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# Effect of Ashfall on Snowmelt Rate at Paradise, Mount Rainier, Washington

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Snowpack data and temperature information in the form of degree-day calculations are analyzed for Paradise, Mt. Rainier, for the weeks following the May 18, 1980, eruption of Mt. St. Helens. The figures are compared with similar computations for the preceding 25 years. The results show that the dark ash layer increased the snowmelt rate by some 40% over what would have been expected from ambient temperatures.

## INTRODUCTION

The Mt. St. Helens eruption of May 18, 1980, provided a unique opportunity to study the effect of a layer of volcanic ash on a mountain snowpack. The only regular reporting weather station receiving an ashfall, and which still had significant winter snowpack on the ground, was at Paradise, Mount Rainier, operated by the National Park Service. Records of temperatures, precipitation, snowfall, and snow on ground are available from Paradise since 1955 [*NOAA*, 1955–1980].

Paradise lies at an elevation of 1658 m on the south side of Mount Rainier. The upslope conditions and prevailing westerlies typically produce prodigious winter snowfalls, with accumulations of over 25 m on four occasions in the past 26 years. The mean annual snowfall is 17.68 m, and the mean greatest depth is about 5.43 m, which occurs in early April (with a standard deviation of about 3 weeks). Melting reaches its peak by late May and June, and the snow usually has disappeared by mid-July, again with a spread of about 3 weeks depending on snowfall amounts and ambient spring temperatures.

## 1980: THE ERUPTION: EFFECTS AT PARADISE

Paradise is located 74 km north-northeast of Mt. St. Helens, at a bearing of 27° east of north from the latter peak. On May 18, 1980, Paradise received an ashfall of 0.0032 to 0.0064 m ('1/8 to 1/4 inch'; Garry Olson, National Park Service, private communication, 1980). The ash cover was evident on the snow until meltoff in late June and early July (despite some late spring snowfall). A subjective impression on the author was that the Paradise snowpack was much harder and more compact following the ash; a person could easily walk on top of the snow, while normally at that time of year one would sink in 0.15 m or more during the heat of the day.

In 1979–1980 the total snow accumulation at Paradise was 16.62 m, a little below normal; maximum depth was 4.55 m, which occurred on April 7 and 10. Melting in April and early May was a bit faster than usual, so that only 2.51 m of snow remained on May 18, compared to a mean of 4.00 m for that date. About 0.31 m of new snow accumulated after May 18, resulting in a total of 2.82 m of snow to be melted after the eruption.

The 25-year mean of snow depletion per day, after May 18, is 0.0711 ± 0.0104 m per day. In 1980 the snow had melted completely by July 1, 44 days after the eruption. The depletion rate for 1980 was therefore 2.82/44 or 0.0641 m/day, a bit below normal, but not particularly unusual.

When temperature data are considered, however, a different picture emerges. Daily temperatures for the 6 weeks after the eruption were among the coldest in 26 years, so that the Paradise snowpack actually disappeared more rapidly than one would expect. This would be due, of course, to lowered albedo and increased absorption of what radiation was present because of the dark ash layer.

## DEGREE-DAY CALCULATIONS

A principal method of heat transfer is by conduction, in which the rate of energy flow is proportional to the temperature difference. To melt snow, temperatures above freezing are needed. This suggests a simple model, using the concept of 'thawing degree days' [*Collins*, 1934; *Foster*, 1949]. A thawing degree day (TDD) can be defined as the difference between the daily mean temperature and freezing, 0° C, if the mean temperature is >0°C and zero otherwise.

In the present paper, a somewhat refined TDD calculation was used. During the melting season under study there were many days when temperatures bracketed the freezing point. For example, the maximum and minimum readings for a day might be +5° and −5°C, which average to 0°C and normally would not yield any thawing degree days. Yet a maximum of +5° obviously allows some thawing.

To account for such days exactly would require hourly temperature data. But a good approximation can be made by assuming a uniform daily temperature cycle. In that case one can easily show that the degree-day calculation may be given by

$$\mathrm{TDD} = \frac{(\max)^2}{2(\max - \min)} \tag{1}$$

when daily maxima and minima are known. For the example, max = +5° and min = −5°, equation (1) yields 1.25 TDD instead of zero. The correction is always positive or zero and can have a significant accumulation during the early part of the melt season.

