U.S. DEPARTMENT OF THE INTERIOR

U.S. GEOLOGICAL SURVEY

Temperature, Snowmelt, and the Onset of Spring Season Landslides in the Central Rocky Mountains

by

Alan F. Chleborad[1]

Open-File Report 97-27

[1]Denver, Colorado

ABSTRACT

Snow meltwater (snowmelt) that seeps into the subsurface is a major factor contributing to the development of landslides during the spring in mountainous areas of the Rocky Mountain region. An examination of historical temperature data in relation to spring season landslide occurrences reveals an association between the landslide events and intervals of rising temperatures that accelerate the production of snow meltwater. Historical climatic data recorded at local weather stations located near the landslide sites are used to show the association and to identify a temperature threshold that may be useful for forecasting the onset of spring season landslides. Historical daily temperature maximums and minimums for unmonitored landslide sites are estimated by applying an elevation correction factor to historical temperature data from nearby weather stations. The proposed temperature threshold (a 6-day moving average of daily maximum temperature of 58° F) is defined by the number and temporal distribution of snowmelt related landslide events. The results of the study suggest that real-time temperature data recorded at weather stations throughout the Rocky Mountain region is potentially a valuable source of information that may be useful for forecasting the onset of spring season landslides.

INTRODUCTION

Landslides triggered by snowmelt or a combination of snowmelt and rainfall are common during the spring in many mountainous areas of the Rocky Mountain region. Spring season landslides, especially debris flows (often referred to as "mudslides" in media news reports), are numerous in years with unusually heavy snowfall and associated deep snowpack. However, few details are known of the sequence, time, intensity, or duration of antecedent climatic conditions that trigger the slope failures. Such information may be useful for mitigation of landslide hazards and for forecasting the occurrence of landslides.

For many years, climatic data, including daily temperature maximum and minimums and precipitation, have been collected at numerous local weather stations (weather observing sites) supervised by the National Oceanic and Atmospheric Administration (NOAA)/National Weather Service. I undertook this study to investigate the usefulness of this source of historical climatic data for identifying associations between antecedent climatic conditions and the onset of spring season landslides in mountainous areas of Colorado and other states in the Rocky Mountain region.

METHODOLOGY AND DATA COMPILATION

For this preliminary report, I have compiled information on 20 landslide events (associated with 18 landslides in the state of Colorado and one in Wyoming) that occurred during the spring in years between 1977 and 1996 . Landslide information was gathered from historical newspaper accounts provided by the Colorado Historical Society, technical reports, and from my recent personal field notes. February thru June issues of local newspapers were searched to obtain information on the earliest reported spring season landslide occurrences. The reports were found in April, May, and June issues of newspapers published in the Colorado mountain communities of Aspen, Dillon, Cortez, Steamboat Springs, Montrose, and Telluride. A reported landslide event was included in this study if it met the following criteria: (1) verifiable information on the location and date of occurrence was provided, (2) pertinent historical climate data from a nearby weather station, including daily temperature maximums and minimums, 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.

Information obtained in the search on individual landslide events, including brief descriptions, dates of occurrence, and sources of information, is presented in Table 1. Locations of the landslides are shown in Figure 1. During the fall of 1996, I visited the landslide sites, plotted their locations on topographic maps, and determined elevations. In this preliminary study, no effort was made to further determine details of the reported slope failures other than to verify the locations, elevations, and times of occurrence.

In most cases, relatively small movements of a landslide mass, often indicated by the development of ground cracks or other surface manifestations, precede complete or catastrophic failure. For the purpose of this report, the date of landslide occurrence is defined as the date of complete or catastrophic failure as indicated by large amounts of movement or total disruption of the landslide mass. An exception to this are dates I have included for initial, spring season movements of a pre-existing landslide in Wyoming (landslide events No.1 and 2 in Table 1) that were detected using borehole instrumentation (Chleborad, 1980).

For each of the landslide events listed in Table 1, I compiled historical daily precipitation and temperature data recorded at a local weather station. Factors that affect the representativeness of the data, such as topographic variations, were considered in the selection process. In most cases, data from the weather station closest to the landslide was selected as most representative. Locations, elevations, distances between weather stations and respective landslides, and differences in elevation between the stations and the landslides are given in Table 2. The climatological data was obtained from published reports of the National Oceanic and Atmospheric Administration (U.S. Dept. of Commerce, 1977-1996). Unpublished compilations of the raw climatological data and information on the location and elevation of weather observing sites were obtained from the Colorado Climate Center, Fort Collins, Colorado.

REPRESENTATIVENESS OF THE CLIMATIC DATA

The following discussion is based on a recent study of climatic data representativeness in western Colorado by Doesken and others (1990). The study was conducted for the Bureau of Land Management to evaluate to what extent weather stations provide representative climatic information for surrounding unmonitored areas. In the study, monthly and seasonal climate variability were described. It was found that precipitation is much more variable than temperature, and that the range of representativeness of local weather station data to surrounding areas is much less for precipitation than for temperature. Also, Doesken and others (1990) showed that there is a good relationship of mean monthly maximum temperatures with elevation. It is stated that during the summer the relationship is so good that you can typically determine the mean monthly maximum temperature to within +/-1 degree Fahrenheit simply by knowing the elevation. Elevation, however, is only a secondary control on minimum temperature, especially during the winter months. Relative cold air trapping and draining characteristics of a given site become the primary control on night time temperatures. A correlation analyses of mean growing season (May-September) temperatures vs. elevation indicated a decrease of 4.5° F per 1000 ft of elevation (r-squared =0.95). Also, correlation patterns developed in the study suggest areas in the same valley, regardless of their distance apart, are more likely to be well correlated than sites on the opposite sides of a mountain barrier. Likewise, stations far apart but with similar aspect relative to local terrain, may be better correlated.

Table 1.--Locations, elevations, dates of occurrence, and descriptions of profiled spring season landslides, Colorado and Wyoming.

LANDSLIDE EVENT NO.	LOCATION/ ELEVATION	DATE OF OCCURRENCE	DESCRIPTION/SOURCE OF INFORMATION[1]
1	Approx. 7 mi. south of Sheridan, Wyoming; T. 54 N., R. 83 W., NW 1/4 of SW 1/4 of Section 6/ 4460 ft.	Inital movement in 1977 occurred between April 2nd and April 15th	I conducted a detailed study of this pre-existing landslide 1977 and 1978. It is a shallow translational slide/earthflow in weathered, Tertiary-age sedimentary deposits. Borehole inclinometer measurements revealed that initial movement in 1977 occurred sometime between April 2nd and April 15th, During that period, 1 to 2 m of drifted snow that covered the slide melted (Chleborad, 1980).
2	do.	Initial movement in 1978 occurred between March 24th and April 4th.	Borehole inclinometer measurements made in 1978 indicate initial movement of the landslide described above occurred sometime between March 24, and April 4. On March 13th, 1978 the slide was covered with approximately 1.5 m of drifted snow. By April 4th all the snow had melted (Chleborad, 1980).
3	Mesa Verde National Park, 9 miles ESE of Cortez, Colorado; T. 35 N., R. 14 W., S 1/2 of Sect. 5/ 7850 ft.	April 18th or 19th, 1979	"A motorist yesterday [April 19th] used his CB to radio for help after being trapped by a slide on the entrance road [to Mesa Verde National Park." (Montezuma Valley Journal, 4/20/79, p. 1).
4	do.	April 29th, 1979	[Photo caption] "...A slide Sunday morning [April 29th] brought down an estimated 2,500 cubic yards of material which was cleared enough to open a lane [of the entrance road to Mesa Verde National Park]." (Montezuma Valley Journal, 5/2/79, p. 1).
5	do.	April 30th, 1979	[Photo caption] "On Monday morning [April 30th], a massive slide of an estimated 150,000 cubic yards sealed the road [entrance road to Mesa Verde National Park] again." (Montezuma Valley Journal, 5/2/79, p. 1).

[1]Information in brackets has been added by the author for the purpose of clarification.

Table 1 cont.

LANDSLIDE EVENT NO.	LOCATION/ ELEVATION	DATE OF OCCURRENCE	DESCRIPTION/SOURCE OF INFORMATION[1]
6	Steamboat Springs, Colorado; T.6 N., R. 84 W., SW 1/4 of NW 1/4 of Sect. 6/ 6900 ft.	Between April 29th and May 13th, 1982	"Mud slides damage ski jumps--Mud season has been particularly harsh on the Howelsen Hill ski jumps. Heavy snow melt has caused tons of earth to slide off both the 70 m and 90 m jumps....Several feet of earth saturated with melted snow broke loose beneath a concrete retaining wall just under the crown of the hill. The mud slid down the landing area of the jump, carrying with it wooden framework and steel reinforcing bars..." (Steamboat Pilot, 5/13/82, p. 1).
7	Approx. 3 mi SE of Steamboat Springs, Colorado; T. 6 N., R. 84 W., NE 1/4 of NE 1/4, Sect. 27/ 7500 ft.	May 21st, 1982	"See Me, see mudslide--With a noise that one witness described as thunderous, tons of mud slid from the lower portion of the Steamboat Ski Areas See Me run last Friday night[May 21st]...The slide left a fracture line 10-12 feet deep according to Mountain Manager Loris Werner....Friday night's slide left a river of mud that stretched hundreds of yards to a small creek adjacent to Mt. Werner road." (Steamboat Pilot, 5/27/82, p. 1)
8	Approx. 5 mi NW of Redstone, Colorado; T. 10 S., R. 89 W., SW 1/4 of Sect. 11/ 8900 ft.	May 27th, 1983	"Redstone mud scare causes evacuation of valley residents--Their homes and safety endangered by the threat of a buildup of water behind a mudslide in Coal Creek, residents in low-lying areas of the Crystal River Valley were evacuated Friday by emergency crews. According to Pitkin County Undersheriff Don Davis, melt water from the exceptionally deep snowpack "had saturated everything" and a sudden mudflow Friday afternoon [May 27th] blocked Coal Creek with a mud plug some 35 feet wide and 25 feet high. The mud flowed from Gold Camp Canyon into Coal Creek which feeds into the Crystal River at Redstone in Pitkin County..." (Aspen Times, 6/2/83, p. 10).
9	Steamboat Springs, Colorado; T. 6 N., R. 84 W., SE 1/4 of SE 1/4 of Sect. 8/ 6800 ft.	May 12th, 1984	"...On Saturday night [May 12th] a mudslide changed the course of Butcherknife Creek at the end of Hill St." (Steamboat Pilot, 5/17/84, p. 1)

[1]Information in brackets has been added by the author for the purpose of clarification.

Table 1 cont.

LANDSLIDE EVENT NO.	LOCATION/ ELEVATION	DATE OF OCCURRENCE	DESCRIPTION/SOURCE OF INFORMATION[1]
10	Approx. 7 miles SW of Telluride, Colorado/ 9600 ft.	May 13th, 1984	"Woman dies in mud slide; melting snow wrecks county roads--A 24-year old woman student at Western State College in Gunnison died a gruesome death after the car she and a friend were driving back to school washed off Highway 145 near Trout Lake Sunday [May 13th] afternoon and tumbled about 150 feet before coming to rest upside down in the mud." (Telluride Times, 5/17/84, p. 1)
11	Approx. 2 mi. north of Oak Creek, Colorado; T. 4 N., R. 85 W., NE 1/4 of SE 1/4 of Sect. 19/ 7300 ft.	May 14th, 1984	"Rising waters flood Route County--As of Tuesday afternoon [May 15th], flood waters and/or mudslides had temporarily closed portions of numerous County roads...A 75-foot section of Colorado 131 slid Monday [May 14th], 14 miles south of its junction with U.S. 40..." (Steamboat Pilot, 5/17/84, p. 1)
12	Approx. 4 mi. north of Silverthorne, Colorado; T. 4 S., R. 78 W., NE 1/4 of SW 1/4 of Sect. 23/ 8800 ft.	June 1st, 1984	"Mudslide blocks Blue River--...the mudslide occurred on the night of Friday June 1st on the east side of the Blue River 4 miles north of Silverthorne." (Summit County Journal, 6/14/84, p. 3)
13	Between Granby and Tabernash, Colorado/ 8160 ft.	April 16th, 1985	"As a result of a small landslide beneath the track, Amtrak's eastbound 14-car California Zephyr passenger train was derailed in the Fraser River canyon, Colorado, between the towns of Granby and Tabernash, on April 16, 1985. Fortunately, no one was killed in the spectacular accident; however, 26 people were injured, and damages totaled about $3.5 million (Schuster, 1986).
14	Approx. 20 mi. NW of DeBeque, Colorado. T. 6 S., R. 99 W., Section 28 and 33/ 6400 ft.	April 24th, 1985	The Roan Creek landslide is a slump-earthflow complex. It is located in the Roan Creek drainage basin in Garfield County, Colorado on the north-facing slope of Kimball Mountain. It initially failed on 24 April 1985 (Umstot, 1989).

[1] Information in brackets has been added by the author for the purpose of clarification.

Table 1 cont.

LANDSLIDE EVENT NO.	LOCATION/ ELEVATION	DATE OF OCCURRENCE	DESCRIPTION/SOURCE OF INFORMATION[1]
15	Approx. 5 mi. West of Telluride, Colorado/ 9000 ft.	April 30th, 1987	"Starting at approximately 8:30 p.m. on April 30, 1987, a series of landslides occurred in a pre-existing landslide source area located along the upper edge of Deep Creek Mesa. As the landslides moved over the edge of the mesa and through a narrow notch in the sandstone rim, they mobilized into debris flows. The debris flows then traveled 2200 ft over slopes of approximately 50% (a vertical drop of 960 ft) into the valley of the San Miguel River. The debris flows crossed State Highway 145 at a point 700 ft upslope from the valley floor.....Damage estimates for Animas Aggregate are on the order $1.5 million, and airport design consultant Greg Isbill gave the Telluride Airport Authority an estimate of $250,000 to $500,000 to repair the landslide scar area." (Stover and others, 1987)
16	Approx 1 mile east of Steamboat Springs, Colorado/ 7000 ft.	Between April 29th and May 5th, 1993.	[Photo Caption] "Lingering snowpack in the mountains above Steamboat Springs mean this recent mudslide across Spring Creek Road isn't likely to be the last one of the spring." (Steamboat Pilot, 5/6/93, p. 8B).
17	Approx. 3 mi SE of Steamboat Springs, Colorado/ 8200 ft.	May 19th or 20th, 1993	"Mud slides down runs at ski area--Super saturated soil conditions triggered a huge mudslide at the Steamboat ski area last week. The slide started just below Betwixt Catwalk in a wooded area. It continued through the trees until it came to Lower Concentration [ski run], then it turned and followed the run down the hill. It wound its way to the base of Thunderhead lift before dying out. The slide apparently occurred late last Wednesday [May 19th] or early Thursday morning [May 20th]. It was discovered by ski area security....Ken Kowynia, Lands Forester with Route National Forest said it was probably caused by 'super-saturated soil conditions' that resulted from heavy winter snows and were exacerbated by last week's severe rainstorms." (Steamboat Pilot, 5/27/93, p.1)

[1] Information in brackets has been added by the author for the purpose of clarification.

