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SUBLIMATION OF INTERCEPTED SNOW AS A GLOBAL SOURCE OF WATER VAPOR

by

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This paper summarizes recent experimental results on sublimation and redistribution of snowfall intercepted by conifer canopies, and interprets these findings in terms of global hydrologic significance. Consideration is limited to continental climates in the northern hemisphere, where frequent snowfalls on forested basins are often followed by clear weather and dry air masses.

A review of the interception process on conifers is followed by discussions of the processes which remove intercepted snow from the canopy; wind redistribution, melt, and sublimation. Sublimation appears to account for much of the snow removal from conifer crowns in cold, continental climates. An estimate of the vaporization from the western portion of the Canadian boreal forest is presented as a conclusion to the paper.

SNOW INTERCEPTION BY CONIFERS

Bunnell et al. (1985) present a most complete review and analysis of previous studies on conifer interception. The fraction of a snowfall caught by conifer crowns depends on storm size. Satterlund and Haupt (1967) described the snow water equivalent (SWE) intercepted by single conifer saplings as a sigmoidal growth function of snowfall amount. Strobel (1978) demonstrated a monotonic growth curve for spruce stands, where interception approached a maximum as storm size approached 10 cm SWE. Calder (1990) reported canopy snow interception measured by gamma ray attenuation. This data for a spruce stand also shows a monotonic rather than a sigmoidal growth function (Fig. 1).

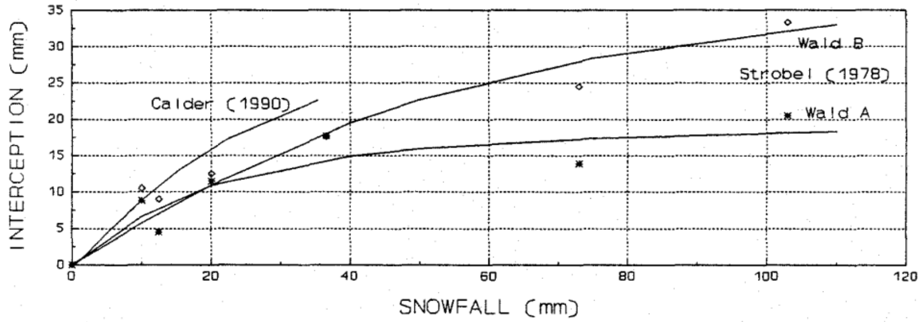

Figure 1. Snowfall (SWE) intercepted by spruce stands, as a function of storm size. Measurements using gamma radiation (Calder 1990) confirm the shape of curves derived by Strobel (1978) from snowboard measurements under canopies of two densities, and in the open.

From a number of the early studies, Harestad and Bunnell (1981) derived a relationship between canopy cover and the ratio of snow water equivalent on the forest floor to that in the open. The portion of snowfall intercepted as a function of canopy cover density showed an inverse dependence on total winter snowpack. That is, the larger the winter's accumulation, the smaller the fraction of total snowfall intercepted, and, in regions of greater total snowfall, stands differing in cover density show smaller differences in interception. Expanding on this result with additional measurements, McNay et al. (1988) presented a conceptual model using mean crown completeness as the measure of

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Presented at the 60th Western Snow Conference, April 14-16, 1992, Jackson, Wyoming.

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canopy cover. This independent variable proved more efficient in predicting interception than other stand parameters, including height, length of crown, crown width, basal area, and stand age.

Schmidt and Pomeroy (1990) found that branch resistance to bending increases with decreasing temperature in the subfreezing range, suggesting that branches might support more interception at colder temperatures (Fig. 5). Increased branch flexibility with warming after snowfall may be an important mechanism for release of intercepted snow.

Schmidt and Gluns (1991) suggested that the pattern of interception growth during snowfall resulted from interaction of three mechanisms--crystal bouncing, cohesive bridging, and branch bending (Fig. 2). Cohesion between crystals builds accumulations that bridge between needles and branches, increasing interception efficiency by increasing surface area. Opposing this, branch bending under the interception load begins to reduce projected area, while increasing the probability that crystals bounce from the surface. Their measurements showed a strong increase in intercepted load as the specific gravity of accumulating snow decreased (Fig. 3). Wind, temperature, and the resulting accumulation density controlled interception on branch tips much more effectively than species growth form.

