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Comparative Snow Accumulation and Melt During Rainfall in Forested and Clear-Cut Plots in the Western Cascades of Oregon

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Snow accumulation was compared between forested and clear-cut plots in the transient snow zone of the western Cascade Range of Oregon, and measured snowmelt in both plots was compared to melt predicted by energy balance analyses. The absence of forest vegetation affected both snow accumulation and amount of energy available for melt during rainfall. Because intercepted snow melted in the forest canopy and reached the ground as meltwater, water equivalents in the clear-cut plot were commonly 2–3 times greater than those in the forested plot. During the largest rain-on-snow event of the study, measured water outflow (rain plus snowmelt) in the clear-cut plot was 21% greater than in the forested plot. Estimates made from microclimatological data show that during the common period of melt, total energy available in the clear-cut plot was 40% greater than that in the forested plot. Because of greater wind speed in the clear-cut plot, combined sensible and latent heat transfers in the clear-cut plot were nearly triple those of the forested plot.

INTRODUCTION

Snowmelt during rainfall, commonly called rain on snow, has a dominant role in many geomorphic processes operating in forested watersheds of the Pacific Northwest [*Harr*, 1981]. The majority of both landslides and high streamflows with attendant channel erosion, particularly in the western Cascade Range, have resulted from the rapid input of water to steep slopes during rain-on-snow conditions. Recently, questions have arisen concerning how clearcutting may affect the rate of water input to soils during rain on snow [*Harr and McCorison*, 1979; *Harr*, 1981; *Beaudry and Golding*, 1983; *Harr*, 1986]. One hypothesis is that clearcutting can increase melt rate by increasing the rate at which energy becomes available to the snowpack, primarily through the wind-dependent transfer of latent and sensible heats. Additionally, elimination of snow interception can result in more water equivalent in clearcut areas than in adjacent forests. Consequently, differences in both snow accumulation and subsequent ablation during rainfall could increase rates of water input to soils and streams. This rate of input could be a major cause of landslides and of higher peak streamflows observed in several streams in western Oregon [*Christner and Harr*, 1982; *Harr*, 1986].

Because snowpacks in the mountains of the central west coast of North America are relatively warm and interior temperatures generally remain at or near 0°C [*Smith*, 1974; *McGurk*, 1983], relatively little energy is necessary to initiate melt. Shallow packs of middle elevations (350–1100 m in the western Cascade Range in Oregon) can yield meltwater quickly during warm or rainy periods because their capacity for storage of additional liquid water is low. In these middle elevations, which are referred to as the transient snow zone, it is not unusual for shallow snowpacks to melt completely during rainstorms.

The transient snow zone of western Oregon, like the zones of California, western Washington, and coastal British Columbia, is influenced by warm, moist air from the Pacific Ocean. Snowfalls generally consist of large, wet snowflakes that are easily intercepted and temporarily stored in dense, forest canopies. Once intercepted, the snow may be blown to the ground, but in most instances, it will cling to the tree branches and needles, melt, and fall to the ground as meltwater or in isolated clumps. Evaporation losses are usually quite small compared to the melt losses of intercepted snow [*Miller*, 1966; *Satterlund and Haupt*, 1970].

This paper reports results of a study to compare snow accumulation and subsequent melt during rainfall between forested and clear-cut plots in the transient snow zone of the western Cascades of Oregon. Measured amounts of meltwater from shallow, transient snowpacks were compared with amounts predicted by energy balance analyses.

THE STUDY

The study area consists of two instrumented plots located at the 900-m elevation in the H. J. Andrews Experimental Forest 72 km east of Eugene, Oregon. One plot was in a 22-ha area clear-cut in 1981 and broadcast burned in 1982, and the other was in an adjacent old-growth forest of Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) and western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) 30–60 m tall. Approximate locations of trees and diameters of tree crowns are shown in Figure 1. The clear-cut plot, located 40 m southeast of the forest edge, had an unobstructed view to the S-SW, the predominant direction of winter frontal winds. The forested plot was located about 130 m from the clear-cut plot and 150 m from the windward edge of the forest. The density of the canopy in the forested plot varied between 80 and 90%. Both plots were on nearly level ground, but gradients of surrounding slopes approach 80%.

