Summer Wind Studies Near the Alpine Visitors' Center, Rocky Mountain National Park

D.E. Glidden

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ABSTRACT

A comprehensive study of winds near the Alpine Visitors' Center (3,596 meters) in Rocky Mountain National Park (RMNP), Colorado was made during the summer of 1980.

Detailed windspeed and gust factor (GF) regimes were established, and compared to prior winter studies in RMNP and other mountain locations. Frequency graphs of various windspeed factors were constructed for easy use by the researcher, hiker, or visitor. Field studies of the variability of winds with slope exposure and height above ground were made.

Average windspeeds for summer 1980 (9.0 meters per second) were found to be higher than those reported in earlier studies of other alpine areas of Colorado, but lower (about 2.5 m/s) than the 30-year summer average for Mount Washington, New Hampshire (1,917 m).

Predominant wind direction was west-southwest. Upslope (southeast-northeast) winds occurred infrequently, although average hourly speeds occasionally exceeded 18 m/s.

Maximum gusts and mean hourly GFs at AVC for the summer were 35 m/s and 1.58, respectively, indicating a turbulent environment.

ACKNOWLEDGMENTS

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Special thanks are necessary for the following individuals who directly participated and contributed to its success:

Dave Stevens, Park Research Biologist; Kim Maher, Jan VanSyckle, Betsy Jewet, Stan Christianson, and Lisa Webbey, Principal Field Assistants.

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Introduction

The dramatic increase in energy costs and our dependence on fossil fuels have provided the incentive, in both private industry and government, for exploring renewable alternatives in many geographic areas of the country.

The National Park Service (NPS) has indicated its support for the solar concept through acceptance of a large photovoltaic electric power system for use in southeastern Utah. Under sponsorship of the Department of Energy, the Natural Bridges National Monument recently became the site of a 100 kW Array, which provides power to the Visitors' Center and Park Administration, as well as the maintenance and residential areas.

The NPS is currently experimenting with solar privies in Rocky Mountain National Park (RMNP) in Colorado, and continues to pursue energy alternatives.

Another component of solar is wind energy. Research into developing more efficient wind energy conversion systems is an evolutionary engineering process which has demonstrated significant potential where the proposed turbine site reflects the proper wind characteristics.

We know from previous research (Glidden, 1974a) that the alpine areas of RMNP provide a source of high wind energy potential during the winter months. The Alpine Visitors' Center (AVC), comprising a cluster of buildings at the 3,600 meter (m) level on Trail Ridge Road, is a remote facility which presently utilizes diesel generators during the summer season of around 150 days. The complex has high visitation rates under moderate energy requirements; and along with the escalating cost of diesel fuel must be added the moderate expense of fuel transportation.

Consequently, considering both the economics in the energy equation and the pessimistic outlook for non-renewables, wind power became more viable and warranted further study.

Some of the things we learned from the winter research were that alpine winds are highly variable and often complex from one site to another, and from one set of meteorological circumstances to another. The extreme nature of winds in winter were documented, and although we knew from basic meteorological principles that the overall wind flow would be less in summer, we needed to know to what extent the unfavorable characteristics would penetrate (for example, in the form of high gust ratios) both the warmer months in general and the site peculiarities in particular.

Thus, as a preliminary measure in establishing the feasibility of generating wind power at AVC - even on a supplemental basis - we were required to undertake some detailed field studies around the proposed site which extended over the summer months, a period in which a serious data gap existed. Although recognizing the inadequacies of a one-year study in taking into account the inter-annual variability of synoptic weather features, such field data is necessary from both a climatological and engineering design standpoint for determining the overall suitability of extracting power from the wind at AVC.

The purpose of this study was twofold, however. It was also concerned with extending the winter data base to include the summer months - a period over which Park research and visitation are most active. Such data would enhance our understanding of the importance of winds in the ecological balance, of their interaction with rugged terrain, and provide a valuable source of information for the hiker, mountaineer, biologist, researcher, or the layman who is generally interested in the nature of mountain weather.

The overall research on winds in RMNP will be published in two parts, of which this is the first, as follows:

Part I - Summer Wind Studies Near the Alpine Visitors' Center

Part II - Winter Wind Studies in Rocky Mountain National Park

PHOTO 1

Principal Field Assistants Kim Maher and Jan VanSyckle on a pleasant day at the Alpine Visitors' Center research site (TR 10).

1. AREA OF STUDY

The research area was located in Rocky Mountain National Park, which is east of the rugged Continental Divide and west of the town of Estes Park, Colorado.