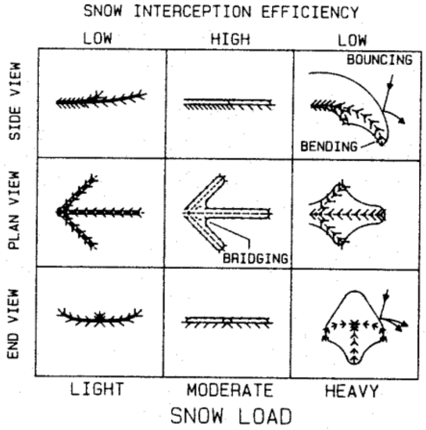


Figure 2. The interaction of snow cohesion and elastic rebound with branch bending determine interception efficiency (Schmidt and Gluns 1991).

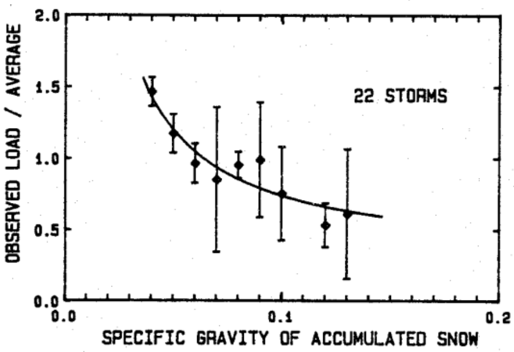


Figure 3. When specific gravity was low the snow mass intercepted by conifer branch tips was greater than the average load for a given storm size (Schmidt and Gluns 1991).

The above work on individual branches indicates that cascading of particles between whorls in a crown, and between canopy elements tree-to-tree, must also play a role in the interception process. The canopy filters particles from the snowfall at rates which depend on stand structure, including height, crown shapes, and clumping of stems. Schmidt and Troendle (1989; and <u>in process</u>) have measured and modeled this filtering, comparing predictions with measurements of snowfall attenuation within a spruce-fir forest (Fig. 4). A conclusion of that effort is that canopy height is an important factor, only partially integrated by measures of mean crown closure.

In their review, Bunnell <u>et al</u>. (1985) also noted that the vertical projected area of a crown was a better predictor of intercepted snow load than its horizontal projected area. They attributed this to the fact that wind most often accompanies snowfall, producing diagonal particle trajectories. The vertical crown component was most effective in predicting <u>interception by individual trees</u> when it was combined with crown width to compute the surface of a cone.

Little has been done to quantify interception of snowfall by a canopy that still holds snow from a previous storm. From observation, branch tips unload first, leaving larger snow masses nearer the boles. On partially loaded canopies, interception of new snowfall should exhibit a combined efficiency of bare branch tips and snow-covered interior crowns. Modeling snowpack accumulation under canopies, using storm precipitation as input, will require simplification of the complex set of antecedent snow-load conditions.

Satterlund and Haupt (1970) concluded, from their measurements on two species of conifer saplings, that meteorological conditions were more important than growth form (of conifers) in determining interception efficiency. Schmidt and Gluns (1991) supported that conclusion, noting the significance of both storm size and snow density in the accumulation process.

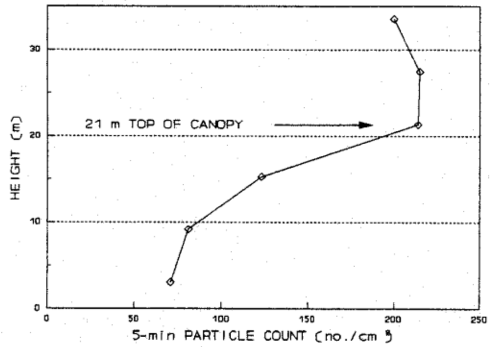


Figure 4. Photoelectric counts of snow particles show strong attenuation with decreasing height in a subalpine forest canopy (Schmidt and Troendle 1989; and <u>in process</u>).

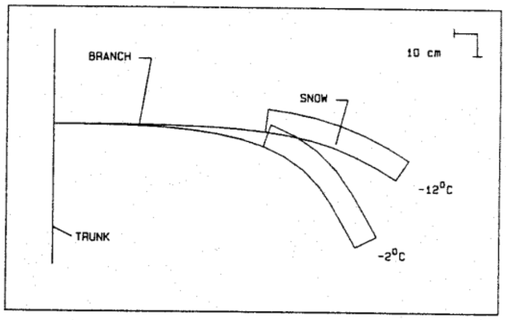


Figure 5. Resistance of conifer branches to bending increases with decreasing temperature, as ice forms in the wood cells (Schmidt and Pomeroy 1990).

