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Use of Air Temperature Data to Anticipate the Onset of Snowmelt-Season Landslides

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ABSTRACT

New data on landslides induced by snowmelt, or a combination of snowmelt and rainfall, confirms previous findings that an air temperature threshold is a powerful index for anticipating or forecasting the onset of snowmelt-season landslides. Analyses of the data shows that a high percentage (85%) of the landslide events occurred within 2 weeks after the first yearly occurrence of an optimal temperature threshold of 58°F (a 6-day moving average of daily maximum temperature). Thus, the analyses indicate the threshold can be useful as an empirical basis for issuing warnings, in a narrow time window, of an increased potential for landslide activity in areas highly susceptible to snowmelt-season landslides. Other potential uses for the threshold include timing observations and the deployment of field instrumentation to monitor hazardous landslides, timing avoidance or mitigation strategies, scheduling construction projects in sensitive areas, and anticipating highway maintenance needs.

INTRODUCTION

Landslides induced by snowmelt or a combination of snowmelt and rainfall occur in many regions of the world each year and are often dangerous and destructive. Snowmelt-related landslides, especially debris flows (sometimes referred to as "mudslides" in media news reports), may be numerous in years with heavy snowfall and associated deep snowpack. Snow meltwater (snowmelt) that seeps into the subsurface contributes to slope instability and the development of landslides by saturating the soil or rock mass, elevating pore pressures, and increasing shear stress.

In 1996, I conducted a preliminary examination and analysis of climatic data associated with historical snowmelt-related landslide events that occurred in the central Rocky Mountains (Chleborad, 1997). The study revealed an air temperature threshold that appears useful for anticipating or forecasting the onset of landslides during the spring snowmelt season. The threshold (a 6-day moving average of daily maximum temperature of 58°F) was defined by the number and temporal distribution of associated landslide events. Historical, daily air temperature data recorded at National Weather Service substations located near the landslide sites was used to estimate site temperatures, to characterize temperature trends, and to identify the temperature threshold (U.S. Dept. of Agriculture, 1925; U.S. Dept. of Commerce, 1979-1997).

The purpose of this report is to present additional data and analyses that tests the validity of the threshold and demonstrates its applicability to other areas of the western U.S. For this report, 11 additional landslide events, including four from Utah, three from Wyoming, three from Colorado and one from Nevada (the eastern Sierras), have been added to the database, increasing the total number to 27 landslide events. Basic information on the 27 landslide events is presented in Table 1. Several of the new additions are well known historic landslides. These include the 1925 lower Gros Ventre landslide, Wyoming (event no. 1, Table 1; Voight, 1978), the 1983 Rudd Canyon debris flow in Utah (event no. 9; Kaliser, 1983), the 1983 Slide Mountain rock and soil slide in Nevada (event no. 8; Watters, 1983), and the 1997 Wolf Mountain slump/debris flow, Wyoming (event no. 25, G. Michael Hager, Wyoming Department of Transportation, personal comm.,1997). Coincidentally, each of those landslide events, directly or indirectly, resulted in loss of life and (or) costly property damage.

Table 1-- Snowmelt season landslide events

Event no.	Date	Type of landslide	Reference area or town	Estimated volume (m^3)	Elevation (m)	Reference
1*	6/23/25	Debris avalanche	Jackson Hole, Wyoming	40×10^6	2740	Voight, 1978
2	4/19/79	Debris slide/flow	Mesa Verde National Park, Colorado	$<1 \times 10^3$	2375	Montezuma Valley Journal, 4/20/79
3	4/29/79	do.	do.	2×10^3	2390	do.
4	4/30/79	do.	do.	1.2×10^3	2375	do.
5*	5/24/79	Debris flow	Pagosa Springs, Colorado	2×10^3	2990	The Pagosa Springs Sun, 5/31/79
6	5/21/82	do.	Steamboat Springs, Colorado	$<1 \times 10^3$	2286	Steamboat Pilot, 5/27/82
7	5/27/83	do.	Redstone, Colorado	$<1 \times 10^3$	2710	Glenwood Post, 5/31/83
8*	5/30/83	Rock and soil slide	Glenbrook, Nevada	7.2×10^5	2500	Watters, 1983
9*	5/30/83	Debris flow	Farmington, Utah	?	2110	Kaliser, 1983; Wieczorek, 1989
10	5/12/84	do.	Steamboat Springs, Colorado	$<1 \times 10^3$	2075	Steamboat Pilot, 5/17/84
11*	5/13/84	do.	Fairview, Utah	?	2620	Fleming and Schuster, 1985
12	5/13/84	Debris flow	Telluride, Colorado	?	2925	Telluride Times, 5/17/84
13	5/14/84	Slide/flow	Oak Creek, Colorado	$<1 \times 10^3$	2225	Steamboat Pilot, 5/17/84
14*	5/14/84	Slide/debris flow	Layton, Utah	1×10^3	2225	Olson, 1985
15*	5/23/84	do.	Farmington, Utah	$<9.0 \times 10^3$	2110	McCarter and others, 1985

*New addition to database

Table 1. Snowmelt season landslide events cont'd

Event no.	Date	Type of landslide	Reference area or town	Estimated volume (m^3)	Elevation (m)	Reference
16	6/1/84	Slide/debris flow	Silverthorne, Colorado	?	2680	Summit County Journal, 6/14/84
17	4/16/85	Slump/debris flow	Granby, Colorado	4×10^3	2490	Schuster, 1986
18	4/26/85	Slump/earthflow	DeBeque, Colorado	?	1950	Umstot, 1989
19	4/30/87	Slides/debris flows	Telluride, Colorado	2.5×10^4	2745	Stover and others, 1987
20	5/19/93	Debris flow	Steamboat, Colorado	?	2500	Steamboat Pilot, 5/27/93
21	5/27/93	do.	Aspen, Colorado	?	2925	Aspen Daily News, 5/28/93
22	5/8/96	do.	Silverthorne, Colorado	4×10^3	2650	Chleborad, unpublished field notes, 1996
23	5/13/96	Debris flow	Aspen, Colorado	3.8×10^3	2955	Chleborad, 1996; Chleborad and others, 1997
24*	4/29/97	do.	Clark, Colorado	$<1 \times 10^3$	2205	Steamboat Pilot, 4/30/97
25*	5/18/97	Slump/debris flow	Jackson Hole, Wyoming	4.6×10^5	2180	G. Michael Hager, Wyoming Department of Transportation personal comm., 1997
26*	5/26/97	Earthflow	Moran, Wyoming	1.1×10^5	2500	U.S. Forest Service, internal memorandum, 5/28/97
27*	5/26/97	Debris flow	Aspen Colorado	$<1 \times 10^3$	2940	Chleborad and others, 1997