The primary focus of the 1980 summer research was near the Alpine Visitors' Center (TR 10, Fig. 1) at Fall River Pass. Situated next to Trail Ridge Road at 11,798 feet (ft) (3,596 meters (m)), the NPS complex overlooks the la Poudre River Valley and the Never Summer Mountains to the west; a higher slope to the north; the extensive Mummy Range, including Mounts Chapin, Chiquita, and Ypsilon to the east; and a semi-permanent snow field which extends in an arch around higher ground to the south. In the heart of RMNP, AVC is about 4 miles (6.5 kilometers) east of Milner Pass and the Continental Divide.

TR 11, near the 12,000 ft (3,658 m) contour, was installed on the high point about 2,000 ft (600 m) north of AVC.

TR 3, a tundra site about 500 ft (150 m) northwest of the former location of Rock Cabins, at 11,600 ft (3,536 m), was established along the eastern portion of Trail Ridge Road at the crest of Hanging Valley, overlooking Forest Canyon and the Continental Divide. This site was originally operated in the 1973-74 winter study, and its reactivation was useful both in sampling the overall site variability of winds and in providing some continuity of data over the summer months.

TR 6 and 12 were sites for recording atmospheric pressure during summer 1980.

Figure 1 details the wind research sites in RMNP, including those established in 1973-74, and offers a general picture of the surrounding, often chaotic terrain.

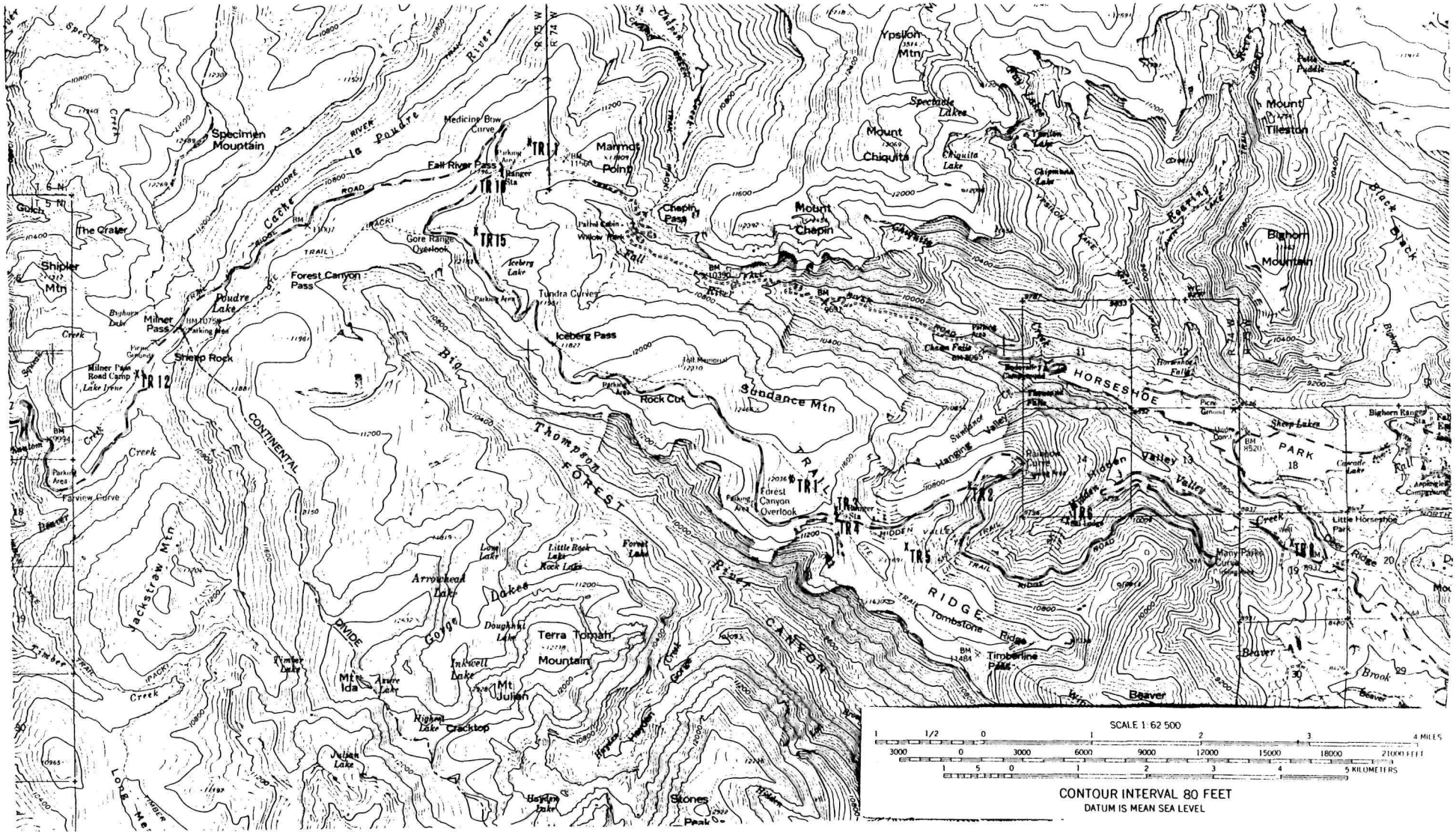


FIG. 1

Wind research sites in Rocky Mountain National Park, 1973-74, 1980. TR 7 (Park Headquarters) is beyond the map boundary.