WIND REDISTRIBUTION OF INTERCEPTED SNOW

Wind after snowfall removes snow from tree crowns, as the smoke-like plumes visible on clear days attest. Snow-free upper crowns with loaded lower branches, especially on exposed ridges, mark the work of wind. However, as new snow gains internal strength by sintering, the effectiveness of wind in redistributing interception decreases, depending on the temperature history since accumulation. Consideration of wind and particle fall velocities required if plumes are visible above the canopy indicates ice particles smaller than the order 0.1 mm equivalent spherical diameter. Intermittent plumes of such small particles cannot account for the mass of snow removed from tree crowns by wind after snowfall. Troendle <u>et al</u>. (1988) confirmed, by electronic particle counts, that the mass of snow in plumes relocated by wind <u>in non-storm periods</u> made a negligible contribution to snowpack accumulation in a downwind clearing at their subalpine site in the central Rocky Mountains. Most of the intercepted snow mass removed by wind <u>after storms</u> falls as larger accumulations, usually from branch tips, often dislodging snow from lower branches. Of this, most reaches the forest floor within a few tree-heights of the tree that intercepted it.

Wind <u>during snowfall</u> plays a more significant role in canopy interception than wind redistribution after storms. Wheeler (1987) reported snowboard measurements showing that the difference in snowfall accumulation between a clearing and the forest floor <u>decreased</u> with stronger winds during snowfall in central Colorado. Bunnell <u>et al</u>. (1985) describe the complex interaction of wind and temperature that determines snow interception efficiency. Snow cohesion increases rapidly as temperatures warm above -5°C. Wind increases interception at these temperatures, plastering the snow to the crowns. With less cohesion at temperatures below -3 to -5 °C, snow crystals are more likely to rebound from branches, needles, and intercepted snow. Wind increases the kinetic energy of incoming snowfall, reducing interception efficiency and eroding previous interception. Also, because initial cohesion is less at colder temperatures, newly intercepted snowfall is most susceptible to being dislodged from branch tips shaken by wind.

MELTING OF INTERCEPTED SNOW

Melt reduces the fraction of intercepted snow that remains exposed on canopies. This occurs primarily through reducing bond strength, allowing the snow mass to slide from the branch. Bunnell et al. (1985) concluded from their review that melting of about 20% of the intercepted snowload was required to cause release from the branches. Calder (1990, p. 112) used 15% as the maximum liquid water content of intercepted snow, in modeling melt from the canopy.

In cold, continental settings, sensible heat and radiation must often overcome the thermal inertia of canopies and snow exposed to nighttime temperatures far below freezing. Melting in quantities sufficient to cause drip often does not occur during midday excursions of air temperature above 0°C (e.g., Schmidt 1991, p. 19, Fig. 10).

SUBLIMATION OF INTERCEPTED SNOW

The rate at which ice is converted directly to water vapor can be expressed as a balance between heat transfer to the ice, and water vapor transfer from the ice. Without air movement, the process is controlled by molecular diffusion along temperature and humidity gradients. Ventilation speeds the process. Schmidt (1972) applied equations verified in the laboratory by Thorpe and Mason (1963) to the sublimation of wind-blown snow. Wind speed, air temperature, humidity, and radiation are the factors controlling the process. These same environmental factors govern sublimation of intercepted snow (Schmidt 1991).

For snow intercepted on a conifer crown, the rate of sublimation also depends on the extent and nature of surface exposed to these controlling factors. Observing the accumulation-sublimation cycle of interception, the ratio of snow surface area to snow mass increases rapidly during initial snowfall on an empty canopy. As bridging between branches begins, the area-to-mass ratio reaches a maximum (Schmidt 1991). Exposed snow area, and the area/mass ratio begin to decrease if the storm continues. After the storm, area/mass ratios follow a much different path back toward the empty condition (Fig. 6). Small masses are lost first, so that area/mass decreases rapidly as sublimation begins. Barring a new storm, scattered remnants of the intercepted load present very small area-to-mass ratios during final clearing of the canopy.

The nature of the exposed surface determines how effectively the environmental factors control heat and vapor transfer to individual exposed ice grains. Experiments with a 1-m tall, artificial conifer showed that, in the same environment, sublimation was cut to about one-half, 8 hr after snowfall. Snow metamorphosed, reducing the crystal areas exposed while the larger scale area appeared not to change (Schmidt 1991). This process is a known function of time and temperature.