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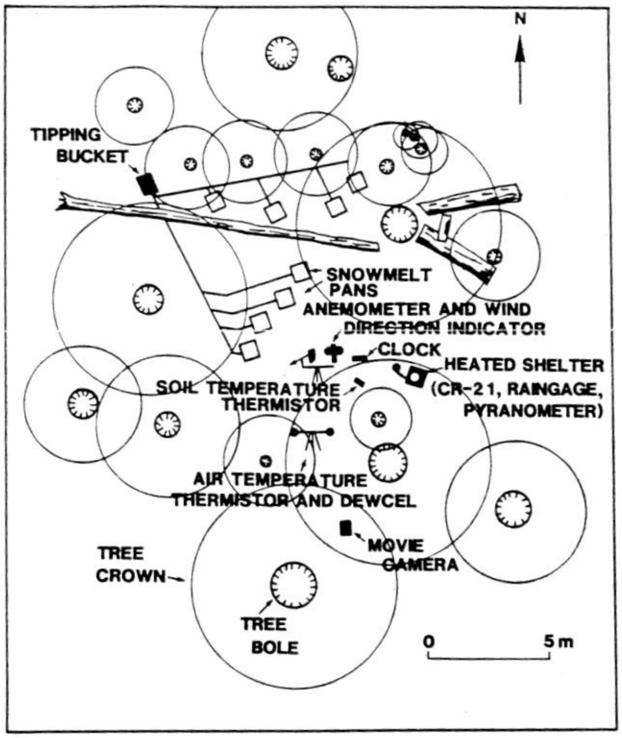

Fig. 1. Plan view of the forested plot.

Instrumentation

Each plot was equipped with micrometeorological sensors connected to a Campbell Scientific CR-21 micrologger (Figure 1). (The use of trade or company names is for the benefit of the reader. Such use does not constitute official endorsement or approval of a product by Oregon State University or U.S. Department of Argiculture Forest Service to the exclusion of others that may be suitable.) Precipitation was measured at each plot with a heated tipping bucket rain gage and augmented by 16 storage rain gages in the forested plot and four in the clear-cut plot. Water leaving each snowpack was measured with a snow melt lysimeter comprised of eight flat, rectangular, fiberglassed, 0.25-m^2 wooden pans connected by buried plastic pipe to a large tipping bucket. Collection pans were scattered throughout the clear-cut plot but were systematically placed under various canopy densities in the forested plot. Wind speed 1.5 m above ground was measured with Weathertronics three-cup, low-threshold, dc generator anemometers. Incoming shortwave radiation was measured with a LI-COR silicon pyranometer calibrated for cloudy conditions. Air and dew point temperatures 1.5 m above ground were measured with shielded thermistors and lithium chloride dew-point hygrometers [*Holbo*, 1981], respectively. Additionally, soil temperature at a depth of 2 cm was measured with a thermistor. The micrologger scanned all sensors every 10 s and computed mean hourly values for shortwave radiation, temperatures, and wind speed, and hourly totals of precipitation and outflow from snowmelt lysimeters.

Each plot was also equipped with time-lapse movie equipment that photographed the plot and vicinity every 15 min. Film records were used to delineate periods of rainfall, snow accumulation, and snowmelt for times when no one was at the site.

When snow was present and rainfall was expected, the plots were visited to measure the density, temperature, water equivalent, and free water content of the snowpacks. Because snowpacks in the transient snow zone are commonly at 0°C and may have free water contents of 10–25% by weight for short periods, the amount of liquid water must be taken into account in this type of study. Free water contents were determined by melting calorimetry [cf. *Yosida*, 1960]. During some visits, snow albedo was measured with upfacing and downfacing Kipp solarimeters, and the temperatures of the cloud base, forest canopy, and tree boles were measured with an infrared thermometer.

Energy Balance Analysis

The following energy balance equation of a melting isothermal snowpack was used to predict hourly snowmelt by heat source at each plot during selected melt periods:

$$Q_m = Q_s + Q_1 + Q_h + Q_e + Q_g + Q_f \tag{1}$$

in which Q_m is net energy flux density used for snowmelt, Q_s is net shortwave radiation flux density, Q_1 is net longwave radiation flux density, Q_h is transfer of sensible heat, Q_e is transfer of latent heat, Q_g is heat transferred from underlying soil, and Q_f is heat transfer due to sensible heat of rain, all in W m^{-2}. For most rain-on-snow conditions, Q_g is relatively unimportant and can be ignored. All terms on the right-hand side of (1) are positive when directed toward the snow pack. *Male and Granger* [1981] provided a thorough review of energy exchange at the snow surface.

Net shortwave radiation, a minor source of heat for snowmelt during cloudy, rain-on-snow conditions, is given by

$$Q_s = (1 - \alpha)K_s \tag{2}$$

where α is albedo, and K_s is incident shortwave radiation. Because of the short life of most shallow snowpacks in the transient snow zone, albedo changes relatively little in the few days generally required to melt the packs. Based on periodic measurements of incoming and outgoing shortwave radiation made with Kipp solarimeters, we assumed $\alpha = 0.85$. This assumption introduced only a small error because there is so little shortwave radiation during cloudy-weather melt.