Table 1 cont.

LANDSLIDE EVENT NO.	LOCATION/ ELEVATION	DATE OF OCCURRENCE	DESCRIPTION/SOURCE OF INFORMATION[1]
18	Approx. 5 mi SE of Aspen, Colorado; T. 11 S., R. 84 W. NE 1/4 of NW 1/4 of sect. 2/ 9600 ft.	May 27th, 1993	"Reconnected Again; The Pass [Independence Pass] Opens Early--A mudslide Thursday morning [May 27th] about three-quarters of a mile from the gate threatened the opening of the pass. But highway crews dispatched several loaders to the slide and were able to clear the debris." (Aspen Daily News, 5/28/93, p. 1 and 6)
19	Approx. 5 mi. NW of Silverthorne, Colorado; T. 4 S., R. 78 W., NE 1/4 of NW 1/4 of Sect. 15/ 8700 ft.	May 8th, 1996	"The flow [debris flow] occurred on May 8th just after noon. The flow was about 6 ft deep and the highway [Colorado Highway 9] was blocked for a couple of hours." (Wes Gauff, Colorado Department of Transportation, personal commun., 1996) The debris flow location is approximately 6 miles northwest of the I-70 Silverthorne exit. The failure began as a slump on the hillside approximately 100 ft above and 300 ft west of the highway. The movement transformed into a debris flow that travelled approximately 400 ft down the hillside and across and beyond Highway 9.
20	Approx. 1 mi. SW of Aspen, Colorado; Keno Gulch in the Castle Creek drainage/ 9600 ft.	May 13th, 1996	"I first observed cracks opening in the snow covering the slide on Sunday May 5th. There was 3 to 5 ft of snow on the slide at that time" (Jim Blanning, personal commun., 1996). "The first debris flow came down the mountain [Keno Gulch] on Monday, May 13th at about 4:30 pm. A second came down the next day [Tuesday, May 14] at about 4:00 pm. The parking lot was covered with mud and debris about 5-ft thick, six cars were virtually buried (4 were totalled). The mud and debris flowed into and structurally damaged the Music Hall and partially filled the large pond beside the Music Hall. Neither flow was moving so fast that you couldn't walk away from it." (David Pearcy, Director, Aspen Day School, personal commun., 1996)

[1]Information in brackets has been added by the author for the purpose of clarification.

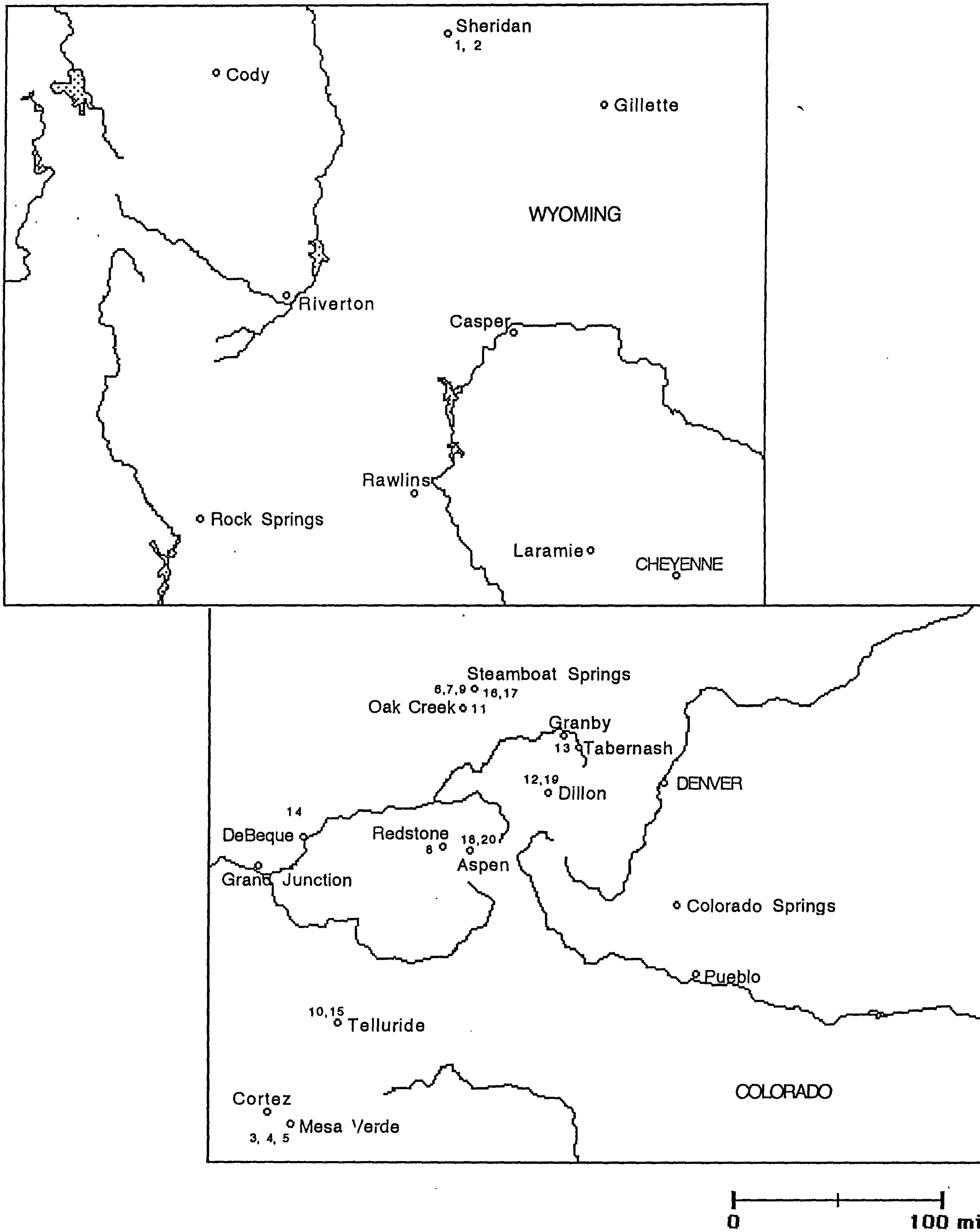

Figure 1.--Index map of Colorado and Wyoming showing the locations of landslides included in the study. Numbers shown are those of landslide events listed in Table 1.

Table 2.--Weather stations used as sources of historical climate data.

WEATHER STATION	LOCATION/ ELEVATION	ASSOCIATED LANDSLIDE EVENT[1]	DISTANCE BETWEEN WEATHER STATION AND LANDSLIDE (MILES)	ELEVATION DIFFERENCE (LANDSLIDE MINUS WEATHER STATION, IN FEET)
Aspen 1SW	1.1 miles SW of Post Office at Aspen, Colorado/ 8163 ft.	18	5	1437
do.	do.	20	1	1437
Altenbern	17 miles NW of Post Office at DeBeque, Colorado/ 5690 ft.	14	3	710
Dillon 1E	0.7 miles ESE of Post Office at Dillon, Colorado/ 9065 ft.	12	6	-265
do.	do.	19	8	-365
Grand Lake 6 SSW	6 miles SSW of Post Office at Grand Lake, Colorado/ 8380 ft.	13	10	-220
Mesa Verde National Park	0.7 miles north of Post Office at Mesa Verde National Park, Colorado/ 7115 ft.	3	10	750
do.	do.	4	10	735
do.	do.	5	10	750

[1]See table 1 for description

Table 2 cont.

WEATHER STATION	LOCATION/ ELEVATION	ASSOCIATED LANDSLIDE EVENT[1]	DISTANCE BETWEEN WEATHER STATION AND LANDSLIDE (MILES)	ELEVATION DIFFERENCE (LANDSLIDE MINUS WEATHER STATION, IN FEET)
Redstone 4W	4 miles west of Post Office at Redstone, Colorado/ 8065 ft.	8	2	835
Sheridan WSO AP	1 mile SW of Post Office at Sheriidan, Wyoming/ 3940 ft.	1	7	520
do.	do.	2	7	520
Steamboat Springs 1W	0.5 miles west of Post Office at Steamboat Springs, Colorado/6700 ft	6	1	200
do.	do.	7	4	800
do.	do.	9	1	100
do.	do.	11	14	600
do.	do.	16	2	300
do.	do.	17	4	1500
Telluride	2 blocks north of Post Office at Telluride, Colorado/8800 ft	10	7	800
Telluride	2 blocks north of Post Office at Telluride, Colorado/8800 ft	15	5	200

[1]See table 1 for description

The Doesken and others (1990) study did not address climatic data representativeness on time scales shorter than a month. It is stated in the report that, in general, variability is increased with shorter sampling periods as you go down in time from monthly or seasonally to daily or weekly. And, for the shorter sampling periods, time series analyses, comparisons and correlations must be performed to attempt to determine representativeness.

For the purpose of estimating historical daily maximum and minimum temperatures at the landslide sites, I have assumed that the reported relationship between temperature and elevation (-4.5° F/1000 ft elevation) is valid for a shorter sampling period. This assumption is based on the proximity of the weather stations to the respective landslide sites, and the apparent absence of significant, intervening terrain factors, such as major mountain divides. Because the range of representativeness is much less for precipitation than for temperature, I have made no attempt to make quantified estimates of historical daily precipitation for the landslide sites.

DATA ANALYSIS and RESULTS

As a first step, I corrected the raw daily temperature data for elevation differences between the weather stations and landslide sites using the relationship of Doesken and others (1990). Subsequent inspection of the corrected daily temperature data 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. In order to examine relationships between dates of landslide occurrence and antecedent temperature trends, I computed 6-day moving averages of daily maximum and minimum temperatures 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. Graphs for the periods of time that show the association between intervals of rising temperatures and dates of landslide events are presented in the appendix (figs. 2-19).

As shown in Figures 2-19, 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. Also note that, in general, the 6-day moving average of daily minimum temperature is less variable than that of the daily maximum temperature.

In a preliminary effort to identify a threshold temperature that might be used to forecast the onset of snowmelt related landsliding, I developed graphs showing the association between the dates of the landslide events and the first yearly occurrence of specific 6-day moving average temperatures. For this purpose, 6-day moving averages of daily maximum temperatures in the range 50° to 70° F were used. The following two measures were used in the attempt to identify the 6-day moving average of daily maximum temperature that would be most useful for forecasting purposes: (1) the total number of landslide events that occurred within 3 weeks after the first yearly occurrence of the potential threshold temperature, and (2) the degree of data clustering near the potential threshold temperature; defined as the sum of the differences between the landslide event dates and the date of the first yearly occurrence of the potential threshold temperature, in days. The potential threshold temperature with the highest number of landslide events, determined by the first measure, and the lowest sum of differences, determined by the second measure, would then be selected for forcasting purposes. Based on these criteria, I selected a 6-day moving average of 58° F as the proposed threshold temperature. However, when the measures were applied only minor differences between the 58° F average temperature and others in the 55 to 60° F range were apparent, suggesting that more sophisticated statistical measures and additional data are needed to refine the estimate. Because landslide events No. 1 and 2 were not complete landslide failures they were not included in the selection process. Landslide events No. 3 and 6 were included by assuming a midrange date of occurrence from within the bracketed range. Figure 20 shows the dates of the landslide events in relation to the first yearly occurrence of a 6-day average ≥ 58° F. As shown, most of the landslide events occurred within two weeks after the first yearly occurrence of the indicated 58° threshold. The one event that definitely occurred before the 58° F threshold was reached (Landslide event No. 16, fig. 15) was preceded by a gradual warming trend that culminated in a 6-day moving average of 57° F on the day of the landslide event.

Because elevation is only a secondary control on minimum temperatures and minimum temperatures are less variable than maximums, I did not attempt to develop graphs similar to that of Figure 20 for the daily minimums. It seems reasonable to expect a close association between the onset of snowmelt related landslides and the first yearly occurrence of sustained daily minimum temperatures above freezing (32° F). However, visual examination of the plots (figs. 2 -19) indicate that, although there appears to be an association, only about half of the 20 landslide events preceded the first yearly occurrence of a 6-day moving average ≥32° F; therefore, it would not be as useful for forecasting the onset of spring season landslides as the 6-day daily maximum average of 58° F.

As previously stated, I have assumed that the reported relationship between temperature and elevation (-4.5° F/1000 ft of elevation increase) is valid for the 6-day sampling periods. A study of temperature representativeness for the relatively short distances considered in this study is beyond the scope of this report. However, the few comparisons I have made of daily temperature data recorded at weather stations separated by similar distances suggests a good correlation. An example is the 6-day moving averages of daily maximum temperature from the Sheridan AP weather station (fig. 2) and that for the same March 6 to April 30, 1977 period from a weather station located 7 mi to the northeast (Sheridan Field Station). Comparison of the data (corrected for an elevation difference of 240 ft) is shown in Figure 21.

DISCUSSION AND CONCLUSIONS

The results of this preliminary study suggest that temperature data recorded at weather stations throughout the Rocky Mountain region is potentially a valuable source of information for forecasting the onset of spring season landslides. Beginning in March of each year, moving averages of real-time daily temperatures obtained from local weather stations could be used to pinpoint the first occurrences of the threshold temperature in the respective areas of interest. Forecasts could then be issued to the media and appropriate government agencies warning of the increased potential for landsliding. In addition to insuring public awareness, the forecasts could be used for such things as planning and scheduling highway maintenance, timing the deployment of field instrumentation, and monitoring potentially hazardous landslide masses.