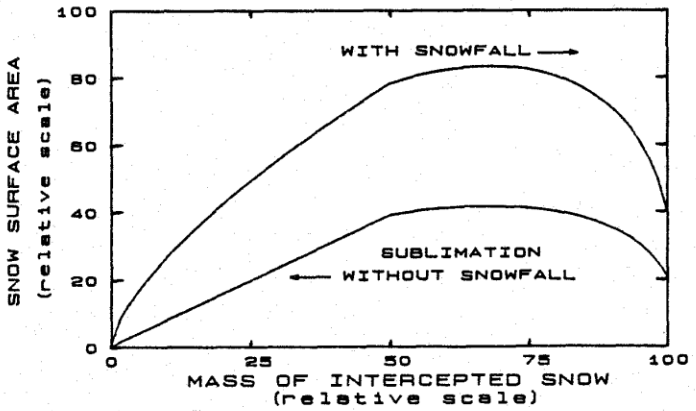
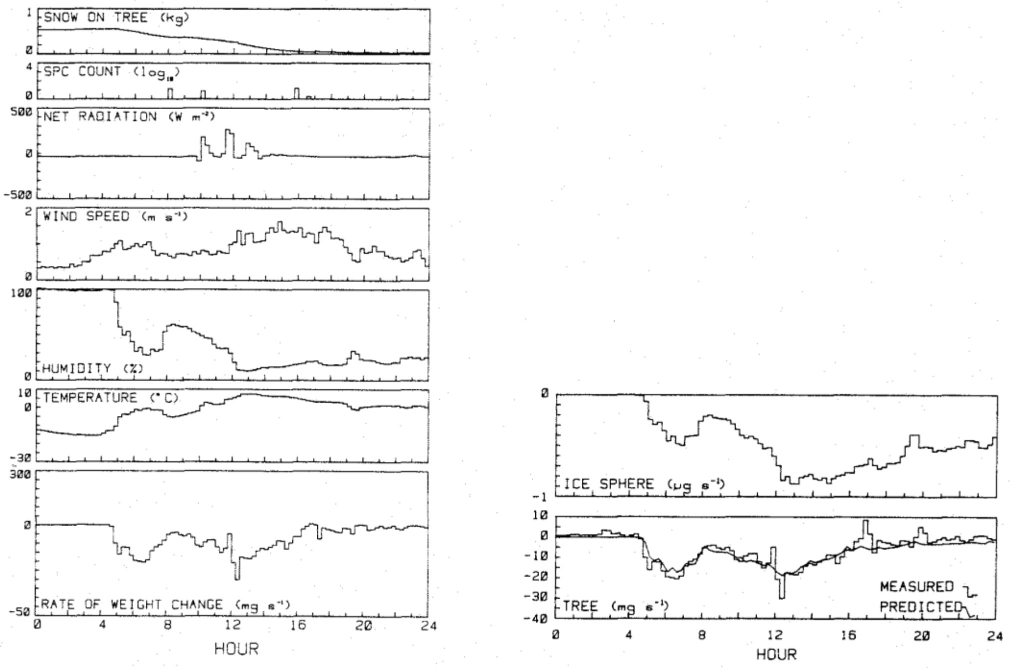


Figure 6. Snow surface area approaches a maximum during snowfall, as bridging first increases, then decreases surface area. During sublimation after snowfall, surface area becomes smaller in proportion to intercepted mass. Schmidt (1991) presents further explanation and experimental verification of this hypothesis.

It may seem surprising that solar radiation has little direct effect on the sublimation of intercepted snow, according to both the experimental measurements and the equations they tested. Most of the energy required for the phase change is extracted from the air, along the temperature gradient that develops as the ice surface temperature drops. The sublimation rate at night is about 90% of the rate with direct solar radiation, given the same air temperature, humidity, and wind speed as the daytime condition. Similarly, if the other environmental factors are the same, the sublimation rate for snow intercepted on a south-slope stand should be only slightly higher than from a north-slope stand that receives no direct sunlight. Indirectly, solar radiation plays the strongest part, of course, by heating the air from which the energy is extracted.