*New addition to database

In most cases, relatively small initial movements of a landslide mass indicated by the development of ground cracks or other surface manifestations precede complete or catastrophic failure. In the preliminary study and in this report a landslide event date is defined as the date of complete or catastrophic failure as indicated by large amounts of movement and total disruption of the slide mass.

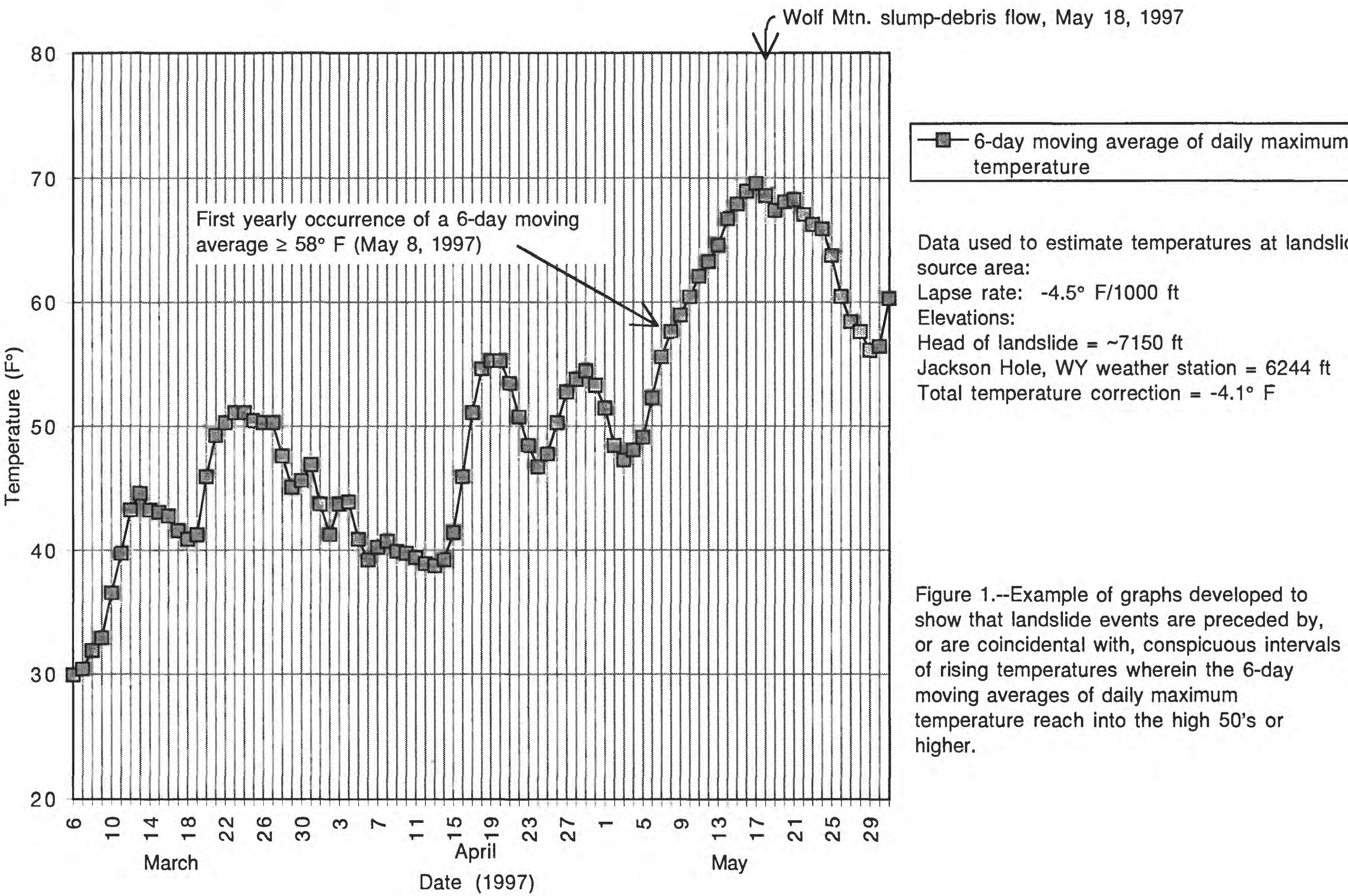
The landslide database for the study was developed by gathering information on the earliest reported spring season landslide occurrences from historical newspaper accounts, technical reports, eyewitness accounts, and my personal field notes. After compiling reports of landslide events, I visited each of the landslide sites, plotted their locations on topographic maps, and determined slide elevations. A reported landslide event was included in the study if it met the following criteria: (1) information on the location and date of occurrence was provided, (2) pertinent historical climatic data from a nearby weather station, including daily maximum and minimum temperatures, was available, and (3) based on available reports and climatic data, snowmelt appeared to be a major factor contributing to the occurrence of the landslide event. Because rockfalls that occur in the Spring are often related to surface or very near surface freeze-thaw cycles (Piteau and Peckover, 1978) they were not included in the study. Also, two of the original 18 landslide events used to identify the temperature threshold (no.s 6 and 16 in the preliminary report) were dropped from the database due to insufficient information on the exact date of occurrence.