Although the combination of deep snowpack and warming trends sufficient to cause significant snowmelt usually occur in the spring of each year in the central Rocky Mountains, it can occasionally occur at other times of the year as well. It follows that the first yearly occurrence of the threshold temperature may, on occasion, arrive before the spring season. Also, areas outside of the area of this study that have significantly different regional climates have experienced widespread landsliding involving snowmelt with rain-on-snow storms during

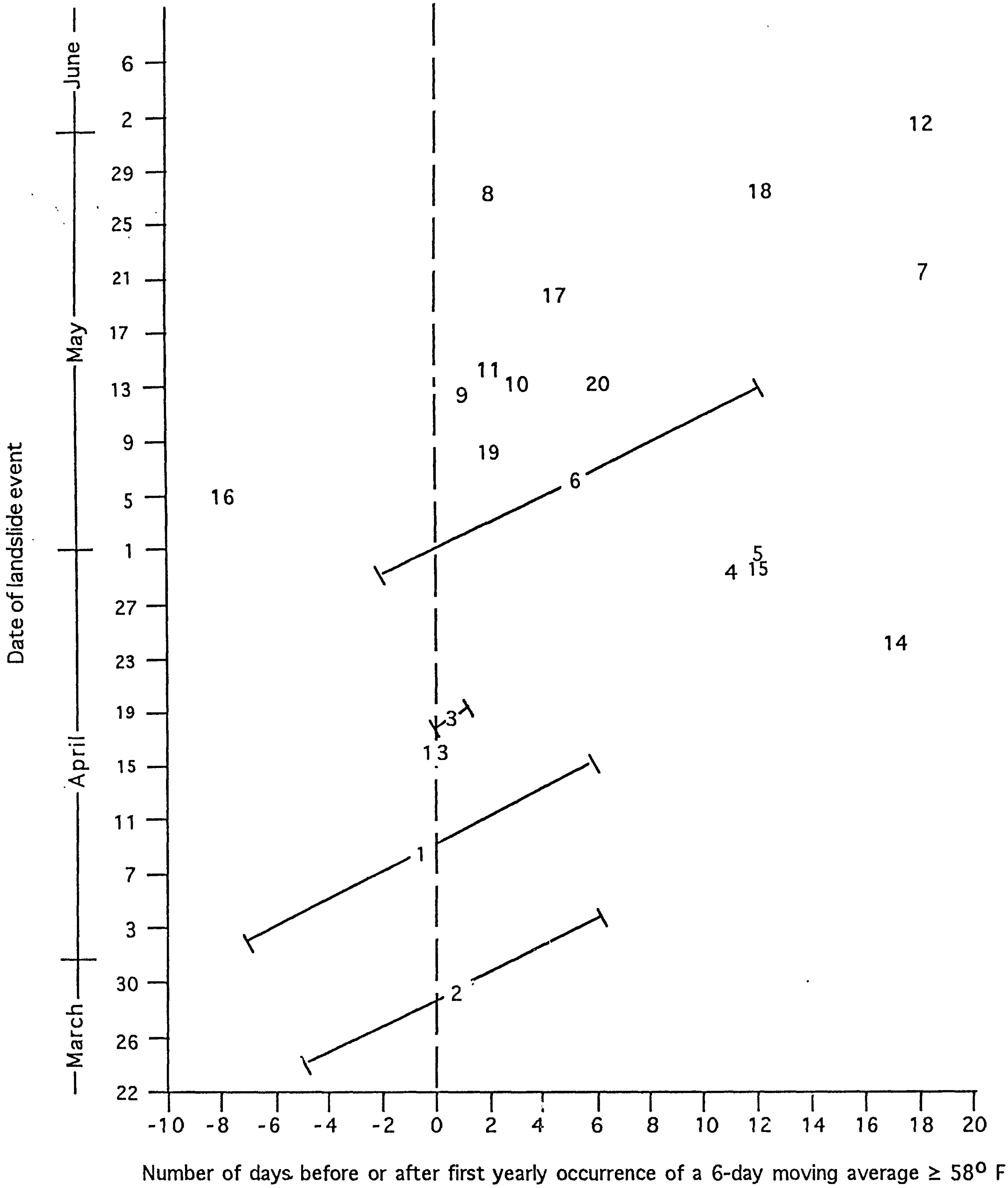

Figure 20.--Plot showing dates of landslide events in relation to the first yearly occurrence of a 6-day moving average of daily maximum temperature greater than or equal to 58° F. Plotted numbers are landslide events identified in Table 1 and Figures 2-19. Note that a high percentage of the landslide events occurred within 18 days after the first yearly occurrence of the proposed 58° F threshold.

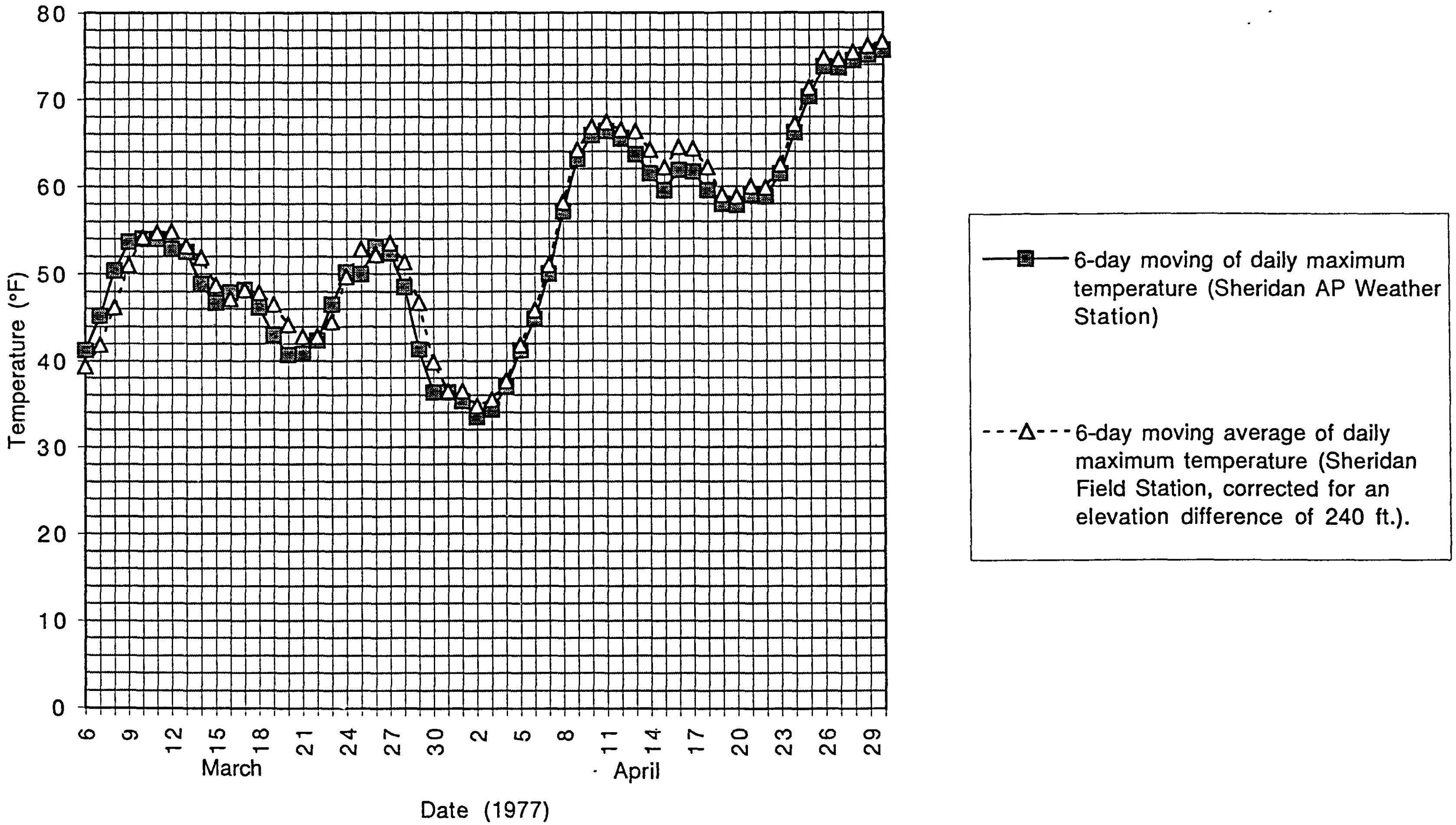

Figure 21. Comparison of 6-day moving averages of daily maximum temperatures recorded at Sheridan AP and Sheridan Field Station weather stations during the period March 6, to April 30, 1977.

the winter months (e.g., Day and Megahan, 1976). Temperatures and temperature trends associated with those events may differ significantly from those of this study.

This study is based on a limited number of spring season landslide events and only minimal amounts of information on the various geologic, hydrologic, and climatic factors that may have contributed to their occurrence. Additional work is needed to expand the landslide database and further evaluate the representativeness of the temperature data. Such work would likely result in refinement of the threshold value and an improved forecasting capability.

REFERENCES

Aspen Daily News, 1993, Reconnected again; the Pass opens early: Aspen, Colorado, May 28, p. 1 and 6.

Aspen Times, 1983, Redstone mud scare causes evacuation of valley residents: Aspen, Colorado, June 2, p. 10.

Chleborad, Alan F., 1980, Investigation of a natural slope failure in weathered Tertiary deposits, western Powder River Basin, Wyoming: U.S. Geological Survey Open-File Report 80-673, 66 p.

Day, N.F., and Megahan, W.F., 1976, Landslide occurrence on mountainous terrain in north-central Idaho: A progress report, 1974-75: Proceedings of the 14th Annual Symposium of Engineering Geologists and Soils Engineeers, Boise State University, April 7,8, and 9th, p. 85-104.

Doesken, Nolan J., McKee, Thomas B., and Kleist, John, 1990, Climatic data representativeness in western Colorado: Colorado State University Climatology Report No. 90-1, 43 p.

Montezuma Valley Journal, 1979, Slides on Mesa Verde: Cortez, Colorado, April 20, p. 1.

Montezuma Valley Journal, 1979, Mesa Verde remains closed: Cortez, Colorado, May 2, p. 1.

Schuster, Robert L., 1986, Amtrak wreck caused by landslide near Granby, Colorado: Ground Failure, National Research Council Committee on Ground Failures, No. 3, Spring 1986.

Steamboat Pilot, 1982, Mud slides damage ski jumps: Steamboat Springs, Colorado, May 13, p. 1.

Steamboat Pilot, 1982, See Me, see mudslide: Steamboat Springs, Colorado, May 27, p. 1.

Steamboat Pilot, 1984, Rising waters flood Route County: Steamboat Springs, Colorado, May 17, p. 1.

Steamboat Pilot, 1993: Mud slides down runs at ski area: Steamboat Springs, Colorado, May 27, p. 1.

Stover, B.K., Cannon, S.H., and Junge, Rahe W., 1987, The April 30, 1987 Telluride Airport landslides and resultant debris flows: Colorado Geological Survey Department of Natural Resources Open-File Report 87-2, 14 p.

Summit County Journal, 1984, Mudslide blocks Blue River: Dillon, Colorado, June 14, p. 3.

Telluride Times, 1984, Woman dies in mud slide; melting snow wrecks county roads: Telluride, Colorado, May 17, p.1.

Umstot, David, 1989, Field studies and modeling analysis of the Roan Creek landslide, Garfield County, Colorado: Colorado Geological Survey Department of Natural Resources Open-File Report 89-1, 67 p.

U.S. Department of Commerce, 1977, Wyoming climatological data: Daily temperature data, v. 86, No.s 1-4.

U.S. Department of Commerce, 1978, Wyoming climatological data: Daily temperature data, v. 87, No.s 1-4.

U.S. Department of Commerce, 1979, Colorado Climatological Data: Daily temperature data,

v. 84, No.s 1-5.
U.S. Department of Commerce, 1982, Colorado Climatological Data: Daily temperature data, v. 87, No.s 1-5.
U.S. Department of Commerce, 1984, Colorado Climatological Data: Daily temperature data, v. 89, No.s 1-5.
U.S. Department of Commerce, 1985, Colorado Climatological Data: Daily temperature data, v. 90, No.s 1-4.
U.S. Department of Commerce, 1987, Colorado Climatological Data: Daily temperature data, v. 92, No.s 1-5.
U.S. Department of Commerce, 1993, Colorado Climatological Data: Daily temperature data, v. 98, No.s 1-5.
U.S. Department of Commerce, 1996, Colorado Climatological Data: Daily temperature data, v. 101, No.s 1-5

APPENDIX

(Figures 2-19)