Measurements of snow sublimation from the artificial conifer in a stand of lodgepole pine showed a diurnal cycle corresponding to the variation in controlling environmental factors. Figure 7 shows a typical example. At the study site in a mountain valley, cold air drainage lowered nighttime temperatures, creating humidity conditions that were saturated with respect to ice surfaces. Sublimation rarely occurred at night. Condensation amounts were also negligible, compared to the daytime sublimation. As temperature and wind speed respond to solar radiation in the morning, humidity drops and sublimation begins. The rates were well-correlated with rates computed for a 1-mm diameter ice sphere.



(a) (b)

Figure 7. An example of sublimation from snow intercepted on a 1-m high artificial conifer in a lodgepole pine stand, during one day; (a) the change in snow mass and the controlling environmental factors, and (b) the close correlation of sublimation from the test tree with sublimation predicted for a 1-mm diameter ice sphere in the same environment (after Schmidt 1991).

The specific heat of air is near 200 cal kg^{-1} °C^{-1}. At an air density of 1 kg m^{-3}, extracting 200 calories from a cubic meter of air would drop its temperature one degree centigrade. Measured sublimation rates ranged as high as 30 mg s^{-1} from snow loads up to 5 kg on the artificial conifer. With latent heat of sublimation from snow at 677 cal g^{-1}, sublimating 30 mg s^{-1} would require about 20.3 cal s^{-1}. In complete calm, the cubic meter of air surrounding the snow and tree would cool at a rate near 1°C every 10 s, or 6°C min^{-1}. With typical canopy wind speeds of 1 m s^{-1}, each cubic meter of air passing the small test tree would cool 0.1°C.

At the same time, both the cooling, and additional water vapor increase humidity of the air. Air near 0°C and 750 mb atmospheric pressure contains about 5 g water vapor in each cubic meter at saturation over ice. If still air at 0°C held water vapor at 60% of saturation, cooling at a rate of 6°C min^{-1} would produce saturation in 1 min, without adding water vapor. Adding water vapor to a cubic meter of air at a rate of 30 mg s^{-1}, without cooling, would increase humidity from 60% to saturation in just over one minute. Together, the cooling and additional water vapor that accompany sublimation of snow would certainly bring the process to a halt quickly in still air. However, even the low wind speeds normal within the canopy apparently provide sufficient energy and water vapor exchange to maintain the sublimation process.

Hoover and Leaf (1967) argued that redistribution by wind had been overlooked as an explanation of the increase in snowpack accumulation after timber harvest. They presented photographic evidence that snow remained on a mixed conifer canopy, exposed to sublimation, during 69% of mid-winter days at a site in central Colorado. Our estimates of the fraction of snowfall intercepted, and the portion of that interception that sublimates, correspond closely with average differences in snowpack between forests and openings or clearcuts (Golding and Swanson 1978), even when these open areas are large (Troendle and Meiman 1984, Toews and Gluns, 1986). Kolesov (1985) reported that 40-45% of snow intercepted on dense spruce canopies reached the soil surface. When 50% or more of snowfall was intercepted, 55-60% of that eventually sublimated. This amounts to 27-30% of total snowfall, close to the 30-35% average deficit by which snowpacks under the forest lag snow accumulation in openings.

A SUMMARY OF THE PROCESSES

The significance of recent work on snow interception by conifers, indeed the motivation for this review, is the improvement now possible in modeling the snow hydrology of forested basins. As an example, Troendle (1991) used an improved model to predict the response of subalpine basins to various climate change scenarios. Those simulations used improved subroutines for estimating snow interception and sublimation. Increases in predicted evapotranspiration under warmer climates, although small, resulted from a 70% increase in intercepted snow sublimation, while only 30% of the increase was attributed to use by vegetation. To help guide additional improvements in these models, our present view of conifer interception as part of the hydrologic cycle is summarized below.

Interception is a greater percentage of a winter's snowfall when storms are small, in the range of 5-25 mm water equivalent. In this range, interception is often more than 50% of snowfall when crown closure is 50% or more (e.g., Fig. 1).

Present knowledge suggests that the order of importance of the factors determining interception of snow on conifer canopies is:

1. storm size,
2. canopy surface area (as indexed by canopy closure),
3. wind-temperature effects (including snow density), and
4. species growth habits.

Redistribution of this interception by wind, and release by melting or branch flexure with warming, may reduce intercepted snow load after some storms. However, densification and thermal inertia resist this unloading. Average values of 30% for net interception (after redistribution from the canopy) are reasonable for dense conifer canopies in cold, continental climates.