Net longwave radiation is given by

$$Q_1 = \varepsilon_s \sigma(\varepsilon_0 T_0^4 - T_s^4) \tag{3}$$

where σ is the Stefan-Boltzmann constant (5.67×10^{-8} W m^{-2} °K^{-4}); ε_0 is the emissivity of clouds, water vapor in the air, and forest vegetation; T_0 is the temperature of the base of clouds and of vegetation emitting longwave radiation received by the snowpack; ε_s is emissivity of snow (0.99) [*Dozier and Warren*, 1982]; and T_s is the surface temperature of the snowpack. Because of the dominance of longwave radiation emitted by predominantly low clouds over the clear-cut plot, we assumed ε_0 to be 0.95 [*Arnfield*, 1979] for the clear-cut plot. Longwave radiation emitted by forest vegetation dominated in the forested plot, so we assumed ε_0 to be 0.97 there. During cloudy, windy rain-on-snow conditions, T_0 may be indexed by air temperature T_a [*U.S. Army Corps of Engineers*, 1956].

Because wet-bulb temperature is commonly substituted for raindrop temperature, heat transfer to the snowpack from the rain is given by

$$Q_f = \rho_w C_w T_w P \tag{4}$$

where Q_f is heat transfer by rainfall (kJ m^{-2}); ρ_w is density of water (10^3 kg m^{-3}); C_w is the specific heat of water (4.218 kJ kg^{-1} °C^{-1}); T_w is wet-bulb temperature (calculated from dew-

TABLE 1. Snowpack Characteristics in the Clear-Cut and Forested Plots

	Clear-Cut Plot				Forested Plot			
Date	Depth, mm	Water Equiv-alent, mm	Density, %	Free Water Content, %	Depth, mm	Water Equiv-alent, mm	Density, %	Free Water Content, %
Winter 1982–1983								
Nov. 30, 1982	100	A*	A*	A*	50	A*	A*	A*
Dec. 19, 1982	220	35	16	8	54	21	39	16
Dec. 22, 1982	168	32	19	10	patchy	B†	B†	B†
Feb. 10, 1983	125	40	32	17	patchy	B†	B†	B†
Winter 1983–1984								
Nov. 27, 1983	135	31	23	14	patchy	B†	B†	B†
Dec. 2, 1983	184	37	20	7	48	16	32	12
Dec. 7, 1983	500	116	23	A*	123	42	34	A*
Dec. 9, 1983	215	75	35	13	68	23	33	27
Dec. 12, 1983	200	63	32	A*	43	16	37	15
Dec. 13, 1983	160	60	37	18	32	12	37	B†
Dec. 27, 1983	141	39	28	0	94	30	32	0
Dec. 31, 1983	30	13	43	12	no snow	B†	B†	B†
Feb. 11, 1984	242	36	15	6	42	16	39	23
Feb. 12, 1984	67	18	27	24	patchy	B†	B†	B†
Feb. 19, 1984	64	21	34	11	no snow	B†	B†	B†
Feb. 23, 1984	93	13	14	14	20	11	54	27
Feb. 27, 1984	253	67	27	11	90	30	34	12
March 18, 1984	56	18	32	22	6	3	B†	B†
April 11, 1984	192	A*	A*	A*	73	A*	A*	A*

*A, measurement was not taken.
†B, lack of snow precluded measurement.

point temperature) used to estimate raindrop temperature; and P is amount of rainfall ($m^3\ m^{-2}$).

The melt components Q_s, Q_1, and Q_f, expressed as kJ m^{-2} for 1-hour periods, were divided by the heat of fusion of water (333.4 kJ kg^{-1}) to give predicted depths of snowmelt M_s, M_1, and M_f, respectively.

Because conditions over snowpacks are commonly stable [e.g., *U.S. Army Corps of Engineers*, 1956; *Moore and Owens*, 1984], predictions of meltwater resulting from the turbulent fluxes of sensible and latent heats were based on the assumption that vertical gradients of sensible heat and water vapor above a snowpack can be reasonably estimated by a power law function [*U.S. Army Corps of Engineers*, 1956]. Incorporating exchange coefficients presented by *Sverdrup* [1936] yields

$$M_h = 6.1 \times 10^{-2}(P_a/P_0)(z_a z_t)^{-1/6}(T_a - T_s)v \quad (5)$$

$$M_e = 1.1 \times 10^{-3}(z_a z_d)^{-1/6}(e_a - e_s)v \quad (6)$$

where M_h is melt (mm h^{-1}) due to transfer of sensible heat; M_e is melt (mm h^{-1}) due to transfer of latent heat; P_a is local atmospheric pressure (Pa); P_0 is atmospheric pressure at sea level (Pa); z_a is height of windspeed measurement (m); z_t is height of air temperature measurement (m); z_d is height of humidity measurement (m); T_a = air temperature (°C); T_s is snow temperature (°C); v is wind speed (m s^{-1}); e_a is vapor pressure of air (Pa); and e_s is vapor pressure of snow (Pa). Originally, we had used transfer coefficients developed by the *U.S. Army Corps of Engineers* [1956]. But, because *Anderson* [1968] noted that the coefficient for sensible heat transfer yielded unrealistically low values of sensible heat transfer, we substituted the coefficients derived by *Sverdrup* [1936].