TDD were computed for Paradise for the period 1955–1980, May 1–18 and May 19 to meltoff. Dividing the May 19 to meltoff TDD by the original snow on the ground on May 18 (adjusted as explained below) gives a measure of the effectiveness of daily temperatures on the thawing process in the snowpack. The choice of May 19 for beginning the calculation allows a comparison of 1980 with the other years. These results are compiled in Table 1 and are plotted in the graph of Figure 1.



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TABLE 1. Snowpack, Melting, and Thawing Degree Day (TDD) Comparisons at Paradise, Mount Rainier, for 1955–1980

| | (*a*) May 18 Ground Snow, m, (adjusted) | (*b*) Days, May 19 to Meltoff | (*c*) TDD May 1–18 | (*d*) TDD, May 19 to Meltoff | (*e*) TDD per Meter of Original Snow |
|---|---|---|---|---|---|
| Year | | | | | |
| 1955 | 5.08 + 0.46 = 5.54 | 79* | 61.28 | 598.30 | 108.1 |
| 1956 | 5.79 + 0.15 = 5.94 | 72 | 83.84 | 580.80 | 97.7 |
| 1957 | 2.92 + 0.00 = 2.92 | 44 | 119.03 | 328.12 | 112.3 |
| 1958 | 3.51 + 0.00 = 3.51 | 38 | 130.25 | 431.94 | 123.2 |
| 1959 | 3.99 + 0.20 = 4.19 | 59 | 54.55 | 431.66 | 103.0 |
| 1960 | 3.63 + 0.20 = 3.84 | 50 | 64.61 | 370.50 | 96.6 |
| 1961 | 4.70 + 0.00 = 4.70 | 55 | 50.62 | 583.54 | 124.2 |
| 1962 | 3.53 + 0.13 = 3.66 | 60* | 22.45 | 369.46 | 101.0 |
| 1963 | 2.84 + 0.00 = 2.84 | 39 | 53.65 | 288.59 | 101.4 |
| 1964 | 5.18 + 0.23 = 5.41 | 74 | 45.08 | 603.26 | 111.5 |
| 1965 | 3.53 + 0.03 = 3.56 | 51 | 59.78 | 410.88 | 115.5 |
| 1966 | 2.51 + 0.13 = 2.64 | 42 | 120.88 | 249.05 | 94.3 |
| 1967 | 5.33 + 0.03 = 5.36 | 56 | 74.93 | 555.31 | 103.6 |
| 1968 | 2.39 + 0.00 = 2.39 | 36 | 78.38 | 217.95 | 91.3 |
| 1969 | 1.90 + 0.03 = 1.93 | 39* | 137.47 | 386.63 | 200.3 |
| 1970 | 3.56 + 0.05 = 3.61 | 47 | 57.46 | 353.68 | 98.1 |
| 1971 | 5.99 + 0.13 = 6.12 | 83* | 103.23 | 752.75 | 123.0 |
| 1972 | 6.50 + 0.05 = 6.55 | 82 | 95.81 | 820.70 | 125.2 |
| 1973 | 2.24 + 0.28 = 2.51 | 46* | 114.76 | 270.98 | 107.8 |
| 1974 | 7.16 + 0.28 = 7.44 | 101 | 41.71 | 922.47 | 124.0 |
| 1975 | 4.80 + 0.36 = 5.16 | 75 | 75.23 | 627.80 | 121.8 |
| 1976 | 4.34 + 0.25 = 4.60 | 74 | 103.06 | 467.23 | 101.6 |
| 1977 | 2.11 + 0.18 = 2.29 | 39 | 38.13 | 249.42 | 109.1 |
| 1978 | 3.58 + 0.13 = 3.71 | 59 | 37.86 | 451.21 | 121.7 |
| 1979 | 2.95 + 0.56 = 3.51 | 54 | 69.37 | 418.62 | 119.4 |
| Means | | | | | |
| 1955–1979 | 4.16 | 58.2 | 75.69 | 469.63 | 113.4 |
| | ±1.47 | ±17.5 | ±31.92 | ±182.89 | ± 21.0 |
| Excluding 1969 | 4.25 | 59.0 | 73.12 | 473.09 | 109.8 |
| | ±1.43 | ±17.4 | ±29.84 | ±185.99 | ± 11.0 |
| 1980 | 2.51 + 0.30 = 2.82 | 44 | 93.47 | 180.10 | 63.9 |

*Days to meltoff partially estimated. See text.