METHODOLOGY AND ANALYSES OF TEMPERATURE DATA

As a first step, I estimated historical daily maximum and minimum temperatures for the 27 landslide sites. This was accomplished by applying standard temperature lapse rates to adjust for differences in elevation between weather stations and the respective sites. Subsequent inspection of the daily temperature data for the sites revealed that most of the landslide events were preceded by, or closely associated with, conspicuous 5- to 10-day intervals of rapidly rising temperatures wherein daily maximum temperatures typically rose from the 30's or 40's to the 60's or 70's. The mean length of the 5- to 10-day intervals was determined to be 6 days. To examine relationships between dates of landslide occurrence and antecedent temperature trends, 6-day moving averages of daily maximum and minimum temperatures were computed for the parts of each calendar year preceding the occurrence of each landslide event. To show antecedent temperature (snowmelt) conditions for specific dates, I then plotted the 6-day moving averages vs. calendar dates as line graphs with the moving average data points coinciding with the last day (calendar date) of the respective 6-day intervals (Figure 1). Inspection of the graphs revealed that the landslide events are preceded by, or are coincidental with, conspicuous intervals of rising temperatures wherein the 6-day moving averages of daily maximum temperature reach into the high 50's or higher.

To identify a temperature threshold most useful for anticipating or forecasting the onset of snowmelt-related landsliding, I then developed a table showing the landslide event dates as the number of days before or after the first yearly occurrence of trial threshold temperatures. For this purpose, trial threshold temperatures (6-day moving averages of daily maximum temperature) in the range 50° to 70°F were used (Table 2). The 11 new landslide events, previously described, were added to the original database to produce the compilation of data shown in Table 2. Inspection of Table 2 shows, for example, that landslide event no. 1 (the lower Gros Ventre landslide of 1925) occurred 15 days after the first yearly occurrence of the 50°F trial threshold and 1 day before the first yearly occurrence of the 63° F trial threshold. Note that often more that one trial threshold temperature arrives on a given day, as in the case

WOLF MOUNTAIN SLUMP-DEBRIS FLOW, JACKSON HOLE AREA, WYOMING



Data used to estimate temperatures at landslide source area:
Lapse rate: -4.5° F/1000 ft
Elevations:
Head of landslide = ~7150 ft
Jackson Hole, WY weather station = 6244 ft
Total temperature correction = -4.1° F

Figure 1.--Example of graphs developed to show that landslide events are preceded by, or are coincidental with, conspicuous intervals of rising temperatures wherein the 6-day moving averages of daily maximum temperature reach into the high 50's or higher.

Table 2.--Landslide event times as number of days before or after first yearly occurrence of trial threshold temperatures.

Event		Trial Threshold Temperatures (6-day moving averages)																					
No.	Date	50°	51°	52°	53°	54°	55°	56°	57°	58°	59°	60°	61°	62°	63°	64°	65°	66°	67°	68°	69°	70°	Nearest Town
1	6/23/25	15	15	15	4	4	3	3	3	2	2	1	1	0	-1	-5	-5	-5	-19	-19	-19	-20	Jackson, WY
2	4/19/79	36	10	10	10	10	9	9	9	1	1	1	1	0	0	0	0	-1	-16	-17	-18	-31	Mesa Verde, CO
3	4/29/79	46	20	20	20	20	19	19	19	11	11	11	11	10	10	10	10	9	-6	-7	-8	-21	Mesa Verde, CO
4	4/30/79	47	21	21	21	21	20	20	20	12	12	12	12	11	11	11	11	10	-5	-6	-7	-20	Mesa Verde, CO
5	5/24/79	38	38	38	37	37	9	8	7	3	3	3	-12	-12	-19	-20	-20	-20	-20	-21	-31	-32	Pagosa Spgs, CO
6	5/21/82	36	36	36	35	25	21	20	19	19	19	18	18	-5	-5	-6	-18	-22	-22	-23	-31	-33	Steamboat, CO
7	5/27/83	34	33	32	18	18	17	16	2	2	1	1	1	1	0	0	-1	-1	-2	-24	-24	-24	Redstone, CO
8	5/30/83	12	11	11	10	9	9	8	8	8	7	7	6	6	5	5	4	4	3	2	1	-46	Glenbrook, NV
9	5/30/83	16	16	16	15	6	6	6	5	5	4	4	4	4	3	3	3	3	2	2	1	1	Farmington, UT
10	5/12/84	24	25	25	2	2	1	1	1	1	1	0	0	0	0	0	0	-1	-1	-1	-1	-1	Steamboat, CO
11	5/13/84	26	25	2	2	1	1	1	1	1	0	0	0	0	0	-1	-11	-11	-12	-12	-14	-18	Fairview, UT
12	5/13/84	27	26	26	26	25	25	3	3	3	2	2	2	2	2	1	1	1	1	1	0	0	Telluride, CO
13	5/14/84	25	4	4	3	3	3	3	3	2	2	2	2	2	1	1	1	1	1	1	0	0	Steamboat, CO
14	5/14/84	27	27	27	27	27	26	25	1	1	1	1	1	0	0	-1	-17	-17	-17	-36	-40	-42	Layton, UT
15	5/23/84	35	35	35	35	34	33	33	10	10	10	9	9	9	9	9	8	8	-9	-27	-28	-30	Farmington, UT
16	6/1/84	42	20	20	20	20	19	19	19	19	19	18	18	18	18	18	17	17	17	16	-15	-23	Dillon, CO
17	4/16/85	5	5	5	4	3	2	1	1	0	-2	-2	-21	-41	-41	-42	-42	-43	-51	-52	-52	-53	Grand Lake, CO
18	4/26/85	39	38	37	36	35	31	30	28	17	17	17	16	16	14	14	13	13	12	10	9	8	DeBeque, CO
19	4/30/87	55	55	55	54	13	13	13	13	12	11	11	11	5	4	4	4	3	3	-12	-35	-35	Telluride, CO
20	5/19/93	19	14	14	6	5	5	5	5	5	4	4	4	4	3	3	3	-15	-28	-28	-29	-29	Steamboat, CO
21	5/27/93	23	22	13	13	13	12	12	12	12	11	11	11	-19	-19	-19	-20	-20	-32	-33	-34	-35	Aspen, CO
22	5/8/96	28	28	27	27	27	3	2	2	2	1	0	0	0	-1	-1	-5	-6	-7	-8	-9	-9	Dillon, CO
23	5/13/96	32	32	32	7	7	7	7	6	6	5	5	4	4	3	0	-1	-2	-3	-4	-4	-31	Aspen, CO
24	4/29/97	34	33	33	32	10	9	9	9	9	8	8	-9	-9	-10	-10	-10	-10	-11	-12	-19	-19	Clark, CO
25	5/18/97	57	56	30	30	30	30	11	10	10	9	8	7	7	6	5	5	4	4	3	2	1	Jackson, WY
26	5/26/97	18	18	18	17	16	16	15	14	13	13	12	11	-9	-9	-9	-9	-10	-12	-12	-35	-35	Moran, WY
27	5/26/97	63	35	18	18	17	17	17	17	16	13	12	10	9	-7	-7	-7	-8	-8	-8	-8	-9	Aspen, CO