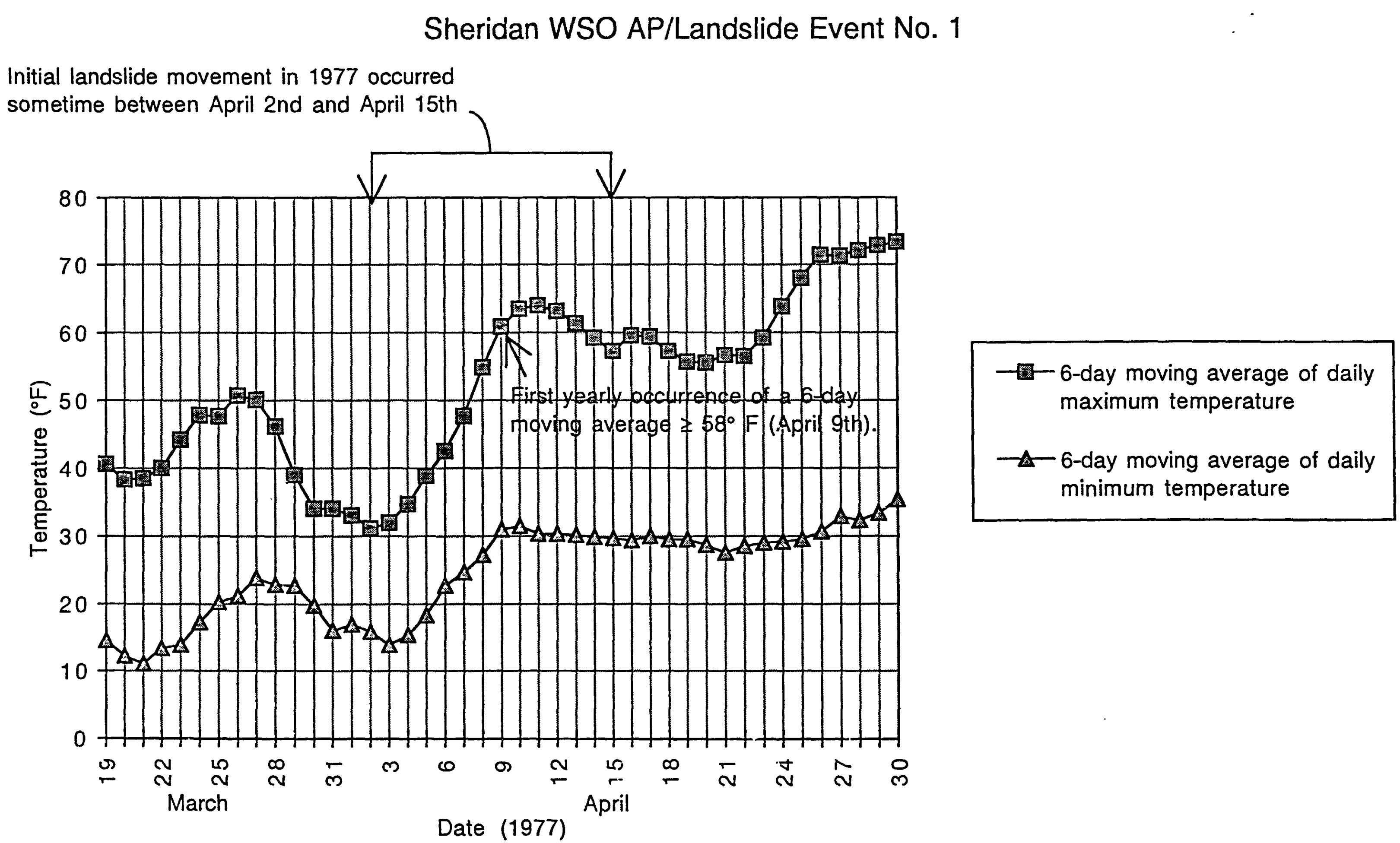

Figure 2. Graph showing the association of landslide event No. 1 with rising temperatures and the first yearly occurrence of a 6-day moving average of daily maximum temperature greater than or equal to a 58° F.

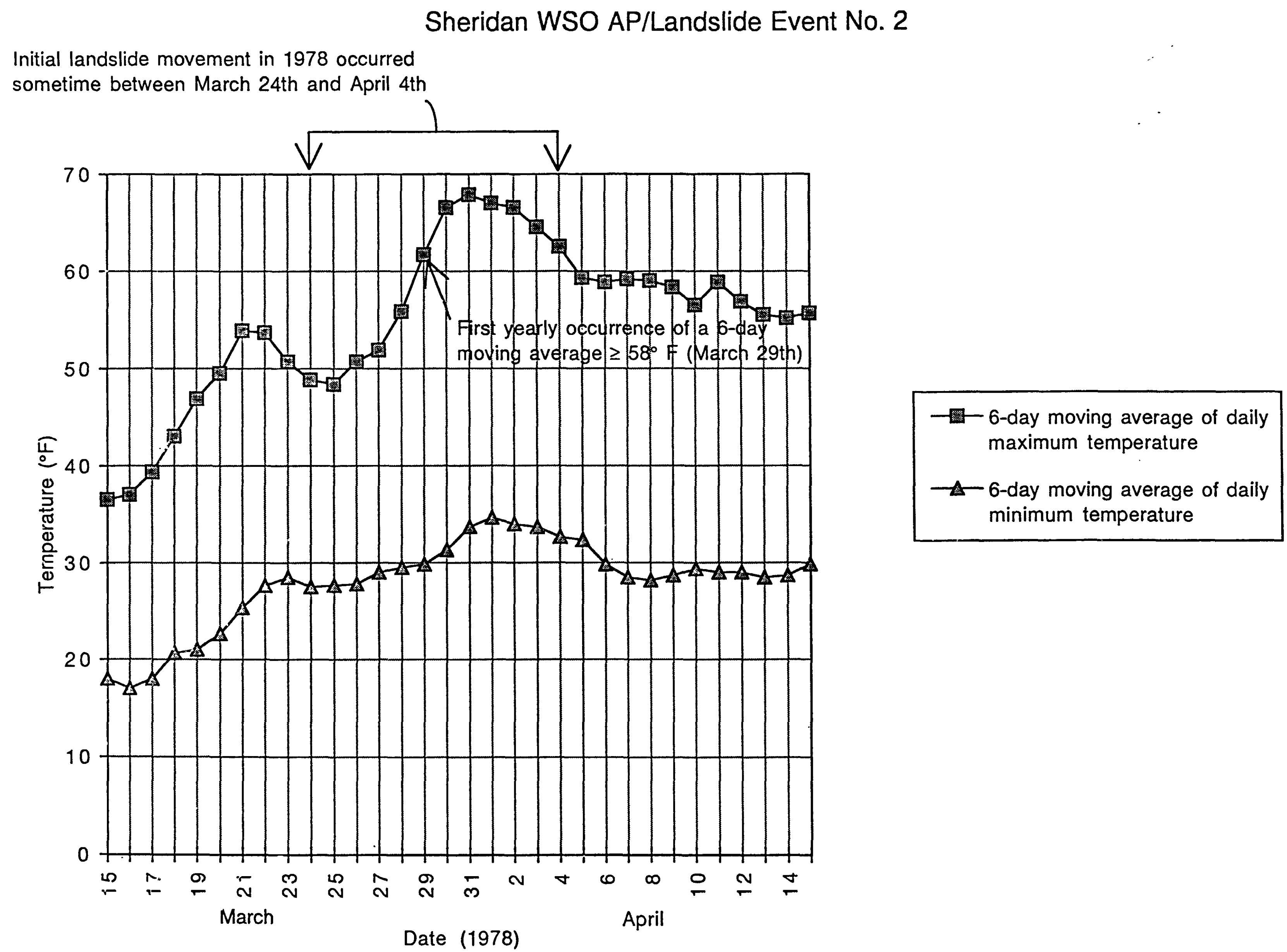

Figure 3. Graph showing the association of landslide event No. 2 with rising temperatures and the first yearly occurrence of a 6-day moving average of daily maximum temperature greater than or equal to 58° F.

Mesa Verde National Park/Landslide Events No. 3, 4, and 5

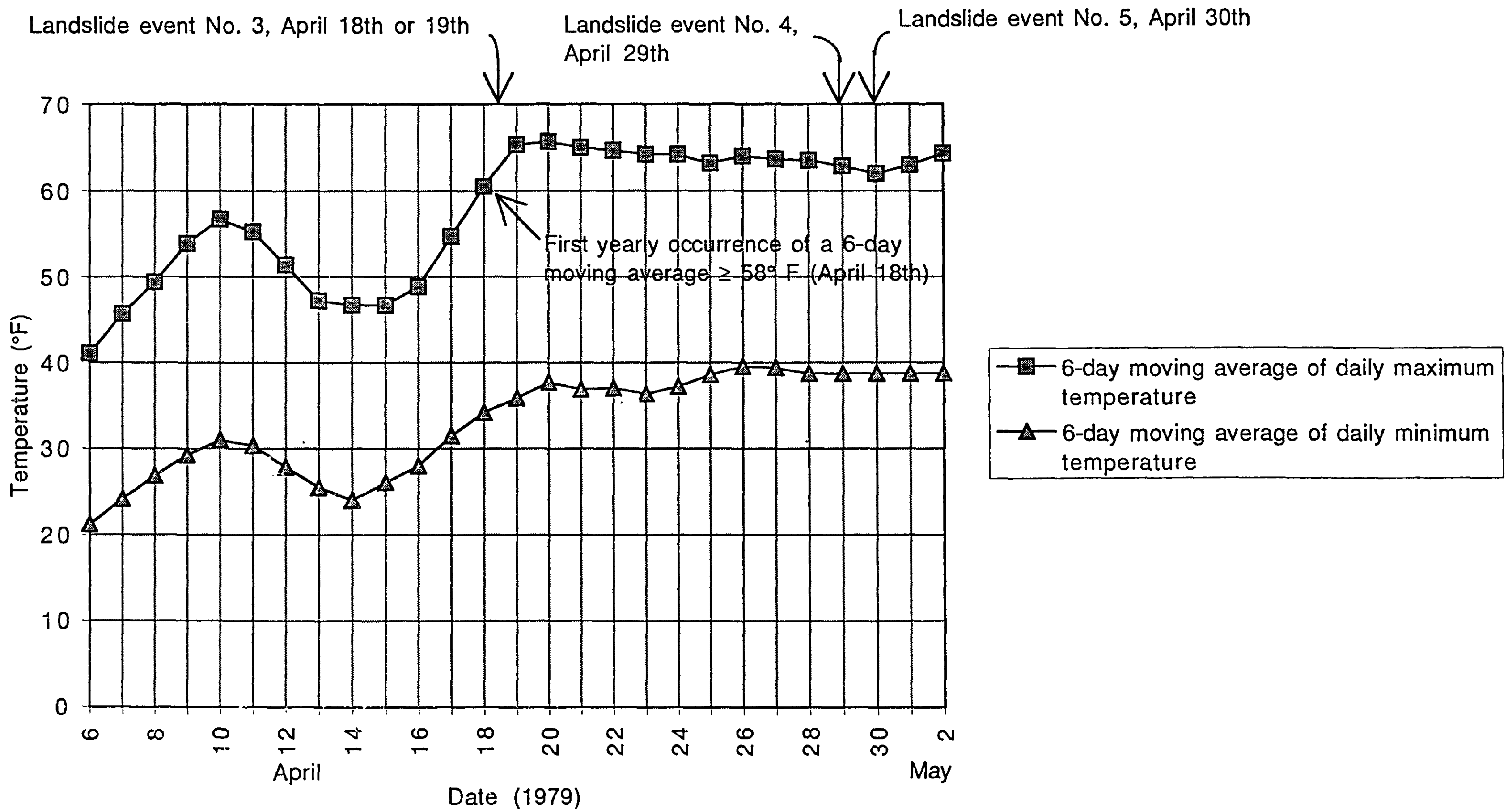

Figure 4. Graph showing the association of landslide events No. 3, 4, and 5 with rising temperatures and the first yearly occurrence of a 6-day moving average of daily maximum temperature greater than or equal to 58° F.

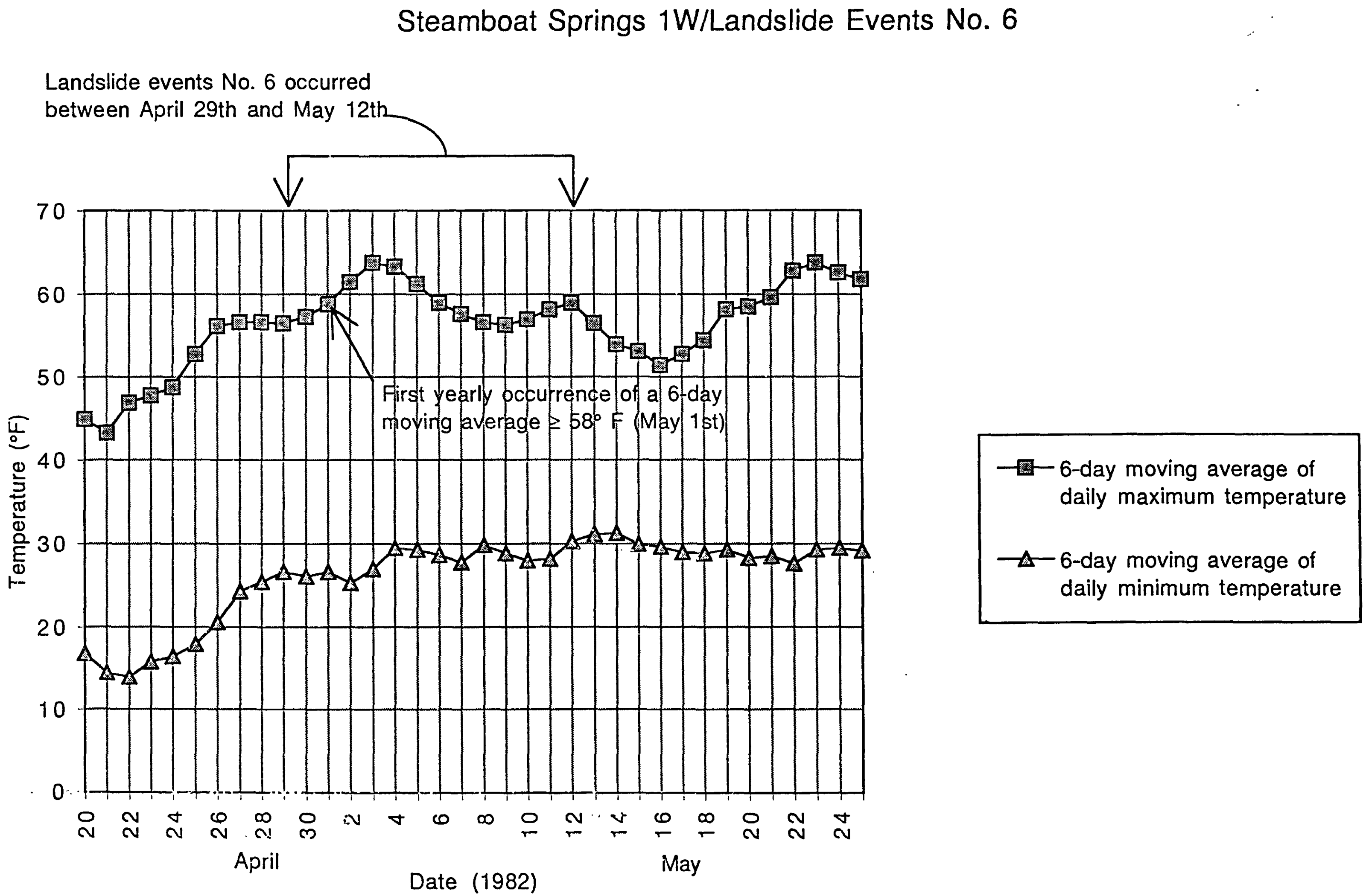

Figure 5. Graph showing the association of landslide event No. 6 with rising temperatures and the first yearly occurrence of a 6-day moving average of daily maximum temperature greater than or equal to 58° F.

