– und Rappengraben von 1915/16 bis 1926/27.** Mitt. Schweiz. Anst. forstl. Versuchswesen 18: 311–416.

Butters, F. K.
1932. **Flora of the Glacier District.** Can. Alp. J. 21:139–147.

Cionco, R. M.
1965. **A mathematical model for air flow in a vegetative canopy.** J. Appl. Meteorol. 4:517–522.

Costin, A. B., Gay, L. W., Wimbush, D. J., and Kerr, D.
1961. **Studies in catchment hydrology in the Australian Alps. III. Preliminary snow investigations.** Australia. Commonwealth Sci. Indus. Res. Organ., Div. Plant Indus. Tech. Pap. 15. 31 pp., illus.

Cramer, H. H.
1960. **Hubschrauber gegen Schneebruchschäden?** Allg. Forstz. 15 (20): 293, 296.

Delfs, J.
1954. **Niederschlagszurückhaltung (Interception) in verschieden alten Fichtenbeständen.** Mitt. des Arbeitskreises "Wald und Wasser" (Koblenz) 1: 31–36.

Delfs, J.
1955. **Die Niederschlagszurückhaltung im Walde (Interception).** Mitt. des Arbeitskreises "Wald und Wasser" (Koblenz) 2, 54 pp. illus.

Delfs, J.
1958. **Die Niederschlagszurückhaltung in den Beständen.** In: **Der Einfluss des Waldes und des Kahlschlages auf den Abflussvorgang, den Wasserhaushalt und den Bodenabtrag. Ergebnisse der ersten 5 Jahre der forstlichhydrologischen Untersuchungen im Oberharz (1948–1953).** J. Delfs, W. Friedrich, H. Kiesekamp, and A. Wagenhoff. (Mitt. aus der Niedersächsischen Landesforstverwaltung.) 3:76–107. Hannover: Aus dem Walde.

Denmead, O. T.
1964. **Evaporation sources and apparent diffusivities in a forest canopy.** J. Appl. Meteorol. 3: 383–389.

Diunin, A. K.
1961. **Isparenie Snega.** Novosibirsk: Izdat. Sibir. Otdel Akad. Nauk. 118 pp. illus.

Doerner, E., Jr.
1965. **Some dimensional relationships and form determinants of trees.** Forest Sci. 11: 50–54.

Dyer, A. J., and Maher, F. J.
1965. **The "Evapotron": An instrument for the measurement of eddy fluxes in the lower atmosphere.** Australia. Commonwealth Sci. Ind. Res. Org., Div. Meteorol. Phys. Tech. Pap. 15, 31 pp. illus.

Eidmann, F. E.
1959. **Die Interception in Buchen– und Fichtenbeständen: Ergebnis mehrjähriger Untersuchungen im Rothaargebirige (Sauerland).** Int. Ass. Sci. Hydrol. Publ. 48: 5–25.

Eitingen, G. R.
1953. **Lesovodstvo.** Ed. 5. Moscow: Gosud. Izdat. Sel'sk. Lit. 423 pp. illus.

Ffolliott, P. F., Hansen, E. A., and Zander, A. D.
1965. **Snow in natural openings and adjacent ponderosa pine stands on the Beaver Creek watersheds.** U. S. Forest Serv. Res. Note RM-53. 8 pp. illus. Rocky Mt. Forest & Range Exp. Sta., Fort Collins, Colo.

Gates, D. M., Tibbals, E. C., and Kreith, F.
1965. **Radiation and convection for ponderosa pine.** Amer. J. Bot. 52: 66–71.

Godman, R. M., and Olmstead, R. L.
1962. **Snow damage is correlated with stand density in recently thinned jack pine plantations.** U. S. Forest Serv., Lake States Forest Exp. Sta. Tech. Note 625, 2 pp. illus.

Goodell, B. C.
1959. **Management of forest stands in western United States to influence the flow of snow-fed streams.** Int. Ass. Sci. Hydrol. Publ. 48: 49–58.