*Event numbers in bold print indicate new additions to the database of trial threshold temperatures 51° through 54° which occurred 21 days prior to the occurrence of landslide event no. 4. This occurs when rapidly rising temperatures elevate the 6-day moving average more than one degree on a given day.

Next, the total number of landslide events that occurred within 1 week, 2 weeks, and 3 weeks after the first yearly occurrence of the respective thresholds (fig. 2) was determined using the data in Table 2. As shown in Figure 2, a high percentage of the events are preceded by threshold temperatures in the narrow 57°F to 60°F range. Note that 14 or 52% of the 27 landslide events occurred within 1 week, 23 or 85% within 2 weeks, and all 27 of the events within 3 weeks after the first yearly occurrence of the 58°F threshold. To further analyze the data, empirical frequency distributions were developed to show the percentage of landslide events that occurred before and after the first yearly occurrence of the respective trial threshold temperatures. Because crowding all 21 curves (50° to 70°) onto one graph made it difficult to visually distinguish the individual curves, they were divided into two sets, 1) a set that includes even-numbered trial thresholds from 50°F to 70°F, and 2) an odd-numbered set that includes trial thresholds from 51°F to 69°F (figs. 3 and 4). As indicated on Figures 3 and 4, significant percentages of the snowmelt-related landslide events occurred before the first yearly occurrence of trial thresholds in the 61°F to 70°F range. For example, in the Figure 3 plots, it can be seen that approximately 40% of the events occurred before the first yearly occurrence of the 64°F trial threshold, consequently, it would not be useful as a threshold. At the other end of the spectrum, temperatures in the 50° to 54° range have a significant percentage of events that occur more than 3 weeks after their arrivals. Therefore, trial thresholds in that range do not provide the narrow time window needed for forecasting and timely hazard mitigation efforts. Conversely, trial thresholds in the 55° to 60° range show a high percentage of events occurring within 2 weeks and a very high percentage within 3 weeks after their first yearly occurrences. Further, of the trial thresholds within the 55° to 60° range that show no landslide occurrences prior to their arrival, the 58°F threshold (fig. 3) has the highest percentage of landslide events occurring within the operative 1-, 2-, and 3-week time intervals.

Figure 5 is a plot showing calendar dates of the 27 landslide events in relation to the first yearly occurrence of the 58°F threshold. The plot shows that most of the profiled landslide events occurred between May 8th and May 31st. Note the small cluster of events that occurred within four days of the threshold during the period May 12 to May 14 (landslide event no's 10, 11, 12, 13, and 14). All of those events occurred in 1984, a high incidence year for snowmelt-related landslides in many mountainous areas of Utah and Colorado. The cluster of landslide activity over such a broad area but within such a narrow time frame indicates the landslide events are related to a common simultaneous trigger such as snowmelt associated with widespread high temperatures. Similarly, a widespread common triggering agent is suggested by landslide event no's 7, 8, and 9 that occurred during a four day period in 1983 in the states of Nevada, Utah, and Colorado.

As previously stated, a standard temperature lapse rate is needed to adjust for elevation differences between the weather stations and the respective landslide sites. Standard lapse rates of -4.5°F per 1000 ft for the Colorado and Wyoming landslide events and -5.5°F per 1000 ft for the Utah and Nevada were selected for the study. Standard mean yearly or mean seasonal lapse rates have been cited or employed as a useful estimate of temperature variation with elevation by several researchers working in the Rocky Mountain region (e.g. Potter, 1969; and Doesken, and others, 1990). However, lapse rates vary somewhat from season to season due to local topography, climatic conditions, and various other factors. In the Rocky Mountain Region lapse rates typically vary between about -3.5°F and -5.5°F/1000 ft during