Steamboat Springs 1W/Landslide Event No. 7

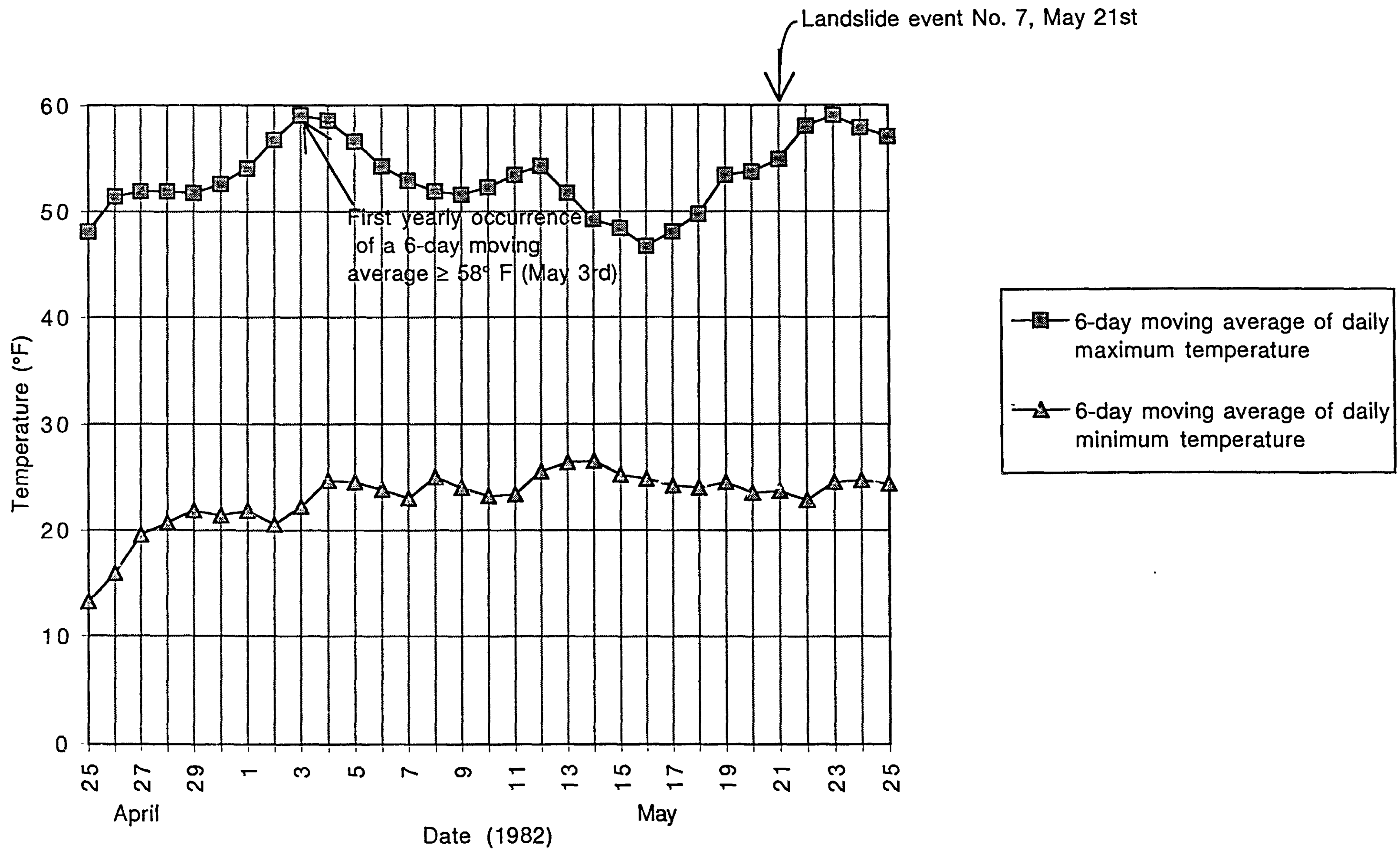

Figure 6. Graph showing the association of landslide event No. 7 with rising temperatures and the first yearly occurrence of a 6-day moving average of daily maximum temperature greater than or equal to 58° F.

Redstone 4W/Landslide Event No. 8

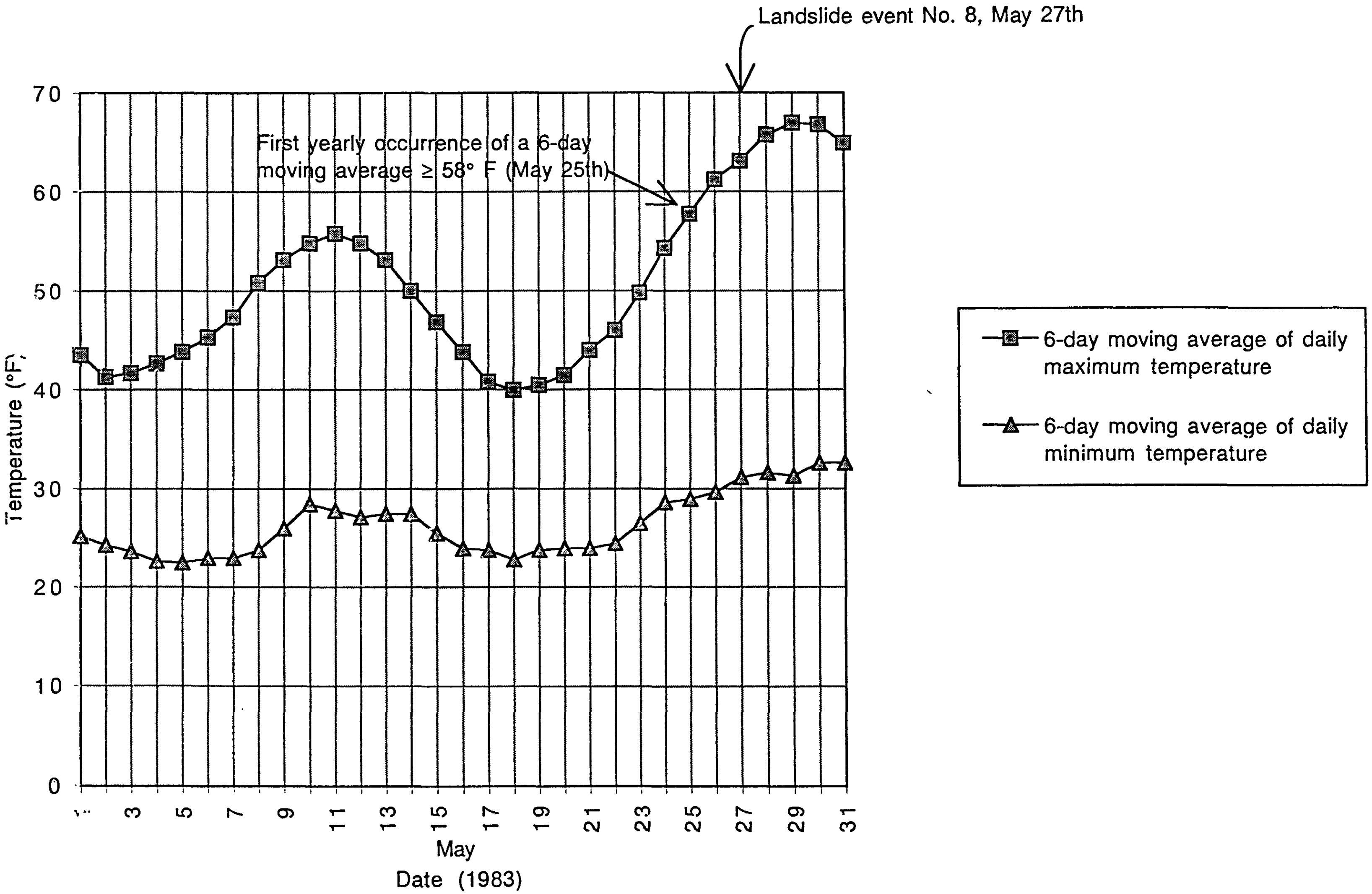

Figure 7. Graph showing the association of landslide event No. 8 with rising temperatures and the first yearly occurrence of a 6-day moving average of daily maximum temperature greater than or equal to 58° F.

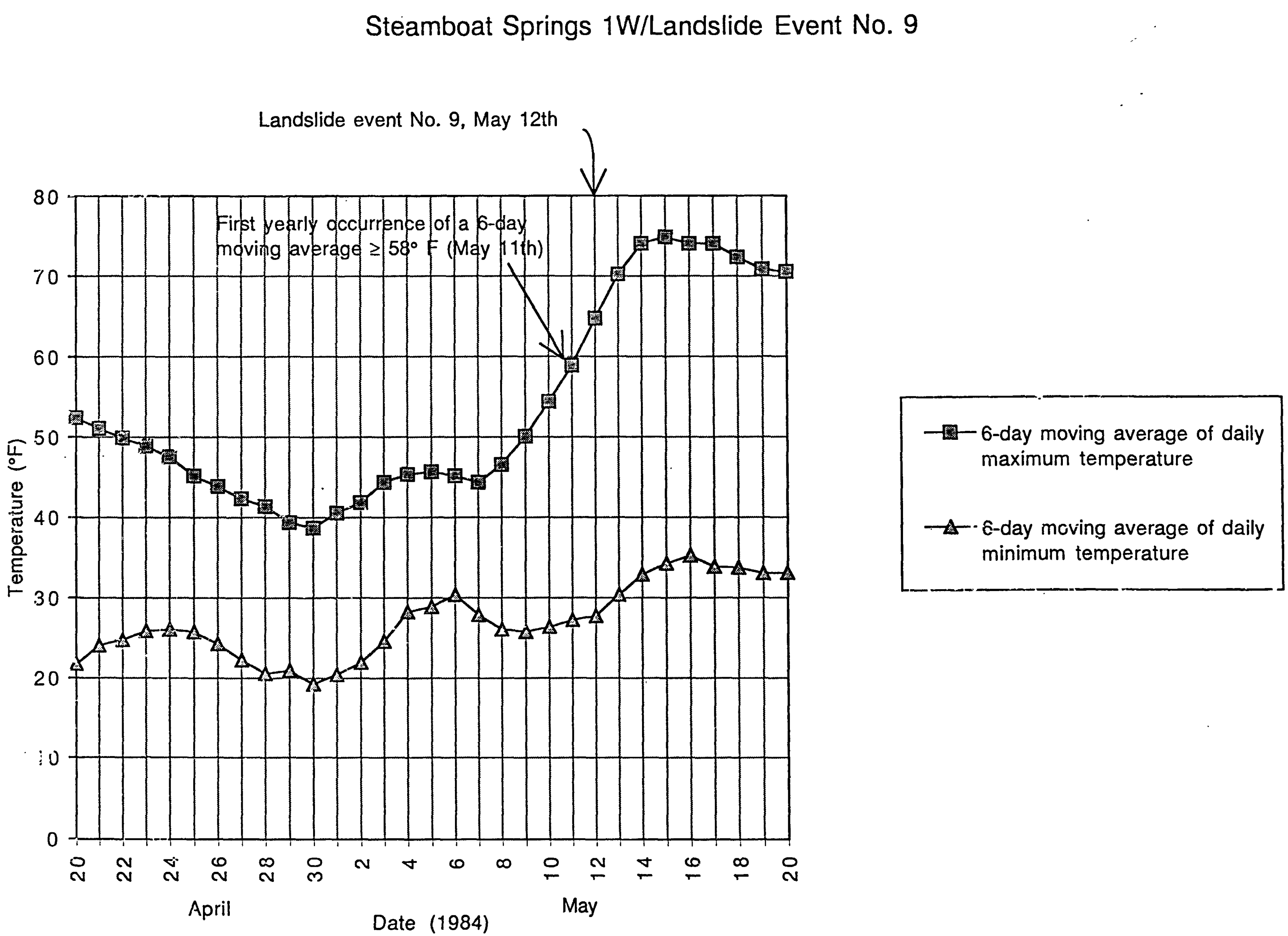

Figure 8. Graph showing the association of landslide event No. 9 with rising temperatures and the first yearly occurrence of a 6-day moving average of daily maximum temperature greater than or equal to 58° F.