Because of the greatly expanded surface area of snow on conifers, sublimation can remove amounts of snow equal to the estimated net interception. Advection of sensible heat is the primary energy source. In continental climates at higher latitudes, small, frequent snowfalls of low snow density, intercepted on stiff, frozen branches increase the fraction of the winter's precipitation that is exposed to sublimation during clear periods between storms.

APPLICATION ON A GLOBAL SCALE

Exchanges between the atmosphere and the Canadian boreal ecosystem are presently the focus of a large research effort (NASA, 1992). In hopes that the sublimation of intercepted snow will not be overlooked in that effort, we undertook an estimate of the water vapor that returns to the atmosphere from the 1.658 million square kilometers of that ecosystem extending northwest from the Great Lakes (80°W). Three classes of forest were delineated from a map provided by NASA (1992, Fig. 6). An overlay with five classes of average peak (April 1) snowpack water equivalent was constructed using data from McKay and Gray (1981, Figs. 5.10 and 5.11). Based on the relationships between interception, snowfall and cover density (reviewed above), we assigned values for interception as a fraction of maximum snowpack to each forest class as follows: broadleaf-conifer 20%; conifer-broadleaf 25%; conifer 30%. These are intentional underestimates. In March, 1992, in Prince Albert National Park, Saskatchewan, snow accumulation in a spruce stand was only 60% of the accumulation in a nearby aspen stand (Dr. John Pomeroy, National Hydrology Research Institute, Canada, personal communication, April 2, 1992). Sublimation of 40% of winter snowfall may be much closer to the actual average vaporization from the conifer type.

Ten net interception/sublimation classes resulted from the snowpack-forest overlay, ranging from 1.4 cm at the southern tip of the broadleaf-conifer class to 7.2 cm in the conifer class with 24 cm SWE, just north of Lake Superior. Average interception sublimated over the 1.658 million km^2 was 4.6 cm. Estimated total water returned to the atmosphere from this portion of the boreal ecosystem during a winter with average snowfall was $7.6 \cdot 10^{10}$ m^3. If this water flowed from the area as one river, during the snow season, November 1 to May 1, the average flow rate would be 4200 m^3 s^{-1}. If this river flowed into Lake Superior, it would raise the water level almost 1 m. The ten classes were combined into four, for presentation in Figure 8.

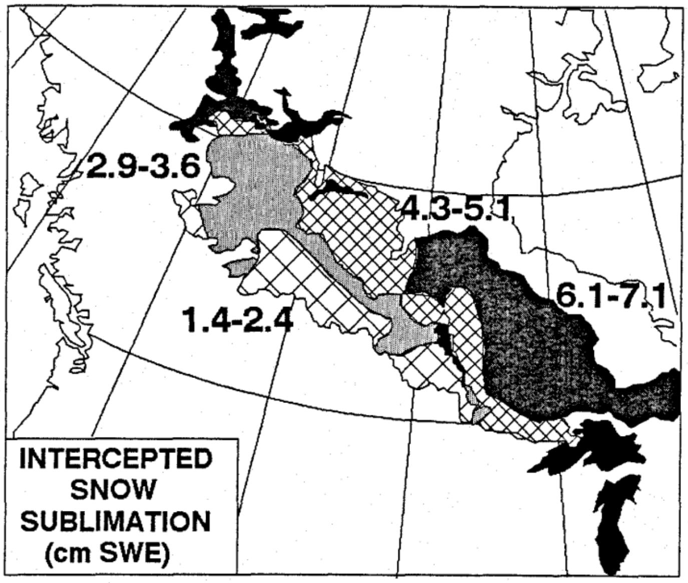


Figure 8. Estimated water equivalent sublimated from an inland portion of the Canadian boreal forest. Average water vapor returned to the atmosphere from the 1.658 million km^2 area was computed at 4.6 cm.

CONCLUSIONS

The greatly expanded snow surface that results when conifer crowns intercept snowfall provides opportunity for much of the intercepted mass to sublimate. In cold, continental climates where such intercepted snow remains exposed during advection of dry air masses following storms, sublimation can reasonably account for removal of the largest portion of interception. As an example, for the western 1.658 million km^2 of the Canadian boreal forests, our estimate that 4.6 cm (SWE) of winter snowfall returns to the atmosphere directly from the forest canopy should be conservative. Climatic changes that alter the distribution of storms by snowfall amount would produce significant adjustments in interception, and perhaps the amount of sublimation. Here, as in other regions of the world, deforesting leads to desiccation of the atmosphere.

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