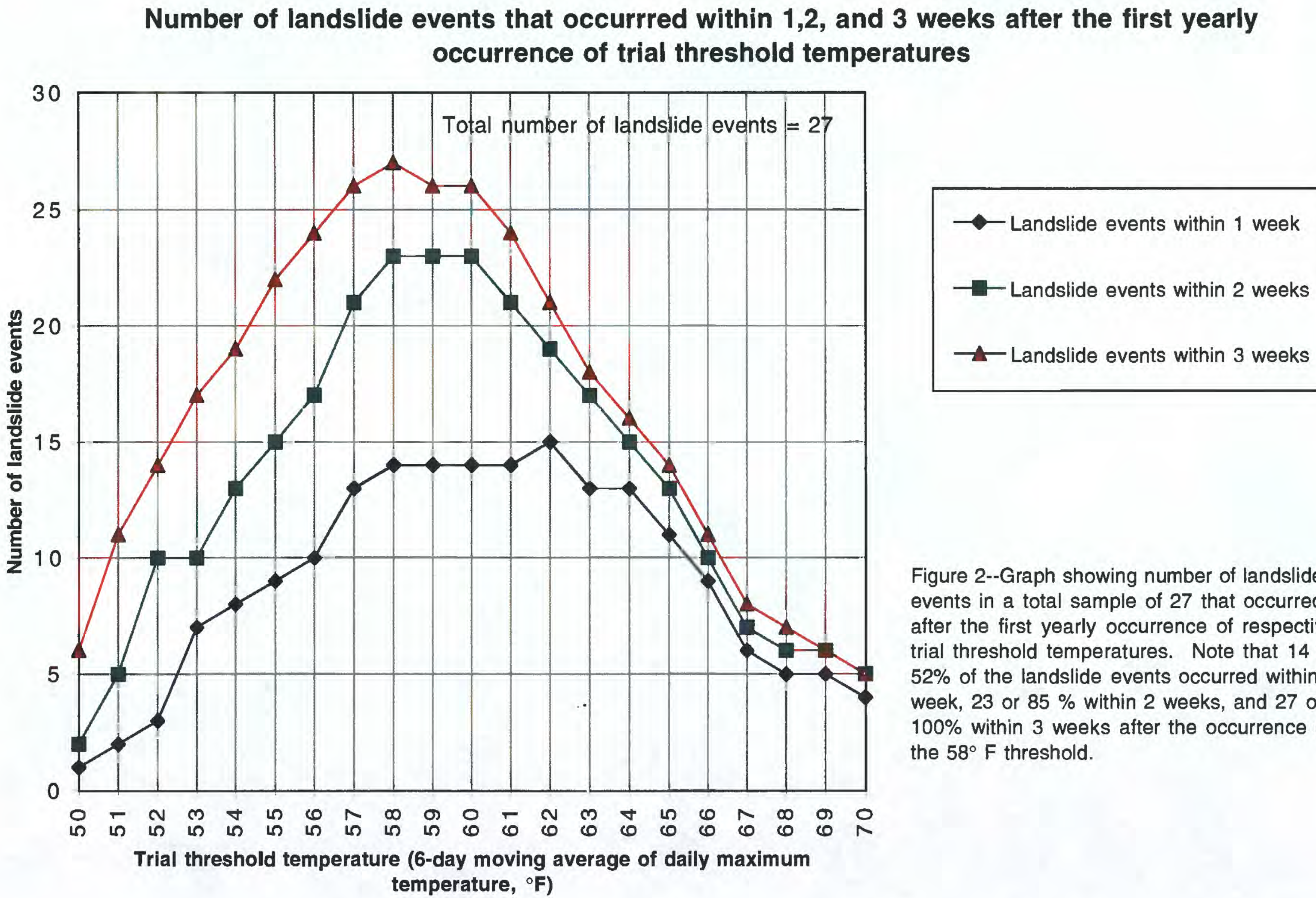


Figure 2--Graph showing number of landslide events in a total sample of 27 that occurred after the first yearly occurrence of respective trial threshold temperatures. Note that 14 or 52% of the landslide events occurred within 1 week, 23 or 85 % within 2 weeks, and 27 or 100% within 3 weeks after the occurrence of the 58° F threshold.

Cumulative Frequencies of Landslide Events Associated with Trial Threshold Temperatures