Telluride/Landslide Event No. 10

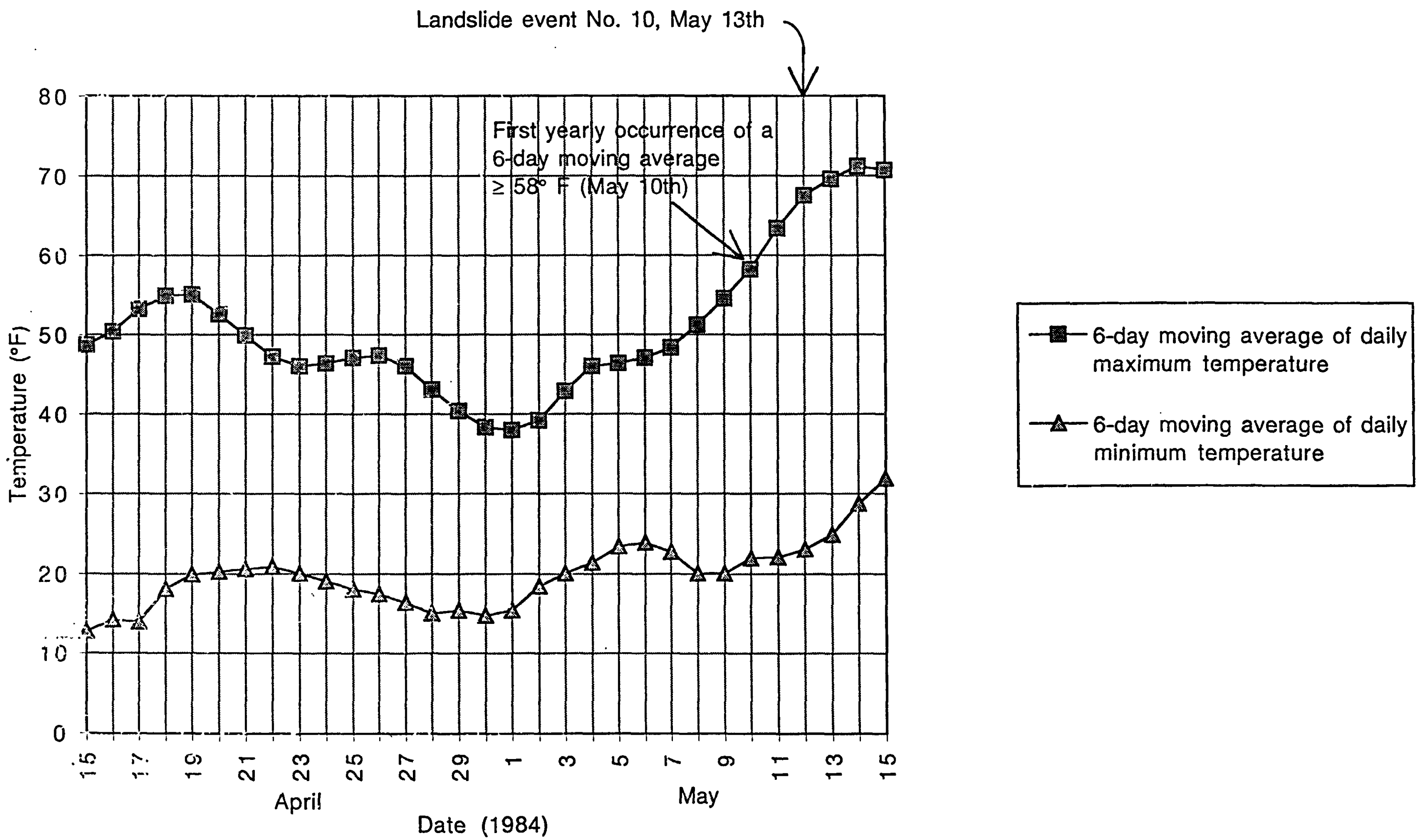

Figure 9. Graph showing the association of landslide event No. 10 with rising temperatures and the first yearly occurrence of a 6-day moving average of daily maximum temperature greater than or equal to 58° F.

Steamboat Springs 1W/Landslide Event No. 11

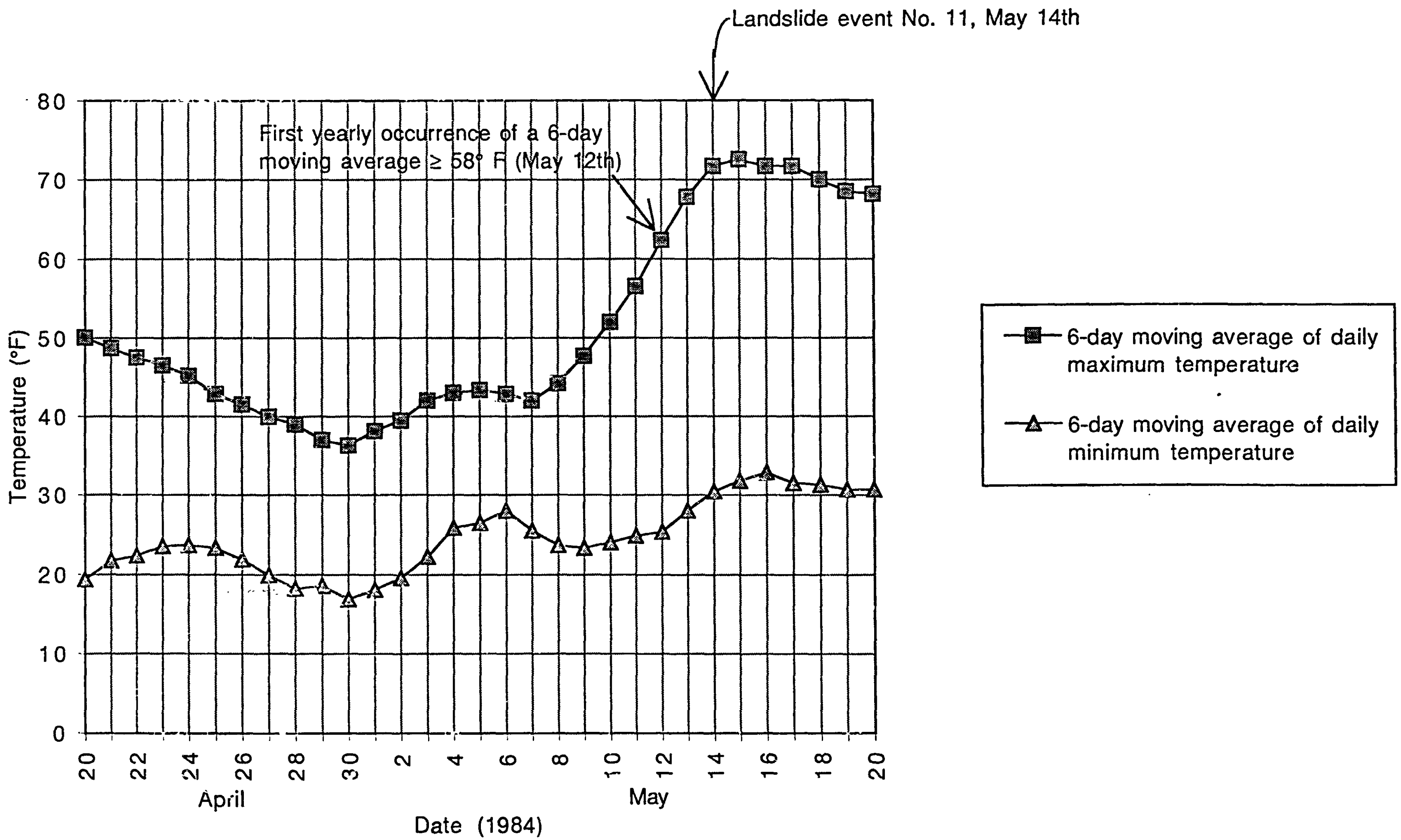

Figure 10. Graph showing the association of landslide event No. 11 with rising temperatures and the first yearly occurrence of a 6-day moving average of daily maximum temperature greater than or equal to 58° F.

Dillon 1E/Landslide Event No. 12

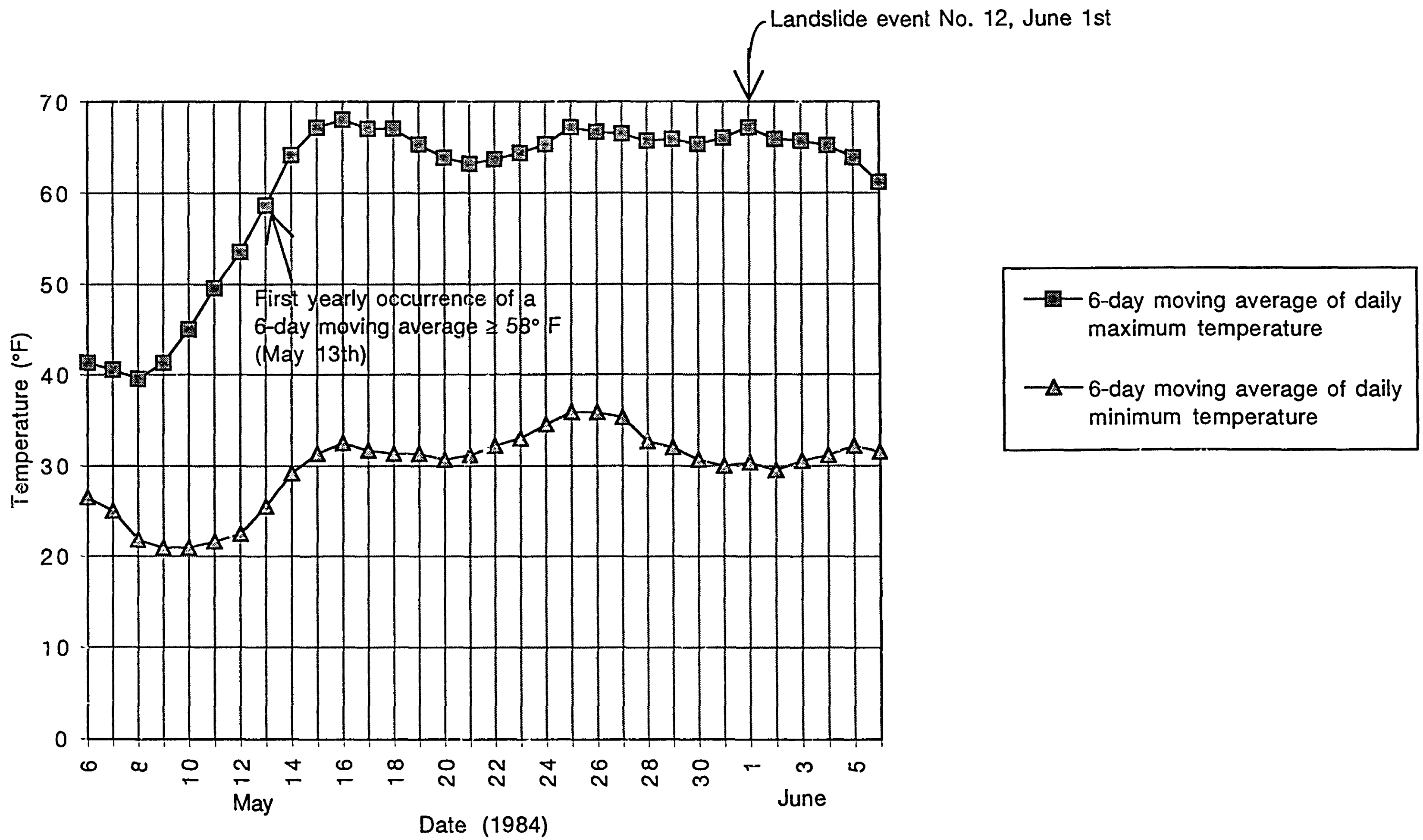

Figure 11. Graph showing the association of landslide event No. 12 with rising temperatures and the first yearly occurrence of a 6-day moving average of daily maximum temperature greater than or equal to 58° F.

Grand Lake 6SSW/Landslide Event No. 13

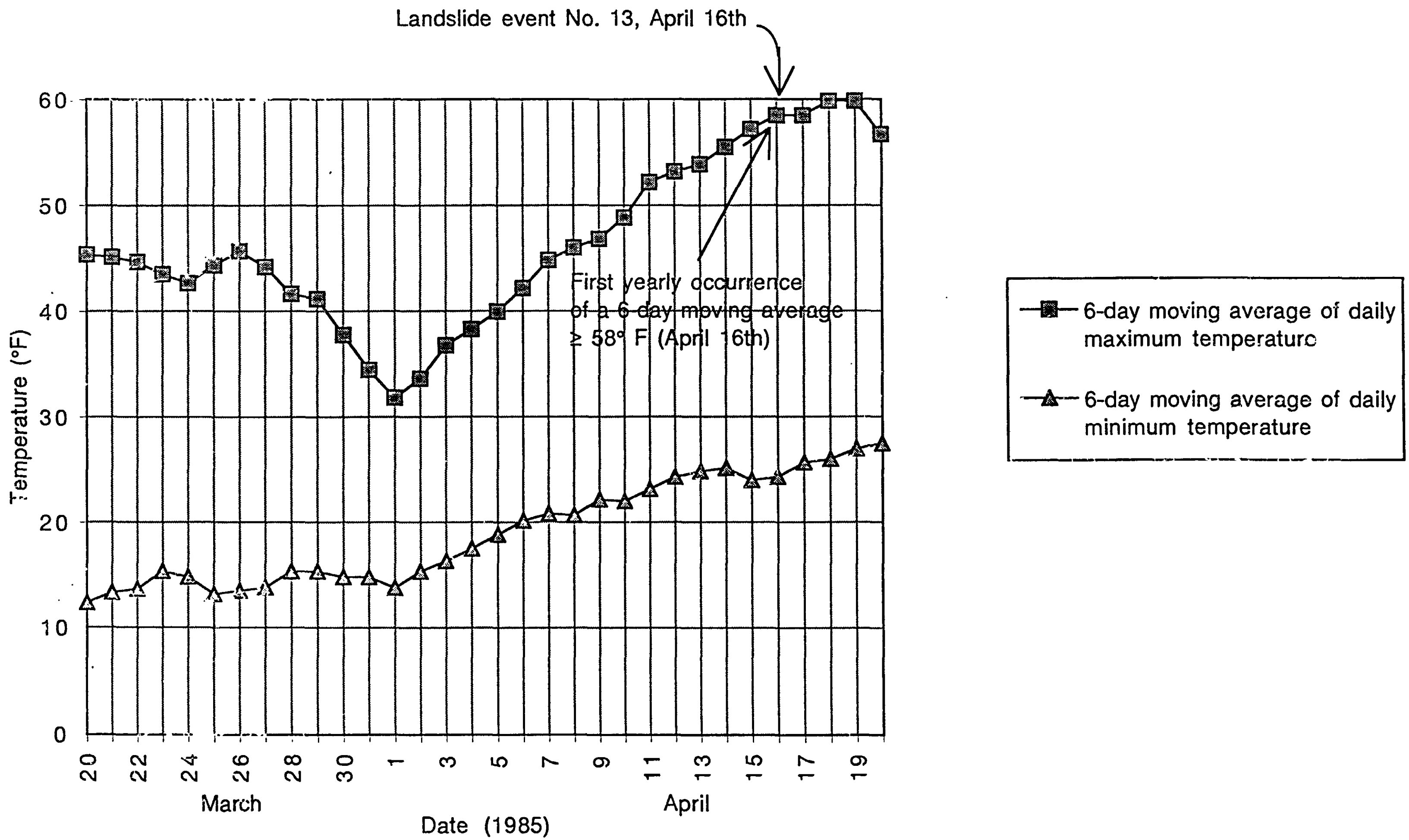

Figure 12. Graph showing the association of landslide event No. 13 with rising temperatures and the first yearly occurrence of a 6-day moving average of daily maximum temperature greater than or equal to 58° F.