Equations (5) and (6) assume that wind speed is zero, air temperature is 0°C, and vapor pressure is 611 Pa immediately above a snowpack whose surface temperature is 0°C. Equations (5) and (6) were also used to predict melt from sensible and latent heat exchanges in the forested plot, although both equations apply strictly to unforested sites.

RESULTS

Changes in Snow Accumulation

Interception of snow by the old-growth forest canopy greatly influenced characteristics of the snowpack in the forested plot. During snowfall, most snow was intercepted by the forest canopy and remained exposed to the atmosphere. When the energy balance of these snow masses became positive, melt began. *Miller* [1967] suggested that the high exposure of intercepted snow combined with its high surface-to-volume ratio assured relatively large energy transfer during these periods. Observations of canopy melt showed that drip of meltwater from the trees was generally accompanied by the release of masses of snow in a variety of sizes.

Greater canopy melt than surface melt in the forest was commonly observed because of the higher exposure of the intercepted snow to energy inputs. The resulting accumulation of snow was much less on the forest floor than in the clear-cut plot (Table 1). This difference was most pronounced during a series of snowfalls separated by periods of temperatures above freezing when intercepted snow left the canopy as meltwater or as clumps of wet snow. The snowpack in the clear-cut plot melted more slowly because it had less surface area exposed to energy from longwave radiation and sensible and latent heats. After canopy melt, the canopy was again able to intercept more snow during subsequent snowfall. The period between November 24 and December 7, 1983, illustrates such differential accumulation of snow caused by interception processes (Table 1). Five snowfalls of 100–150 mm during this period

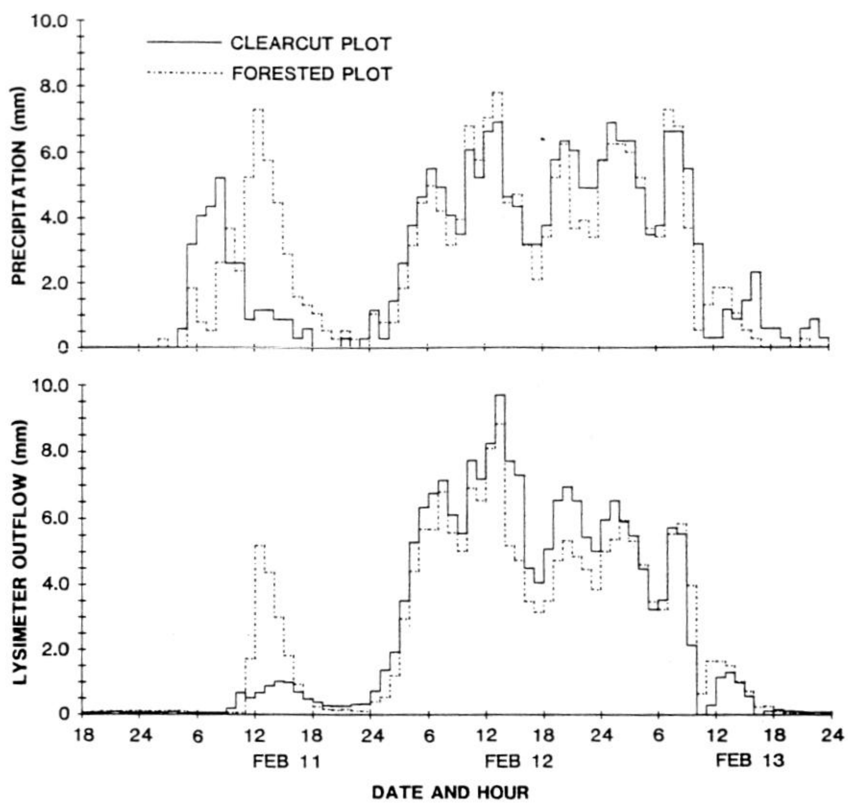

Fig. 2. Precipitation intensity and lysimeter ouflow, February 10–13, 1984.

were separated by periods of canopy melt. By December 7, the snowpack in the clearcut plot was 377 mm deeper and contained 74 mm more water equivalent than the snowpack in the forested plot.