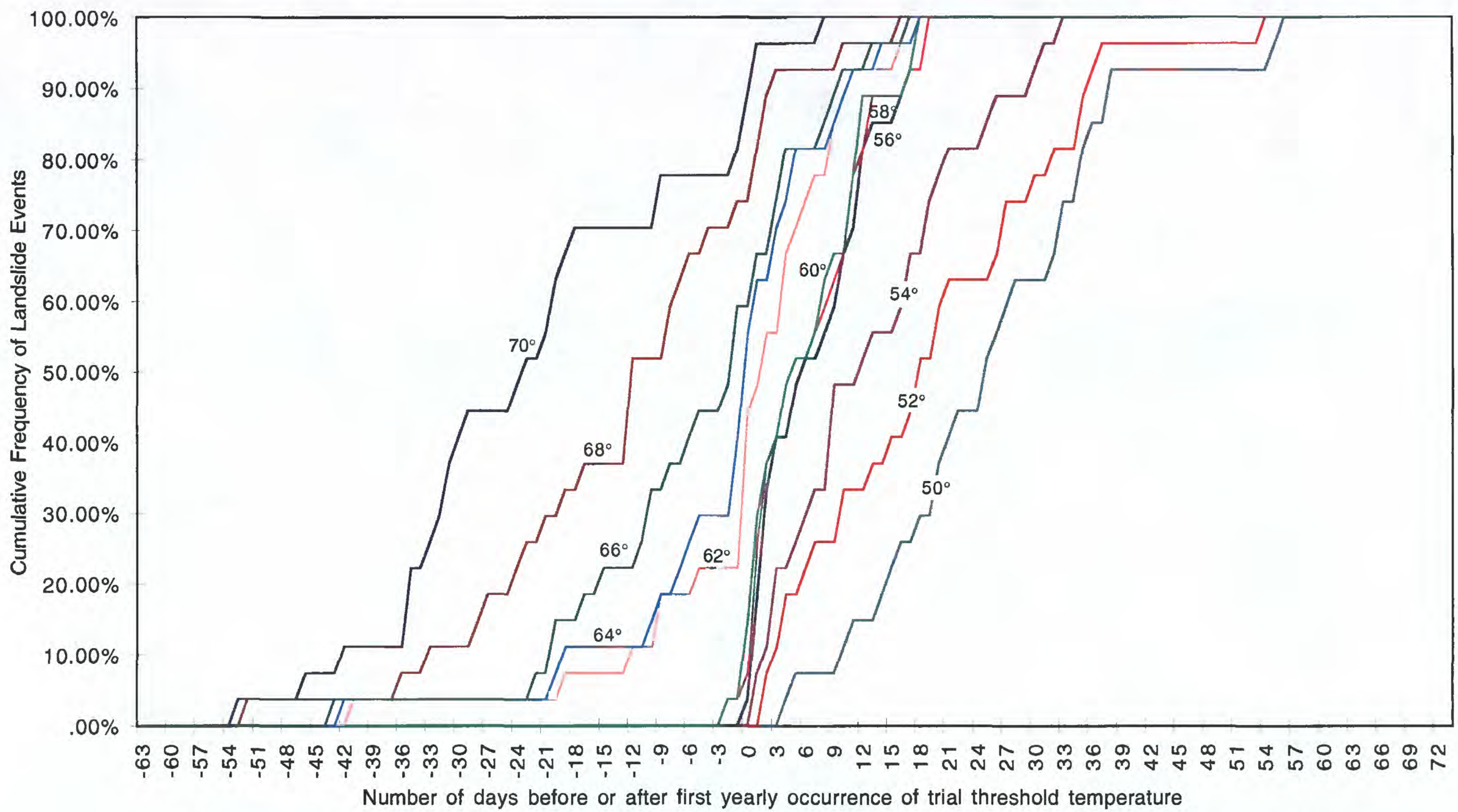


Figure 3.--Cumulative frequency of landslide events associated with first yearly occurrence of even numbered trial threshold temperatures in the 50°F to 70° F range. Trial threshold temperatures are 6-day moving averages of daily maximum temperature. Note the high percentage of landslide events that occur within 3 weeks after the arrival of trial thresholds in the 56° F to 60° F range.

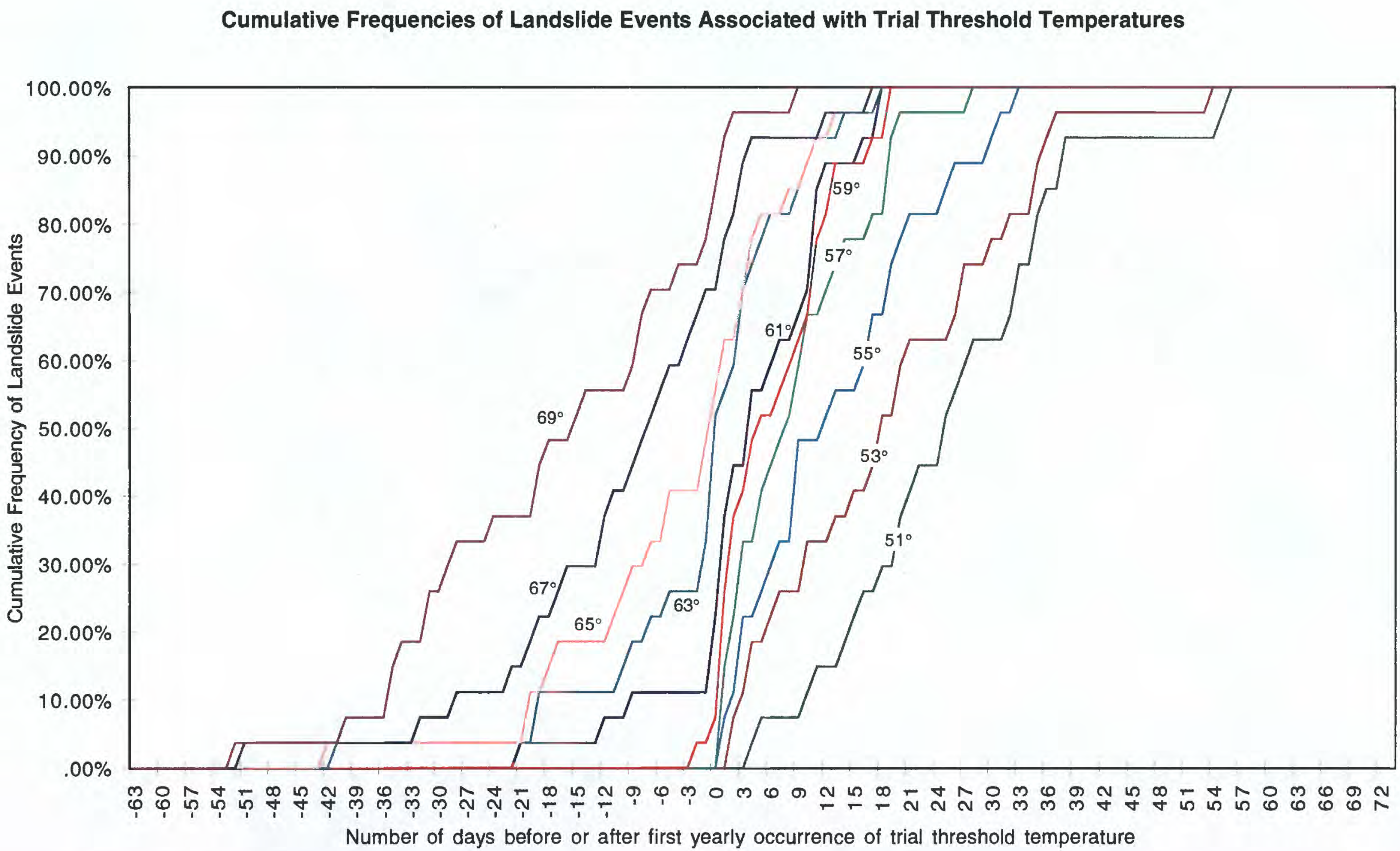


Figure 4.--Cumulative frequency of landslide events associated with first yearly occurrences of odd numbered trial threshold temperatures in the 51° to 69° F range. Trial threshold temperatures are 6-day moving averages of daily maximum temperature. Note the high percentage of landslide events that occur within 3 weeks after the arrival of the 57° F and 59° F trial thresholds.