## Explanation of Table 1: Data Adjustments

*Column a. Ground snow on May 18 (adjusted).* The first figure is the reported snow depth on May 18 (5.08 m in 1955). The added figure (0.46 in 1955) represents any reported increases in ground snow depth (not actual snowfall amounts). The final figure (5.54 in 1955) represents what the snow depth on May 18 would have been, if all late snowfalls had occurred on that day. This seemed to be the most reasonable way to account for additions of snow after May 18. The sum figure is the one compared with TDD after May 18 in Column e. (Note: Original calculations were made in English units, as given in the NOAA data, and were converted to metric for this paper. Snow depths are rounded to the nearest 0.01 m, and any apparent discrepancies in addition are due to round off in the first two numbers.)

*Column b. Number of days, May 19 to meltoff.* This is the number of days from May 19 to and including the first reported day with zero snow (or a trace). On a few occasions there were apparent missing data near the time of final snow disappearance. In such cases (denoted by an asterisk in Table 1) the snow depths and final dates of snow on the ground were estimated from temperature data. The days thus added to totals, and corresponding added TDD, are as follows: 1955, 3 days, 37.5 TDD; 1962, 2 days, 10.5 TDD; 1968, 3 days, 22.8 TDD; 1969, 5 days, 17.9 TDD; 1971, 2 days, 40.0 TDD; 1973, 4 days, 21.2 TDD. (See also later remarks concerning 1969 data.)

*Column c. Thawing degree days for May 1–18.* This allows temperature comparisons prior to the eruption. Occasional missing temperature data are accounted for by interpolation between given data so as to avoid gaps in TDD totals.

*Column d. TDD, May 19 to meltoff.* Occasional gaps in data are filled in by interpolation as in column c. See also adjustments in column b above.

*Column e. TDD per meter of original snow.* This is column d divided by column a, using adjusted ground snow as explained above.

It will be noted that the year 1969 had an anomalously high value of TDD per meter, 200.3 compared to the mean of 113.4 ± 21.0. In that year there were 4.14 m of snow on the ground on May 1, following a peak snow depth of 6.50 m on February 10. There was unusually rapid ablation of the snowpack during the first 18 days of May, resulting in only 1.90 m remaining on that date. Thereafter the decrease in

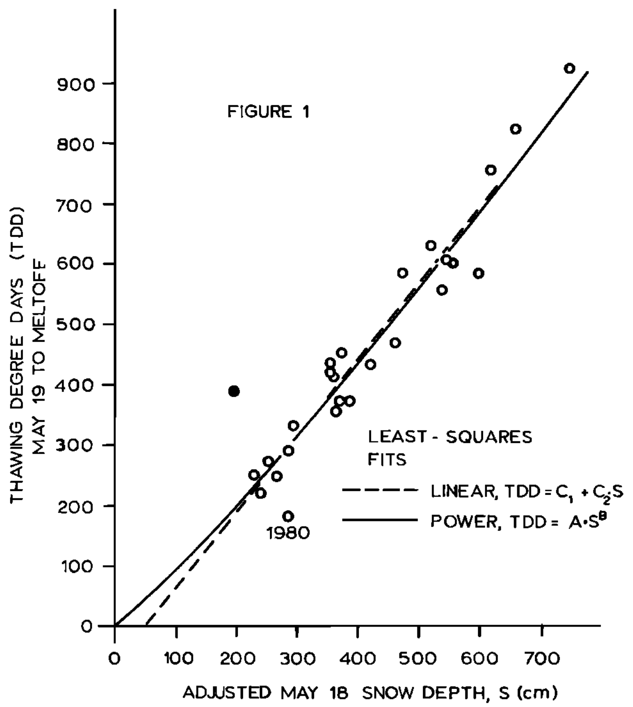


Fig. 1. Thawing degree days (TDD) versus adjusted May 18 snow depth (S) at Paradise, Mount Rainier, for the period 1955–1980. Least squares curves omit 1969 data point (solid circle).

depth was much less rapid, although temperatures were similar to those in the first part of May. One could postulate unusual snow densities that year or possibly abnormal drifting patterns in the measurement area. Actually, if one could use data from May 1 through meltoff, the 1969 totals come out near normal: 121.4 TDD/m.