Not only did the forest canopy play a strong role in reducing the accumulation and water equivalent of the forest snowpack, but according to snow survey measurements, snowpacks beneath the forest canopy were usually denser and had higher free water contents than snowpacks in the clear-cut plot (Table 1). The impact of saturated snow masses falling from the canopy increased the density of both the falling masses and the snow already on the ground. Canopy drip also helped to saturate the snowpack in the forest before the snowpack in the clear-cut plot was saturated. Similar observations have been made elsewhere [e.g., *Smith*, 1974; *Beaudry*, 1984].

Changes in Snowmelt

During rain-on-snow periods, the forest canopy also modified the microclimate at the forest floor. The forested plot consistently had lower air and dew-point temperatures, lower wind speeds, and less shortwave radiation than the clear-cut plot. The canopy sheltered the snowpack on the forest floor from the large energy inputs that contribute to snowmelt during rainfall. As a result, energy inputs to snowpacks were consistently greater in the clear-cut plot.

The effect of observed differences in microclimate between the forested and clear-cut plots during this study are illustrated best by the rain-on-snow event of February 11–13, 1984 (Figure 2). Between February 8 and 11, 242 mm of wet snow with 36 mm of water equivalent accumulated in the clear-cut plot compared to only 42 mm of snow with 16 mm of water equivalent in the forested plot. Snow accumulation was followed by 2 days of rainfall totaling 163 mm, the largest rainstorm of the 1982–1984 study period. According to long-term rainfall records for 24-hour rainfall at the H. J. Andrews Experimental Forest, this storm had a return period of roughly 2 years.

Time-lapse photography showed snow disappeared from the two plots at different times. The initial forest snowpack with a water equivalent of 16 mm (snow in the forest canopy could not be measured) completely melted by 1900 hours on February 12. The initial snowpack with a water equivalent of 36 mm in the clear-cut plot did not melt completely until 0300 hours on February 13. Local peak streamflows associated with this rain-on-snow event occurred between 0900 and 1000 hours on February 13. The peak flow at watershed 8, a small gaged watershed located 1 km from the study area, had a return period of 3–4 years.

Precipitation falling as snow during the early morning hours of February 11 became light rain at 0900 hours. The influence of the forest canopy on precipitation intensity and snowmelt lysimeter outflow can be seen in Figure 2. During the snowfall period before 0900 hours, most of the snow falling on the forest was trapped by branches of the forest canopy and was not measured as precipitation. The heated raingage in the clear-cut plot, however, did measure the snowfall, and more precipitation was measured in the clear-cut. After precipitation changed from snow to rain, precipitation measured in the forest consisted of not only rain, but also meltwater from intercepted snow and wet clumps of snow dropping from the canopy. Lysimeter outflow was greater in the forest once rain began because both canopy melt and snow fell from the canopy, whereas in the clear-cut plot, initial rainfall was stored temporarily in the snowpack.

Because we could not differentiate rain and snow in the forest during the first portion of the event, the energy balance