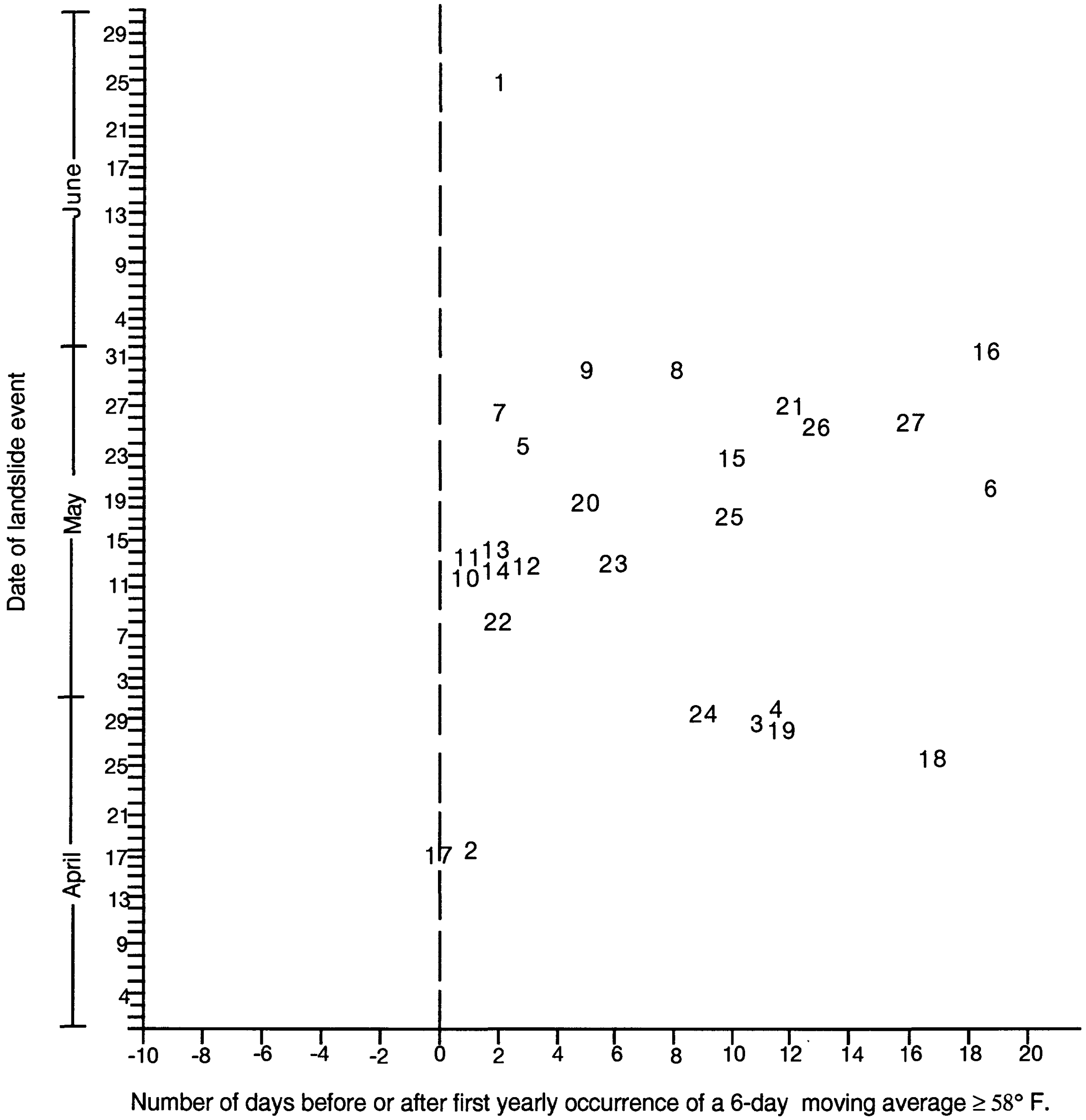


Figure 5.--Plot showing dates of landslide events in relation to the first yearly occurrence of a 6-day moving average of daily maximum temperature greater than or equal to 58° F at the respective sites. As shown, a high percentage of the 27 landslide events (85%) occurred within 2 weeks after the first yearly occurence of the 58° F threshold and all occurred within 3 weeks of its occurrence. Also, the graph shows that a high percentage occurred during the calendar period April 25 to May 31. Numbers are keyed to landslide events listed in Tables 1 and 2.

the spring snowmelt season. To evaluate the effect of lapse rate variation on the observed relationship between the 6-day moving averages of daily maximum temperature and the landslide events, cumulative frequency distributions were developed for the optimal 58° F threshold using lapse rates of -3.5°F, -4.5°F, and -5.5°F/1000 ft (fig. 6). As indicated on Figure 6, varying the lapse rate did not greatly effect the total number of landslide events occurring within the operational 3 week period after the first yearly occurrence of the threshold. Using just the -5.5°F lapse rate on all 27 of the landslide events indicates that all of the events occurred within 3 weeks after the arrival of the 58° threshold. And, when using the -3.5°F and -4.5°F lapse rates approximately 93% occur within the 3-week period. Also, the analysis shows that regardless of which lapse rate is used, a high percentage of the events occur within 2 weeks after the arrival of the 58° threshold.

DISCUSSION AND CONCLUSIONS

Analyses of the expanded database confirms preliminary findings (Chleborad, 1997) that identify a 6-day moving average of daily maximum temperature of 58°F as an optimum threshold useful for anticipating the onset of snowmelt-season landslides. Of the 11 new additions to the landslide database it was found that 5 occurred within 1 week after the arrival of the 58°F threshold and 10 within 2 weeks (Tables 1 and 2). Also, the analyses has helped identify temperatures in the narrow 55° to 60° range as potentially useful operational thresholds, wherein 55° is the most conservative option and 60° the least (figs. 3 and 4). For example, 55° would give the least chance of a late warning but a potentially longer deployment time, whereas a selection of 60° would mean a greater chance of a late warning but likely a shorter deployment time.

The strong association between the landslide events and intervals of rising temperatures is evidence of the important role played by snowmelt in the development of the slides. However, a combination of snowmelt and rainfall likely triggered many of the events. For example, two different scenarios of debris flow development are represented by landslide events no's 23 and 27 that occurred near Aspen, Colorado in 1996 and 1997, respectively. In 1996, major debris flows mobilized during a significant warming trend with rapid snowmelt but little or no precipitation, but in 1997 minor debris flow activity began shortly after a significant warming trend and during a period of rainfall and continued snowmelt on ground apparently saturated or nearly saturated by prior snowmelt (Chleborad, and others, 1997). In both cases the events were preceded by the first yearly occurrence of the 58° threshold (see Table 2).