Altenbern/Landslide Event No. 14

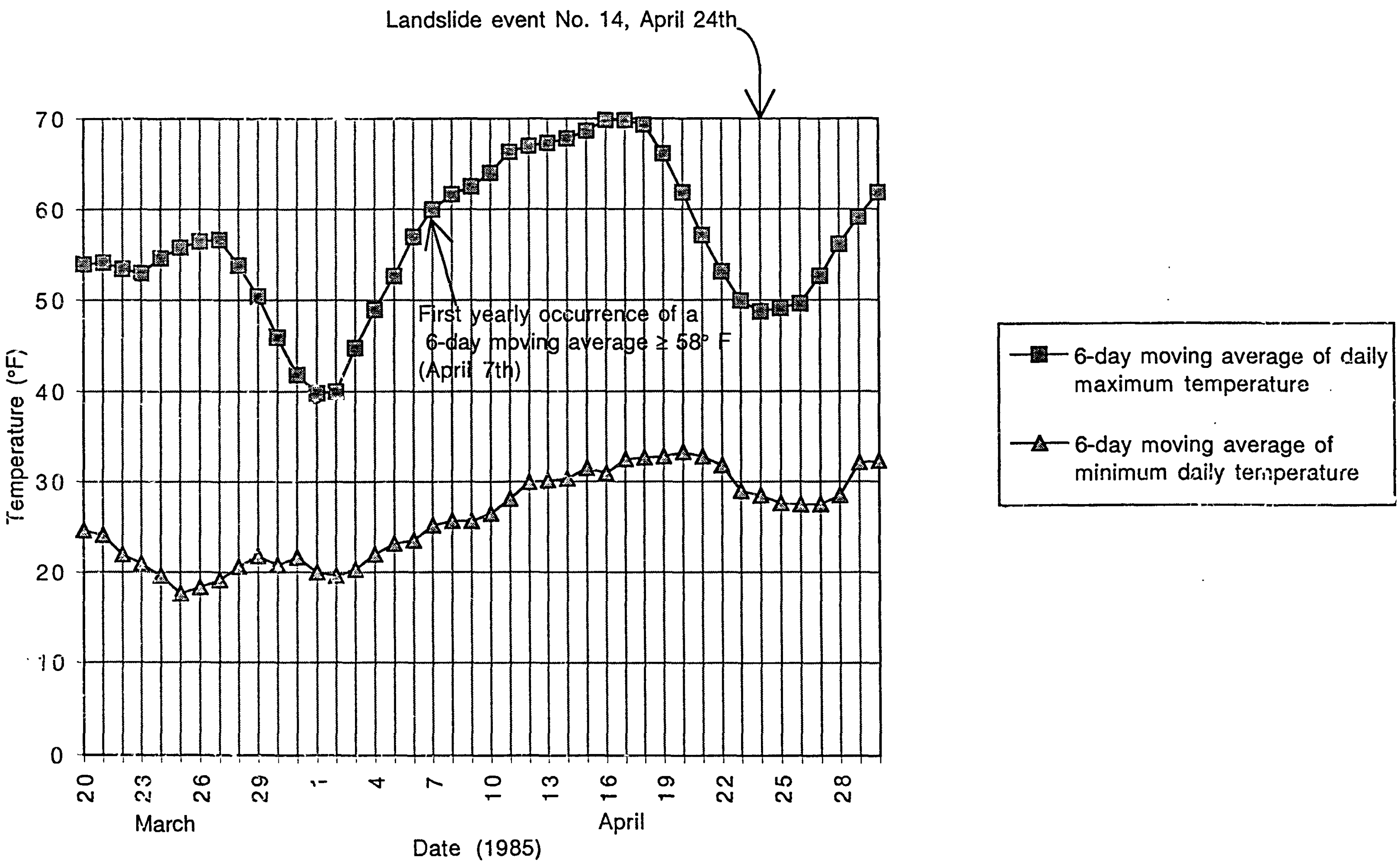

Figure 13. Graph showing the association of landslide event No. 14 with an antecedent interval of rising temperatures and the first yearly occurrence of a 6-day moving average of daily maximum temperature greater than or equal to 58° F.

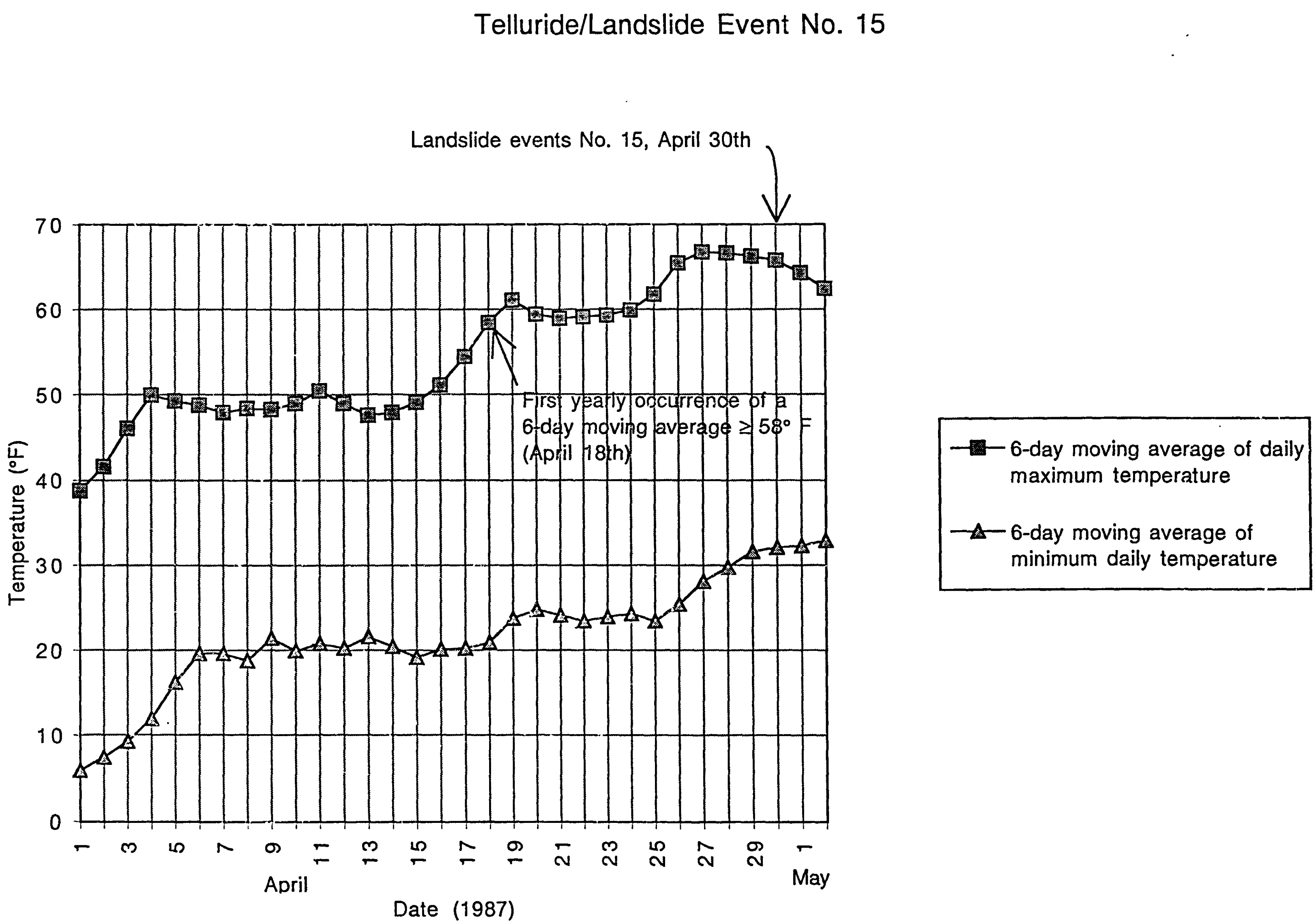

Figure 14. Graph showing the association of landslide event No. 15 with rising temperatures and the first yearly occurrence of a 6-day moving average of daily maximum temperature greater than or equal to 58° F.

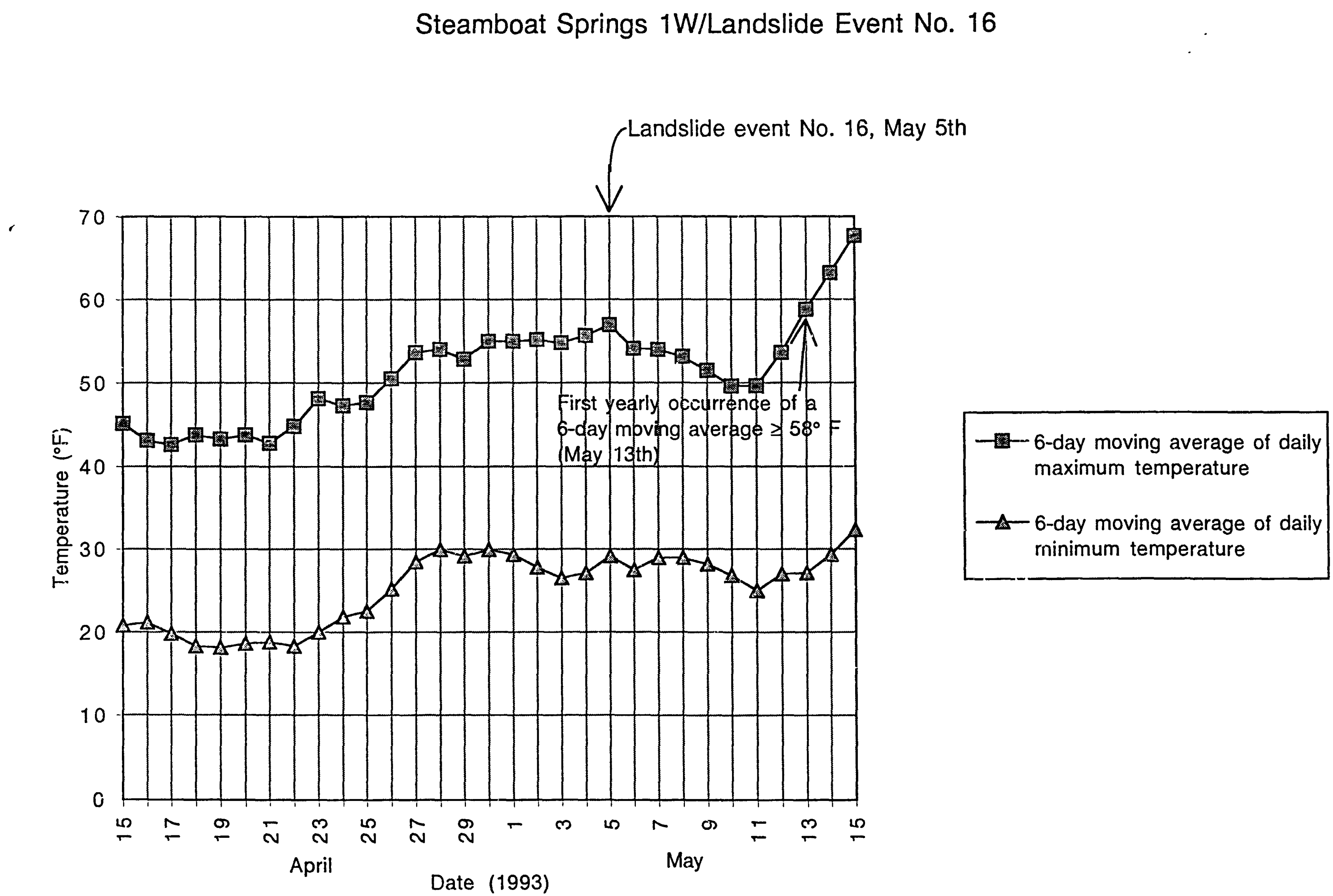

Figure 15. Graph showing the association of landslide event No. 16 with rising temperatures and the first yearly occurrence of a 6-day moving average of daily maximum temperature greater than or equal to 58° F.