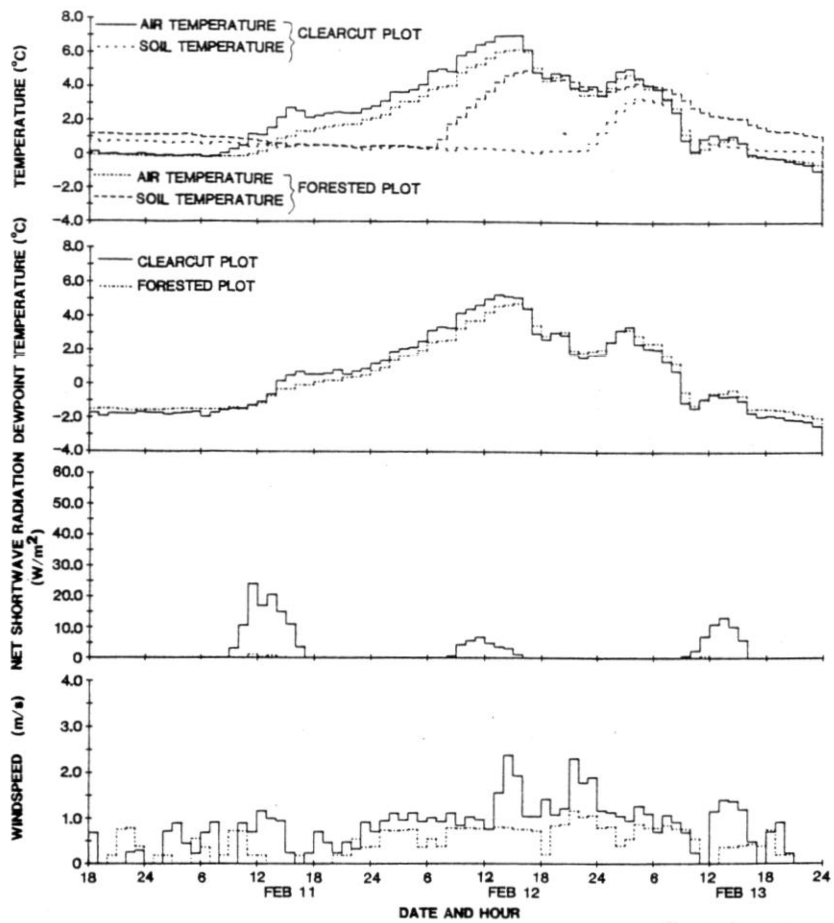

Fig. 3. Measured microclimatic variables, February 10–13, 1984.

analysis began at 2300 hours on February 11 for both plots. At this time, no intercepted snow remained in the forest canopy. The times snow disappeared from the plots (1900 hours on February 12 in the forested plot and 0300 hours on February 13 in the clear-cut plot) were designated as the ends of the respective energy balance analyses. During the 28-hour period of analysis for the clear-cut plot, 122 mm of rain fell compared to 113 mm measured in the forested plot. During the 20-hour period of analysis for the forested plot (the length of time snow remained on the ground in the forest), however, rainfall totaled only 73 mm.

The clear-cut plot consistently had higher air and dew-point temperatures, higher net shortwave radiation, and higher wind speeds during the energy balance analyses (Figure 3). Thus computed melt attributable to the various sources of heat were higher for the clear-cut plot (Table 2). Net shortwave radiation, which was very low during the entire rain-on-snow event, peaked at only 6.6 W m^{-2} on February 12 in the clear-cut plot and was barely measurable in the forested plot. Time-lapse photographs substantiate extremely dark daylight hours with low, thick clouds. Net shortwave radiation accounted for 1% or less of total energy available for melt. A 3-hour period of relatively large increases in sensible and latent heat melts began at 1300 hours on February 12 as a result of increased wind speed. A second 3-hour period of increased wind speed that began at 2100 hours on February 12 did not cause as great an increase in either sensible or latent heat melt because both air and dew-point temperatures were much

TABLE 2. Melt Predicted by the Energy Balance Model Versus Measured Melt

	Clear-Cut Plot*			Forested Plot†		
	Predicted Melt		Measured Melt,	Predicted Melt		Measured Melt,
Energy Source	mm	%	mm	mm	%	mm
Shortwave radiation	0.3	1		0.0	0	
Longwave radiation	2.9	13		2.8	25	
Sensible heat	7.8	35		2.7	24	
Latent heat	4.8	22		1.8	16	
Rain	6.4	29		3.9	35	
Total	22.2	100	25.1	11.2	100	11.9

*From 2300 hours February 11, 1984, to 0300 hours February 13, 1984.
†From 2300 hours February 11, 1984, to 1900 hours February 12, 1984.

lower. Small patches of bare ground appeared in the forest at 0700 hours and in the clear-cut at 1500 hours on February 12. The patches grew gradually until the ends of the analysis periods when all of the snow had disappeared from the lysimeter pans. We could not account for the small amounts of advected heat from bare ground.

In the absence of wind speeds above 1 m s^{-1} for a major portion of the February 11–13 melt period, longwave radiation and rain heat were greater relative sources of snowmelt during this rain-on-snow event (Table 2) than would have been the case had wind speeds been higher. Because wind speeds in the forested plot were lower than in the clear-cut plot, rain heat was the major source of heat for melt in the forest. Combined sensible and latent heats, which together often accounted for 40–50% of total melt during the rain-on-snow conditions studied by the *U.S. Army Corps of Engineers* [1956], were 40 and 57% in the forested and clear-cut plots, respectively.

Snowmelt predicted by the energy balance model agrees well with that measured in both plots (Table 2). Predicted melt was 88% of measured melt in the clear-cut plot and 94% of measured melt in the forested plot. Predicted melt and measured melt in the clear-cut plot were both approximately double the size of their counterparts in the forested plot, but part of this difference is due to an 8-hour longer melt period in the clear-cut plot. During the common period of melt, predicted melt and measured melt in the clear-cut plot were both about 40% greater than those in the forested plot. The agreement between measured melt and melt predicted by energy balance analysis reflects somewhat the transfer coefficients used in (5) and (6). For example, using coefficients developed by the *U.S. Army Corps of Engineers* [1956] yields predicted transfers of sensible and latent heats that are only 29 and 80% of the respective values shown in Table 2 and predicted total melts that are 72 and 83% of measured melts in the clear-cut and forested plots, respectively.