Occasionally, other triggering agents may be involved as well. For example, Voight, 1978, concluded that snowmelt, rainfall, and earthquakes were all causative factors in the development of the 1925 Lower Gros Ventre landslide (event no. 1, Table 2). The arrival of the 58°F threshold 2 days prior to the Lower Gros Ventre landslide (see Table 2) supports the contention that snowmelt played a major role in that event.

Possible uses of the temperature threshold include the issuing of warnings to the public of an increased potential for landslide activity, timing of observations and the deployment of field instrumentation to monitor hazardous slide masses, timing avoidance or mitigation strategies, and anticipating highway maintenance requirements during the spring snowmelt season.

Recently, the threshold was used successfully to time the deployment of instrumentation prior to the occurrence of debris flow activity at a site near Aspen, Colorado (Chleborad, and others, 1997). Beginning in March of 1997, 6-day moving averages of daily maximum temperatures were tracked using daily temperature data from a nearby weather station. Additionally, once it was determined that the 6-day moving average had reached the mid-fifties,

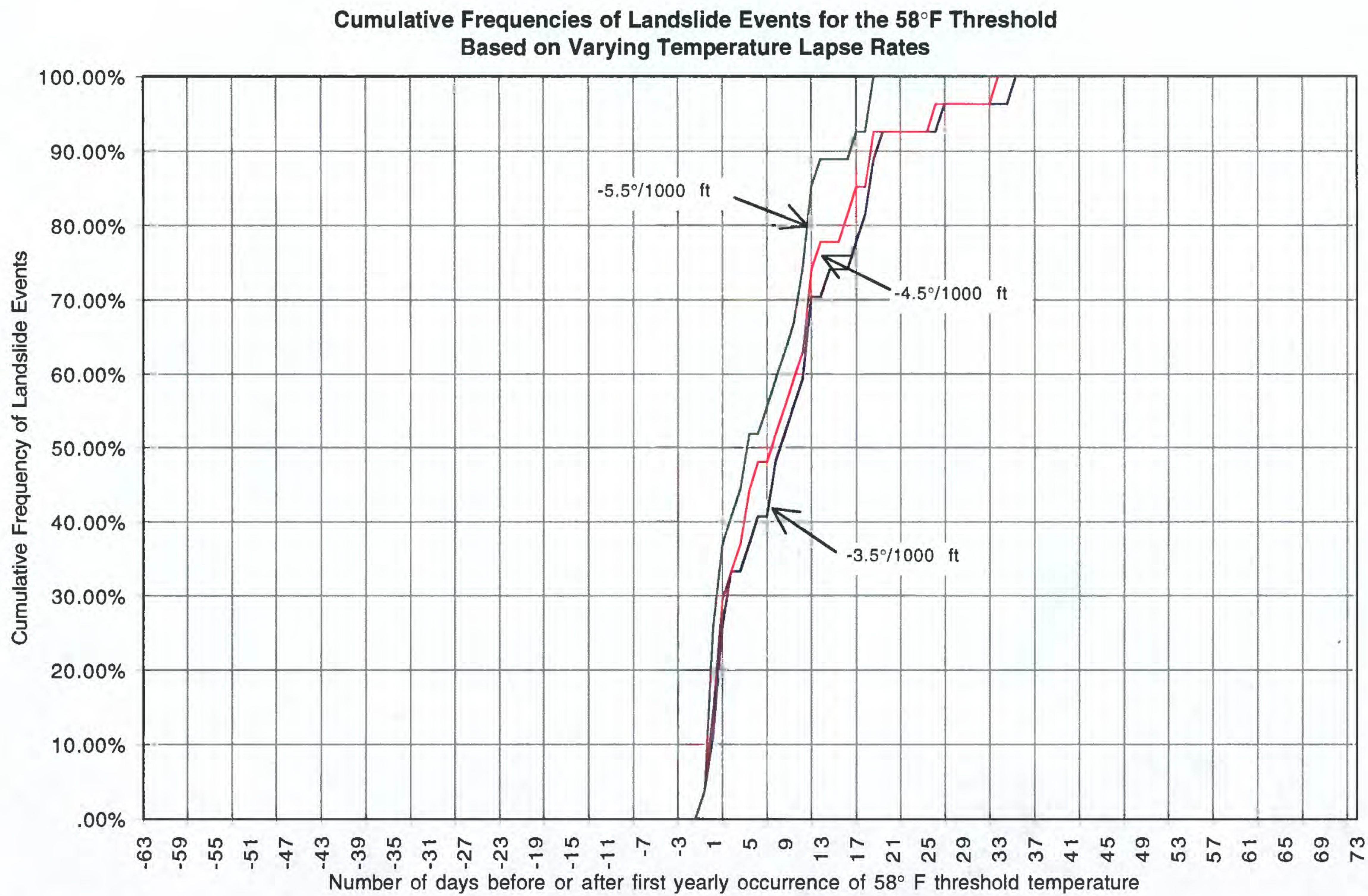


Figure 6.--Cumulative frequency of landslide events associated with the 58° F threshold and varying temperature lapse rates.

4- and 5-day temperature forecasts available on the Internet were used to project the likely arrival date of the threshold. As the daily tracking of the 6-day averages progressed it became apparent the first week of May that a significant warming trend was underway that would likely result in the first yearly occurrence of the threshold temperature at the landslide site. Based on that information the decision was made to immediately deploy instrumentation. The threshold arrived the first week in May shortly after the instrumentation was deployed and debris flow activity was observed about two weeks later.

Although analyses of the database presented in this report indicates that a high percentage of snowmelt-season landslides can be expected to occur after the first yearly occurrence of the threshold temperature, it does not preclude the possibility of landslide activity prior to its arrival. Additional work is needed to expand the database and evaluate the effect of other factors such as variations in regional climate, slope aspect, and man-made alterations of natural hydrologic conditions. Such work could result in refinement of the method and an improved forecasting capability.

ACKNOWLEDGEMENTS

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