Steamboat Springs 1W/Landslide Event No. 17

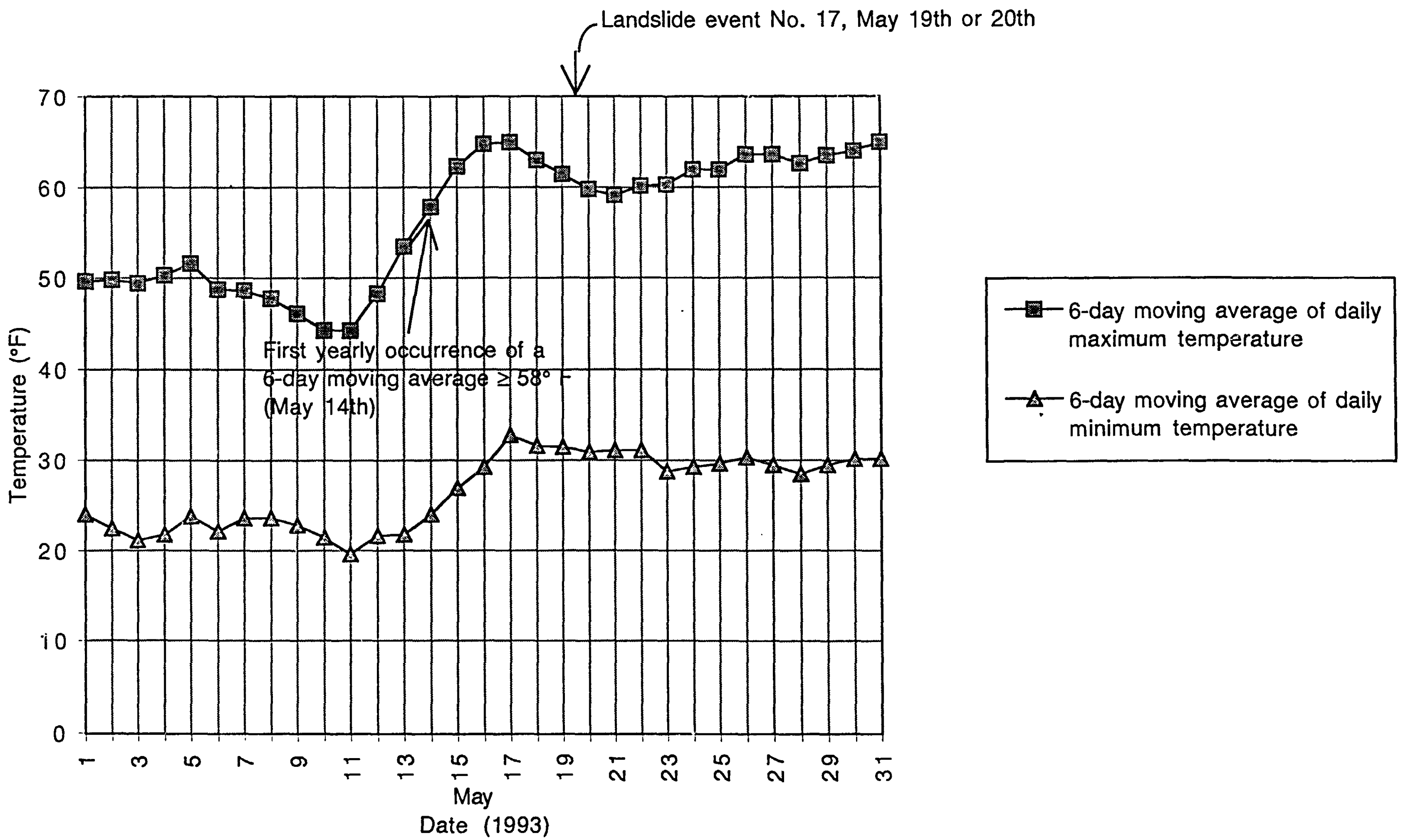

Figure 16. Graph showing the association of landslide event No. 17 with rising temperatures and the first yearly occurrence of a 6-day moving average of daily maximum temperature greater than or equal to 58° F.

Aspen 1SW/Landslide Event No. 18

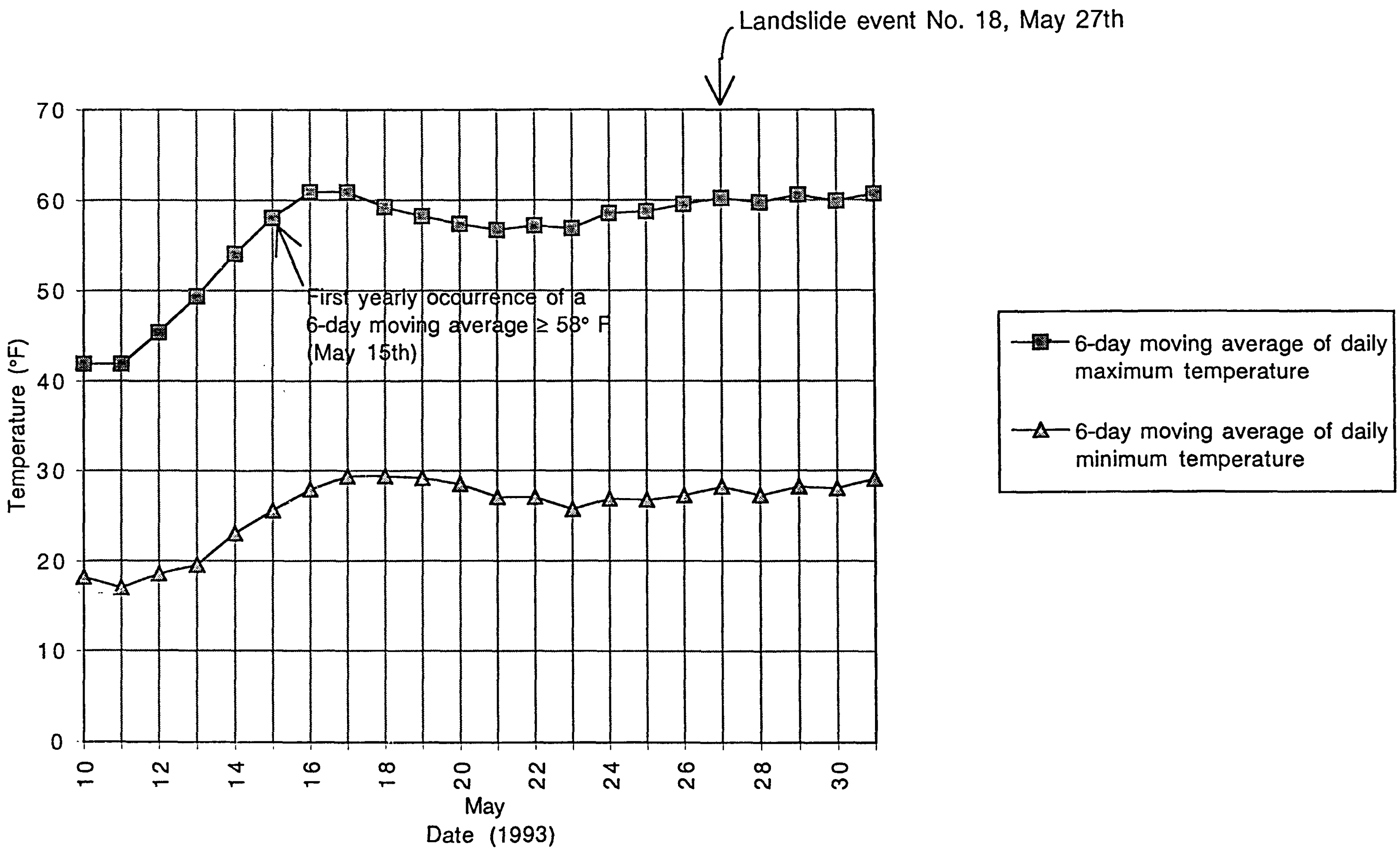

Figure 17. Graph showing the association of landslide event No. 18 with rising temperatures and the first yearly occurrence of a 6-day moving average of daily maximum temperature greater than or equal to 58° F.

Dillon 1E/Landslide Event No. 19

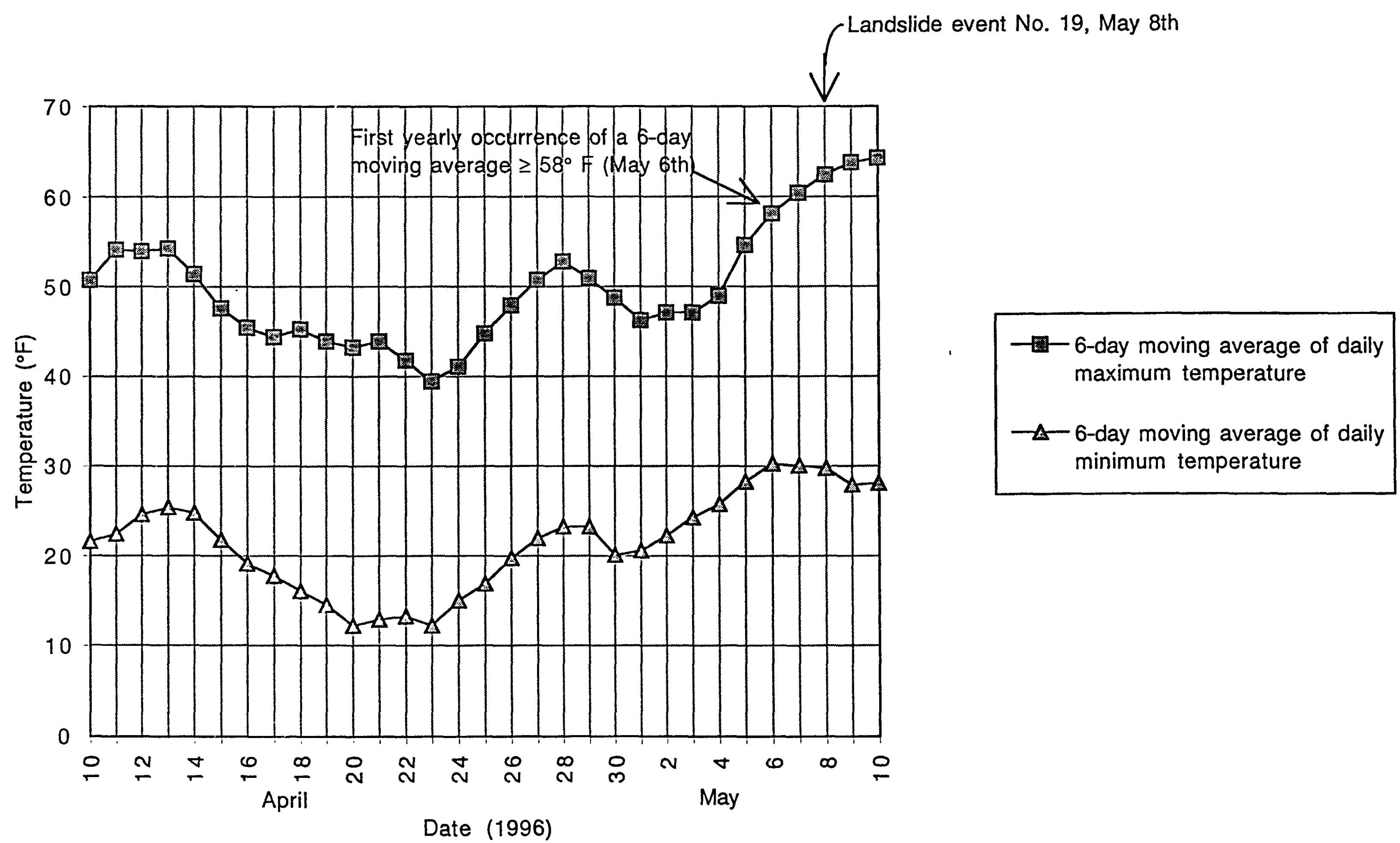

Figure 18. Graph showing the association of landslide event No. 19 with rising temperatures and the first yearly occurrence of a daily maximum temperature greater than or equal to 58° F.

Aspen 1SW/Landslide Event No. 20

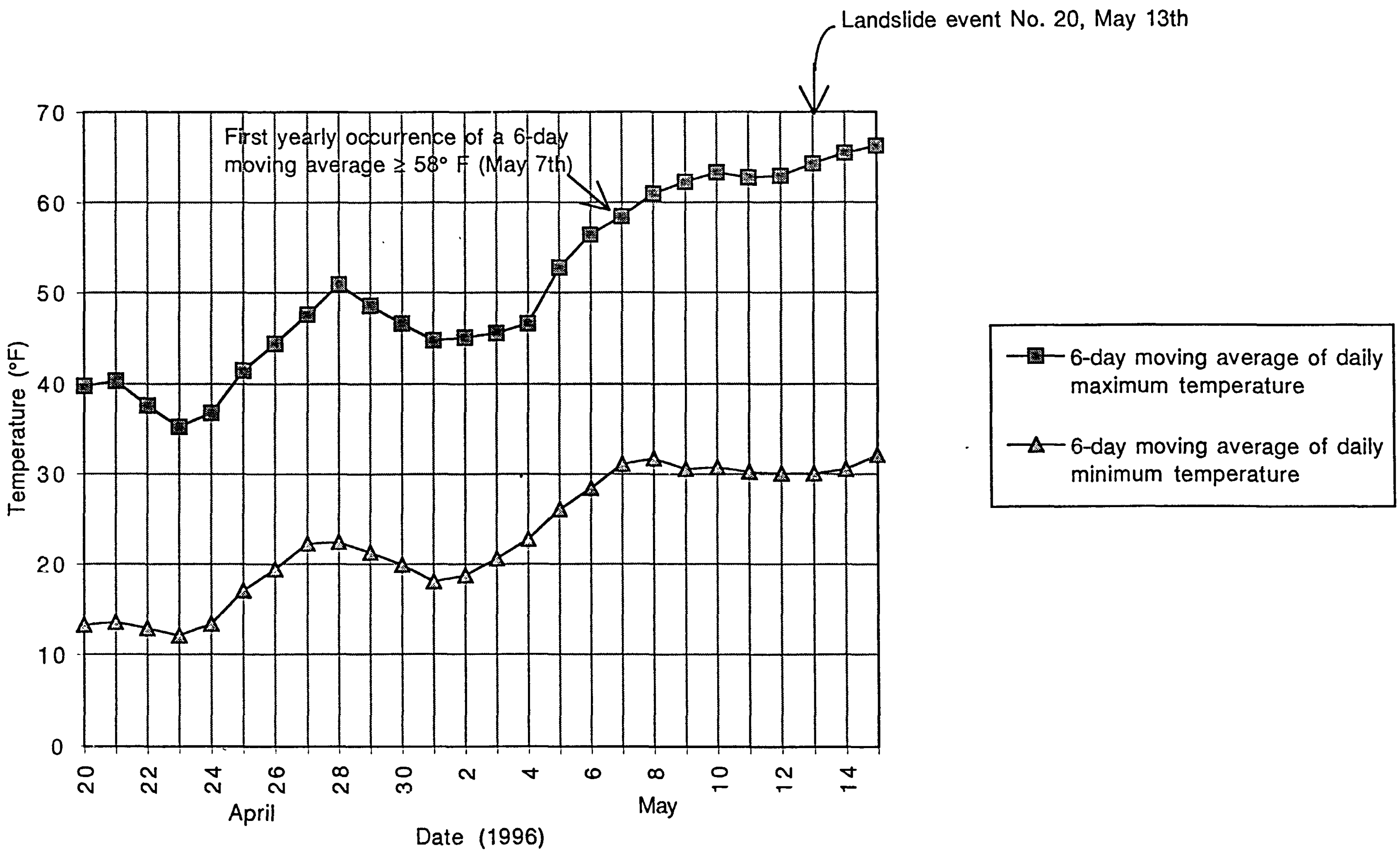

Figure 19. Graph showing the association of landslide event No. 20 with rising temperatures and the first yearly occurrence of a 6-day moving average of daily maximum temperature greater than or equal to 58° F.