A separate estimate of melt was obtained from snow survey information (Table 1) adjusted for rainfall and snowmelt that occurred between the time of the survey and the start of the energy balance analyses. In the clear-cut plot the 26 mm of melt predicted from snow survey data agrees very well with both the measured melt and melt predicted by energy balance analysis. In the forested plot, however, the 17 mm of melt predicted by snow survey data was greater than both the measured melt and melt predicted by the energy balance analysis. Most likely this discrepancy resulted from different snowpack conditions over lysimeter pans compared to where snow measurements were made.

Because the transfers of latent and sensible heats to snowpacks are dependent on wind as a driving mechanism, they can be combined into an overall turbulent energy flux. In this way the importance of wind in melting snow becomes evident. Although the rain-on-snow event described here did not have high winds (the highest mean hourly wind speed was only 2.4 m s^{-1}), snowmelt caused by the turbulent energy fluxes was nonetheless very important. Differences in wind speed between plots accounted for most of the differences in energy available for snowmelt not only in the February 11–13 event described here but also in the other rain-on-snow events in the study.

The relative (29%) contribution of rain heat to snowmelt in the clear-cut plot during the February 11–13, 1984, rain-on-snow event is greater than the contribution of rain heat observed in other studies. For example, *Fitzharris et al.* [1980] determined that transfer of rain heat contributed 19% of the total heat flow during rains of over 10 mm h^{-1} for 25 hours. Also, *Anderton and Chinn* [1978] found that rainfall provided 19 and 11% of the total energy supply on two successive days of rain. In other studies, however, heat from rain accounted for less than 8% of total melt [*Braun and Zuidema*, 1982; *Prowse and Owens*, 1982; *Moore and Owens*, 1984].

Shortwave radiation, particularly in the forested plot, played a minor role in this study. Dense, low cloud cover and considerable melt during darkness combined to make net shortwave radiation the least important source of heat for melt. This contrasts markedly with snowmelt during clear, sunny weather when net shortwave radiation is the dominant source of heat for melt [e.g., *Anderson*, 1968; *Hendrie and Price*, 1979; *McKay*, 1979].

An error analysis adapted from the technique described by *Scarborough* [1966] indicated large relative probable errors for several melt components under certain conditions [*Berris*, 1984]. Because the study had been designed to examine larger rain-on-snow events than occurred during the 2-year study, relative probable errors were smallest when values of microclimatological variables approached those commonly associated with larger rain-on-snow events. The February 11–13 rain-on-snow event, although the largest of the study, was marginal when compared with larger rain-on-snow events of the past 20 years. Melt conditions were characterized by $T_a = 4°–7°C$, $T_d = 3°–5°C$, $v = 1 - 2.5$ m s^{-1}, and $P = 4 - 6$ mm h^{-1}. Under these conditions, relative errors are as follows: M_s, 28%; M_1, 25–37%; M_h, 10–21%; M_e, 28–48%; and M_f, 25–39%. The error associated with M_s is inconsequential because M_s contributed little to total snowmelt. Much of the error associated with M_1 results from the assumption that cloud base and vegetation temperatures can be indexed by T_a; according to measurements made with an infrared thermometer, both were overestimated. Errors in M_h and M_e resulted from errors in measuring T_a, T_d, and v, and error in M_f was caused primarily by error in measuring T_d and T_a from which wet-bulb temperatures were determined. Error in snowmelt measurement was estimated to be 10%.

DISCUSSION

Results of this study suggest several critical conditions that determine whether a forested area or a clear-cut area will have higher outputs of water (higher rates of water input to soil). During snowfall when air temperatures are near or above 0°C or when rainfall occurs while intercepted snow is present in the forest canopy, the forested area will exhibit higher outputs of water [*Harr and McCorison*, 1979]. This is the result of canopy snowmelt, described earlier. If light rain (less than 3 mm h^{-1}) is falling and no snow is in the forest canopy, water outflow may be greater in either the forested or the clear-cut area depending on differences in snowpack characteristics such as patchiness, free water content, and density. Finally, at rainfall rates greater than 5 mm h^{-1} without snow present in the forest canopy, water outflow from the clear-cut area will be greater than that of the forested area once the snow's water-holding capacity has been satisfied. In our study the difference resulted from both greater accumulation of snow and greater inputs of energy to the snowpack in the clearcut area. If rainfall is accompanied by warm, windy conditions, the outflow from the clear-cut area will be increasingly greater as wind speed increases.