Further, the 1969 data reported 0.28 m of snow on the ground on June 20, and none the next day, although on May 21 and on succeeding days it was cool and should not have caused that much snow to melt. Accordingly, 5 more days were estimated for actual meltoff. If these 5 days are excluded, the 1969 result would be 188.5, still far above normal.

Means are computed both with and without 1969 data. The mean of TDD/m has a much lower standard deviation if 1969 is omitted; and the 1969 value, being high, raises the mean value while the 1980 figures were much lower than usual. For these reasons the best comparisons of 1980 data seem to be with means omitting 1969.

## Discussion of Results

The thawing degree days needed to melt a meter of snow, for Paradise during the period 1955–1979, May 19 to meltoff, averaged fairly consistently to 109.8 ± 11.0, if one omits 1969. Yet in the ashfall year of 1980 this value dropped abruptly to 63.9 TDD/m, 41.8% below normal and 30% below the next lowest value, 91.3 in 1968. This means that the heat transfer processes were altered in 1980; solar radiation was more effective than usual in melting snow, owing to lowered albedo of the snow, from ash.

Other comparisons of 1980 with previous years are possible. The 5 years 1957, 1963, 1966, 1968, and 1973 all had May 18 adjusted snow depths near the 1980 value of 2.82 m. The mean value of TDD/m for those years was 101.4 ± 8.8; 1980's value was 37% lower.

Calculations were also made of the TDD needed to remove 2.82 m of snow regardless of dates of occurrence in each of the years under study. The mean for 25 years was 119.0 ± 21.2 TDD/m, compared with the 1980 value of 63.9 (46% lower). The mean number of days required to remove this much snow was 36.5 ± 8.1, so that 1980's 44 days were on the high side, owing to the lower daily temperatures.

Indeed, the temperature patterns before and after the eruption are themselves of interest. Column c of Table 1 shows that 1980 had 93.47 TDD from May 1–18, while (from column d) there were 180.10 TDD from May 19 to meltoff (July 1). If one divides the TDD by the number of days, one obtains a kind of effective thawing temperature for that period; for temperatures always above freezing, it would be simply the mean daily temperature. This effective temperature for 1980 was 5.2°C for May 1–18, but only 4.1°C for May 19 to July 1. The means for the other years (excluding 1969) are 73.12 TDD for May 1–18 (4.1°C) and 301.68 TDD for May 19 to July 1 (6.9°C). Thus the weather patterns changed abruptly following the eruption, from warmer than normal to much colder than normal. Indeed, 1980 was by far the coldest period for May 19 to July 1 in the 26 years of study. It would be of interest to study the extent and causes of this weather pattern.

## Least Squares Curves

Least squares fits (plotted with data, Figure 1; snow depths in centimeters) of the results were made by using (1) a linear relation and (2) a power curve. Thawing degree days (TDD) are plotted with the original (adjusted) snow depths, $S$; (1969 is omitted in least squares calculation.)

Linear

$$\text{TDD} = C_1 + C_2 S \qquad C_1 = -65.098 \qquad C_2 = 1.2666 \tag{2}$$

Coefficient of determination $r^2 = 0.9423$.

Power curve

$$\text{TDD} = A(S)^B \qquad A = 0.5098 \qquad B = 1.1271 \tag{3}$$

Coefficient of determination $r^2 = 0.9461$.

Equation (3) is a slightly better fit, although not significantly. However, (3) does pass through the origin, while (2) does not, so the former makes somewhat better sense (no thawing should produce no melting).

## Energy Considerations

There is insufficient information for accurate calculation of energy transfer in this situation. However, it is instructive to make some order-of-magnitude estimates of the energies involved.

First, from the observed 180.1 TDD at Paradise in 1980, one would expect a snowmelt of 1.94 m from equation (2) or 1.82 m from equation (3). The observed snowmelt was 2.82 m, leaving a discrepancy of 0.88 or 1.00 m more snow melted than anticipated. Equation (3) is probably more accurate in the lower portion of the curve, so we shall use the value of 1.00 m in our calculations.