Goodell, B. C.
1963. **A reappraisal of precipitation interception by plants and attendant water loss.** J. Soil Water Conserv. 18: 231–234.

Government Forest Experiment Station, Japan.
1952. **Study of the fallen snow on the forest trees (snow crown), (first report).** Govt. Forest Exp. Sta. (Meguro) Bull. 54:115–164, illus.

Grah, R. F., and Wilson, C. C.
1944. **Some components of rainfall interception.** J. Forestry 42(11):890–898.

Grunow, J.
1965. **Die Niederschlagszurückhaltung in einem Fichtenbestand am Hohenpeissenberg und ihre messtechnische Erfassung.** Forstwiss. Centralbl. 84: 212–229.

Hamilton, E. L., and Rowe, P. B.
1949. **Rainfall interception by chaparral in California.** U. S. Dep. Agr. Forest Serv. & Calif. Dep. Nat. Res., Div. Forestry, 43 pp. illus.

Heikenheimo, O.
1920. **Suomen Lumituhoalueet ja Niiden Metsät.** Metsätieteelisen Koelaitoksen julkaisuja, Publ. 3, 134 pp. illus.

Hirata, T.
1929. **Contributions to the problem of the relation between the forest and water in Japan.** Japan. Imp. Forest Exp. Sta. (Meguro). 41 pp.

Hirata, T., and Hotta, Y.
1951. **On the snow-storm damage (14–15, Feb. 1951) in the University Forest, Chiba Prefecture.** Tokyo Univ. Forests, Misc. Inf. 8:45–55.

Hoffmann, D.
1964. **Zu: Schneebruchschäden—einmal anders gesehen.** Allg. Forstz. 19: 258–260.

Hoover, M. D.
1960. **Prospects for affecting the quantity and timing of water yield through snowpack management in Southern Rocky Mountain area.** Proc. Western Snow Conf. 1960: 51–53.

Hoover, M. D.
1962. **Water action and water movement in the forest.** In: **Forest Influences.** Food & Agr. Org. United Nations, Forest and Forest Prod. Stud. 15: 31–80, 282–289.

Horton, R. E.
1919. **Rainfall interception.** Mon. Weath. Rev. 47: 603–623.

IAshina, A. V.
1960. **Rol' snega v formirovanii rastitel'nogo pokrova.** In: **Geografiia Snezhnogo Pokrova.** Moscow: Izdat. Akad. Nauk. p. 90–105.

Jaenicke, A. F., and Foerster, M. H.
1915. **The influence of a western yellow pine forest on the accumulation and melting of snow.** Mon. Weath. Rev. 43: 115–124.

Kataoka, K.
1954. **[Snow loads on branches and leaves].** Seppyo 16, No. 3: 1–3, illus.

Kittredge, J.
1953. **Influences of forests on snow in the ponderosa—sugar pine—fir zone of the Central Sierra Nevada.** Hilgardia 22 (1): 1–96, illus.

Kittredge, J., Loughead, H. J., and Mazurak, A.
1941. **Interception and stemflow in a pine plantation.** J. Forestry 39: 505–522.

Knoerr, K. R., and Gay, L. W.
1965. **Tree leaf energy balance.** Ecology 46: 17–24.

Krutzsch, H.
1864. **Die zu forstlichen Zwecken eingerichteten meteorologischen Stationen und die Resultate der Beobachtungen im Jahre 1863.** Jbuch. K. sächs. Akad. Forst– und Landwirthe zu Tharand, 16: 216–226.

Leonard, R. E.
1961. **Interception of precipitation by northern hardwoods.** U. S. Forest Serv. NE. Forest Exp. Sta., Sta. Pap. 159, 16 pp. illus.

Leyton, L., and Carlisle, A.
1959. **Measurement and interpretation of interception of precipitation by forest stands.** Int. Ass. Sci. Hydrol. Publ. 48: 111–119.

Luchshev, A. A.
1940. **Osadki pod pologom lesa.** U.S.S.R. Vses. Nauchn. - Issl. Inst. Lesn. Khoz., Trudy, vyp. 18: 113–148.