From the standpoint of forest management, some of the situations described above are considerably more important than others. Landslides and erosion of stream channels are dependent on relatively high rates of water input to soils over prolonged periods of at least 12–24 hours. Thus differences in water outflow between forested and clear-cut areas that might result from the presence of intercepted snow in the forest canopy appear to be of minimal concern. The maximum amount of water that can be stored as intercepted snow seems insufficient to have a major effect on the rate of water input to soils during the latter part of the water input event, the critical part from an erosion point of view. In other words, maximum streamflows and landslides do not occur at the beginning of a rain-on-snow event when melting of intercepted snow would have its greatest relative contribution.

On the other hand, a series of snowfalls separated by periods when intercepted snow melts will maximize the differences in snowpack water equivalent between forested and clear-cut areas. This could set the stage for large differences in water outflow that could affect both onsite geomorphic processes (mass erosion in clearcut areas on steep slopes) and those offsite (stream channel erosion due to higher peak flows caused by a higher rate of water delivery to streams), particularly if appreciable winds accompany the rainfall. This is illustrated by the rain-on-snow event of February 11–13, 1984. Cumulative outflow from the melt lysimeter in the clear-cut plot was 27 mm (21%) greater than in the forested plot between 2300 hours on February 11 and 0300 hours on February 13, when the snow of both plots had disappeared. This increased outflow was due to not only greater accumulation of snow in the clear-cut plot, but also an increased melt rate that resulted from greater inputs of energy. Because of the low slope of the plotted frequency curve of water input for the H. J. Andrews Experimental Forest where this study was conducted [*Harr*, 1981], an increase in water input of 21% would more than double the size of the return period of the water input event. In other words, larger water input events would become more frequent simply because of the removal of forest vegetation.

Estimates of relative frequencies of occurrence of the critical conditions that could lead to both increased mass erosion and higher peak streamflows during rain-on-snow events are necessary to place the results of this study in perspective. Mass erosion and streamflows high enough to modify stream channels or to carry sediment are of concern to forest land managers. Although it seems clear that the combination of greater accumulation of snow and energy inputs to snowpacks in clear-cut areas can cause greater rates of water input to soil, we need to know how often this situation occurs. In the 2-year study described here, there were seven series of snowfalls that resulted in accumulations of at least 100 mm of snow in the clear-cut plot with little or no snow in the forested plot. But in only two of these instances did subsequent rainfall remotely approach amounts generally associated with mass erosion and high streamflows in the region. This appears contrary to the occurrence of large rain-on-snow events over the past 20 years. Based on weather records for the H. J. Andrews Experimental Forest, we estimate that substantial rainfall on a snowpack at least 100 mm deep and containing at least 25 mm of water equivalent has occurred 3-6 times a year. Thus the conditions during this study seem uncommon and are far removed from the conditions needed to produce a rain-on-snow event with a return period of about 5 years, the size event likely to result in erosion.

Before results of this study can be incorporated into forest management guidelines, the study should be replicated. Additional information will be needed on how forest regrowth modifies both the snow accumulation and melt conditions of a clearcut area. Preliminary results from a companion study indicate that energy inputs to snow in a thinned, 25-year-old plantation of Douglas-fir are intermediate between those of the forested and clear-cut plots described here. Interception in the plantation, however, appears to be vastly different than in the old-growth forest. The more flexible branches of 25-year-old trees will not support intercepted snow long enough for it to melt; rather, the snow slides off the branches and accumulates in donut-shaped piles around the tree boles. The resultant snowpack is very irregular with maximum depths of snow around the bases of individual crowns that may exceed depths in an adjacent clear-cut area.

CONCLUSIONS

Results of this study illustrate several important ways clearcut logging in the transient snow zone can affect snow-related processes that may drastically alter the land's ability to route water during rain-on-snow events. First, the forest canopy, by intercepting snow that eventually melted and reached the forest floor as meltwater, allowed the forest to route water offsite earlier than in the clear-cut plot. Snow interception in any given snowfall may have had only a minor effect on water outflow, but the additive effect of a series of snowfalls separated by periods of small inputs of energy for snowmelt was substantial. Such a situation is common in the transient snow zone where air temperature often hovers around 0°C. As a result, the forested plot commonly routed up to 70% of its snow as meltwater prior to a rain-on-snow event.

Second, the absence of forest trees resulted in consistently higher inputs of energy to snow in the clear-cut plot. Although net longwave radiation and net shortwave radiation were greater in the clear-cut plot, the greatest portion of the difference in energy exchange between the forested and clear-cut plots was attributed to differences in sensible and latent heat fluxes. Even during periods of relatively low wind speeds that prevailed during this study, calculated sensible and latent heat fluxes in the clear-cut plot were generally 2–3 times greater than in the forested plot. During one 3-hour windy period, computed melt from combined sensible and latent fluxes in the clear-cut plot was more than 6 times that in the forested plot. Because of dense clouds and few daylight hours, shortwave radiation was a minor source of energy for snowmelt.

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