The snow density is unknown, but a typical value that time of year is 500 kg/m$^3$. The energy needed to melt one cubic meter of snow would then be about 0.1668 billion joules.

One can compute the total incident solar radiation during the period in question form the solar constant (1353 joules m$^{-2}$ s$^{-1}$), astronomical tables giving times of sunrise and sunset, and from calculations of the average of the cosine of the angle of incidence of sunlight [*Percy,* 1980]. These calculations yield a value of 1.864 Gj/m$^2$ over the 44-day period of snowmelt at the latitude of Paradise.

The albedo of clean corn snow is about 0.75 and of dirty snow about 0.4–0.6. The albedo of the ashed snow at Paradise is not known. *Driedger* [1981] reported the albedo of Mt. St. Helens ash itself was near 0.16 when wet. It would seem that the albedo of a thin layer of ash on white snow would be somewhat higher than 0.16, owing to ineffectiveness in covering irregularities in the snow and possible partial cancelation of the ash effect by late snowfalls. So the actual albedo of the Paradise snow was probably somewhere between 0.16 and 0.40, which gives an absorbtivity between 0.84 and 0.60. The increase in absorbtivity, over the clean corn snow value, is then between (0.84 − 0.25) = 0.59 and (0.60 − 0.25) = 0.35. Multiplying by the amount of solar radiation, 1.864 Gj/m$^2$, gives, 1.100 and 0.635 Gj/m$^2$ absorbed, respectively. These figures are 6.6 and 3.9 times the radiation needed to melt one cubic meter of snow. However, many of the days during late May and June were cloudy, so that much less than 1.864 Gj/m$^2$ actually reached the ground. Cloudiness data is not available, but one can conclude that the observed excess snowmelt rate is consistent with a value of between 15 and 25% of available incident radiation reaching the ground.

The model presented here is rather simple in not considering other factors in melting. Wind, humidity, and cloud cover data are not available. Rainfall figures are available, and rainwater temperatures could be estimated; but calculation of heat supplied by this source seems pointless in the absence of the other data. Of course, it would have been better to use water content of snow, rather than snow depth, in all calculations, for the amount of ice melted is the significant parameter. Again, water content data were not available to the author.

*Driedger* [1981] has conducted controlled experiments on lowering of a snow surface by Mt. St. Helens ash and found that an ash layer of 0.003 m was the most effective thickness in ablation of a snowpack; thick deposits apparently insulate the snow from radiation. *Fujii* [1977] found that nonvolcanic glacial debris of a thickness of 0.005 m was most efficient in ablation of the surface of the Khumbu Glacier on Mt. Everest, Nepal. It is of interest that these thicknesses are very close to the values reported by U.S. Park Service at Paradise on May 18.

## Conclusion

Ashfall in the amount received at Paradise was very effective in accelerating the melting of the spring snow cover. Similar effects on adjacent glaciers should have produced increased runoffs during the summer of 1980.

*Note added.* A referee has raised the question of whether the cool temperatures at Paradise during the last 6 weeks of snowmelt were due to a change in atmospheric circulation or to less sensible heat because of increased melting rates. I believe the cooling was due primarily to a circulation change, but there could be a slight effect owing to increased melting. Most of the far west had below-normal temperatures during late May and June (a reversal from positive temperature departures in mid-April to mid-May, and contrary to NOAA long-range predictions in their *Average Monthly Weather Outlook*). The state of Washington as a whole averaged 1.4°C below normal during June.

Paradise averaged 3.2°C below normal in June, significantly more than most Washington stations, which would lend support to the absorption hypothesis. However, the Longmire station, 7 km southwest of Paradise at an elevation of 842 m, had nearly as great a temperature departure, −2.7°C, although it had no snow on the ground (but did have ashfall.) Paradise's mean June temperature, 4.3°C, was the coldest in the 26 years of the present study, while Longmire's 10.1°C was the second coldest at that station.

I agree with another referee that a study of the origin of the low temperatures would be of interest. In particular, could the atmospheric circulation pattern have been affected by the temporary infusion of ash into the prevailing westerlies? Was there simply less insolation at ground level over the west owing to atmospheric ash? Or was the cooling just coincidental?

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