Lull, H. W., and Rushmore, F. M.
1961. **Further observations of snow and frost in the Adirondacks.** U. S. Forest Serv. NE. Forest Exp. Sta., Forest Res. Note 116, 4 pp. illus.

Mattoon, W. R.
1909. **Measurements of the effects of forest cover upon the conservation of snow waters.** Forestry Quart. 7: 245–248.

Maule, W. L.
1934. **Comparative values of certain forest cover types in accumulating and retaining snowfall.** J. Forestry 32: 760–765.

Miller, D. H.
1955. **Snow cover and climate in the Sierra Nevada, California.** Univ. Calif. Publ. Geog. 11, 218 pp., illus.

Miller, D. H.
1961. **Meteorological influences on interception of falling snow.** Abstract Bull. Amer. Meteorol. Soc. 42: 289.

Miller, D. H.
1964. **Interception processes during snowstorms.** U. S. Forest Serv. Res. Pap. PSW-18, 24 pp. Pacific SW. Forest & Range Exp. Sta., Berkeley, Calif.

Morey, H. F.
1942. **Discussion of: W. M. Johnson. The interception of rain and snow by a forest of young ponderosa pine.** Trans. Amer. Geophys. Union: 569–570.

Naegler, W.
1940. **Grosser Schneefall und Schneebruch im Dezember 1939.** Z. angew. Meteorol. 57: 30–31.

Ney, C. E.
1894. **Der Wald und die Quellen. In: Aus dem Walde; Wochenbl. f. Forstwirtschaft; Zeitung aus der Praxis für die Praxis der Forst–, Domänen-u. Jagdverwaltung; Organ der Sterbekasse für das deutsche Forstpersonal.** Tübingen. 101 pp., illus.

Nordon, P.
1963. **Forced convective mass transfer in absorption and desorption.** Nature 200: 1065–1066.

O'Loughlin, J. R.
1966. **Evaporation from a draining liquid film.** Amer. Soc. Mech. Eng. J. Heat Transfer 88 C 1:77–79.

Ovington, J. D.
1954. **A comparison of rainfall in different woodlands.** Forestry 27: 41–53.

Pearson, G. A.
1913. **A meteorological study of parks and timbered areas in the western yellow pine forests of Arizona and New Mexico.** Mon. Weather Rev. 41: 1615–1629.

Pruitt, W. O., Jr.
1958. **Qali, a taiga snow formation of ecological importance.** Ecology 35: 169–172.

Ratzel, F.
1889. **Die Schneedecke, besonders in deutschen Gebirgen.** Forschungen z. deut. Landes-Volkskunde 4(3): 109–277.

Rauner, I͡U. L.
1963. **Izmenenie teplo– i vlagoobmena mezdhu lesom i atmosferoi pod vliianiem okruzhaiushchikh territorii.** Izves. Akad. Nauk. Ser. Geog. 1963, 1: 15–28.

Rogers, R. R., and Tripp, B. R.
1964. **Some radar measurements of turbulence in snow.** J. Appl. Meteorol. 3: 603–610.

Rosenfeld, W.
1944. **Erforschung der Bruchkatastrophen in den Ostschlesischen Beskiden in der Zeit von 1875–1942.** Forstwiss. Cbl. u. Thar. forstl. Jrb. No. 1: 1–31.

Rowe, P. B., and Hendrix, T. M.
1951. **Interception of rain and snow by second-growth ponderosa pine.** Trans. Amer. Geophys. Union 32: 903–908.

Rusanov, F. N.
1938. **Snegoval kak faktor, ogranichivaiushchii rasprostranenie pustynnoi rastitel'nosti.** Builleten' Sredneasiatskogo Gosudarstvennogo Universiteta 22: 375–379.

Rutter, A. J.
1963. **Studies in the water relations of Pinus sylvestris in plantation conditions. 1. Measurements of rainfall and interception.** J. Ecol. 51: 191–203.

Saeki, M., and Sugiyama, T.
1965. **Danger zone in snow damage to forest trees by the snow crown.** Govt. Forest Expt. Sta. (Meguro) Bull. 172: 117–137. Engl. summary illus.

Sakharov, M. I.
1949. **Vliianie vetra na pochvu v lese.** Pochvovedenie 1949: 734–738.

Salamin, P.
1959. **Le manteau de neige dans les forêts de Hongrie.** UGGI, Ass. Int. d' Hydrologie Scientifique. Bull. 15: 47–79.

Salamin, P.
1960. **A hótakaró magyarország erdöiben. [The snow cover in the forests of Hungary.]** Erdészeti Kutatások 56:171–195.

Satterlund, D. R., and Eschner, A. R.
1965. **The surface geometry of a closed conifer forest in relation to losses of intercepted snow.** U. S. Forest Serv. Res. Pap. NE-34, 16 pp.

Seppänen, M.
1959. **On the quantity of snow lodging on branches of trees in pine dominated forest on January 16, 1959, during the time of snow destructions in Finland.** Int. Ass. Sci. Hydrol., Publ. 48: 245–247, illus.

Seppänen, Maunu
1961. **On the accumulation and the decreasing of snow in pine dominated forest in Finland.** Fennia 86(1):1–51, illus.

Shidei, T.
1954. **Studies on the damages on forest tree by snow pressures.** Govt. Forest Exp. Sta. (Meguro), Bull. 73: 89 pp., illus.

Shiotani, M., and Arai, H.
1954. **Snow control of the shelterbelt.** Int. Union Geod. Geophys., Int. Ass. Sci. Hydrol., Assem. Rome 1954 Proc.: (4):82–91.

Slatyer, R. O.
1965. **Measurements of precipitation interception by an arid zone plant community (*Acacia anuera* F. Muell).** UNESCO Arid Zone Res. 25:181–192.

Stalfelt, M. G.
1963. **On the distribution of the precipitation in a spruce stand: an attempted analysis. In: The water relations of plants: A symposium of British ecology.** A. J. Rutter and F. H. Whitehead, eds. pp. 115–126. London: Blackwell Scientific Publications.

Sugiyama, T., and M. Saeki
1963. **A survey on the snow damage to forests in Hokuriku District by the snowfall at the end of December 1960.** Japan. Forest Exp. Sta. Bull. 154: 73–95. [Engl. summary.]

Suominen, O.
1963. **Susceptibility of stands to devastation by snow: Investigation into snow devastation in South Finland in winter 1958–59.** Silva Fennica 112(5): 1–35, illus. [Engl. summary.]

Takahashi, K.
1953. [**Snow accumulation on cedars**] Seppyo 15 (3): 25–31.

Takahashi, K.
1962. **Studies on vertical distribution of the forest in Middle Honshu.** Govt. Forest Exp. Sta. (Meguro) Bull. 142: 1–171. illus. [Engl. summary]

Theakston, F. H.
1962. **Snow accumulation about farm structures.** Agr. Eng. 43: 139–141, 161.

Watanabe, S., and Ôzeki, Y.
1964. **Study of fallen snow on forest trees. II. Experiment on the snow crown of the Japanese cedar.** Japan. Govt. Forest Exp. Sta. (Meguro) Bull. 169: 121–139. illus. [Engl. summary]

Wellington, W. G.
1950. **Effects of radiation on the temperature of insectan habitats.** Sci. Agr. 30: 209–234.

West, A. J.
1961. **Cold air drainage in forest openings.** U. S. Forest Serv. Pacific SW. Forest & Range Exp. Sta. Res. Note 180, 6 pp. illus.

West, A. J., and Knoerr, K. R.
1959. **Water losses in the Sierra Nevada.** J. Amer. Water Works Ass. 51: 481–488.

Wilson, W. T.
1954. **Analysis of winter precipitation observations in the Cooperative Snow Investigations.** Month. Weath. Rev. 82: 183–195.

GPO 973-551