PHOTO 2

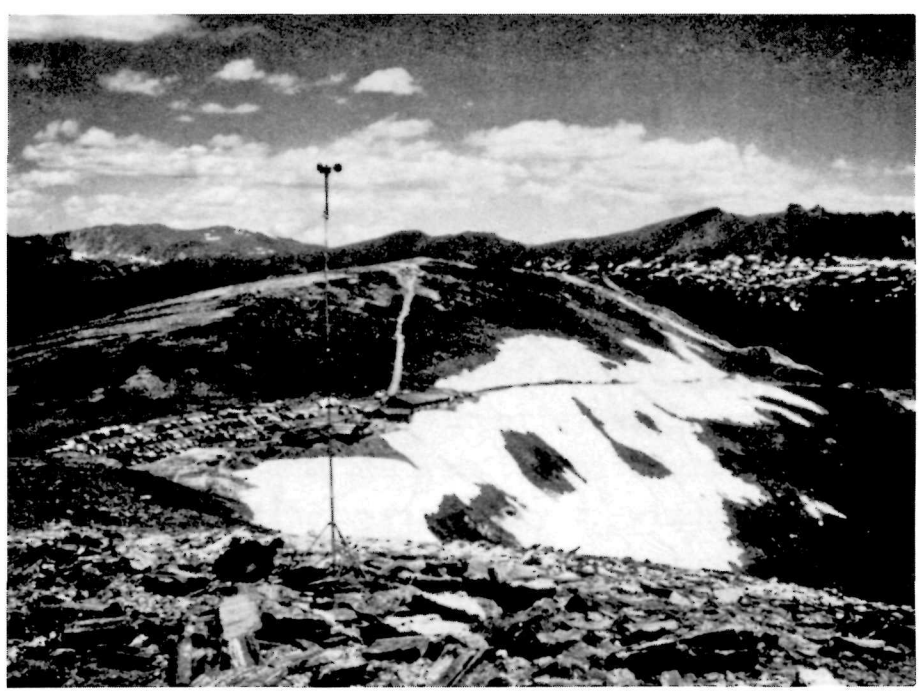


PHOTO 3

Two views of AVC at Fall River Pass. Photo 2: Hauling instrument tower sections up to TR 11 in early June. View is looking south with AVC in the background. TR 15 is located atop ridge at upper left. Photo 3: View from TR 15 (temporary field site) looking north toward AVC. The trail behind AVC leads up to TR 11.

2. RELATED STUDIES

Data which is suitable for extensive summary and analysis of surface wind characteristics are rare for the alpine areas of the Colorado Rockies. Some general wind data has been published for several sites to the south of RMNP, at Niwot Ridge and Berthoud Pass. However, for the detail which is necessary in studying the wind climatology of mountains, or the localized assessment of wind energy potential, the available information is inadequate.

Historically, climatological assessments of wind for a particular region relied extensively on daily or monthly averages. It has become increasingly clear, in the realm of mountain climatology, that an accurate determination of wind potential must be concerned with the specifics of on-site variability, on a scale ranging from years down to seconds.

Marr et al. (1967, 1968a, 1968b) provided valuable climatological summaries for Niwot Ridge (32 km south of RMNP) under the auspices of the Institute of Arctic and Alpine Research (INSTAAR) at the University of Colorado. All of the early wind data was derived from totalizing anemometers, which recorded averages of wind travel over long periods of time.

In later years, INSTAAR updated its instruments and data banks to include, among other meteorological parameters, summaries of wind data from its D-1 station (12,300 ft; 3,750 m) on Niwot Ridge. Barry (1972) presented data for D-1 which spanned several years and was based on 10-min averages for each hour. The same author (1973) summarized general climatological data for Niwot Ridge.

Judson (1965), in a study supporting avalanche research during winter, provided data on the average monthly windspeeds at Berthoud Pass (11,880 ft; 3,621 m) for the 1963-64 summer seasons. More recently (1977) he produced a summary of climatological tables compiled for the Berthoud Pass area in winter.

Early data from totalizing anemometers were collected in RMNP to supplement the on-going biological work of Willard (1963) and others.

Criteria for selecting instrument sites are often based on the convenience or practicality of servicing the stations, or on meeting particular biological research needs, rather than on a representative exposure for climatological or wind research purposes.

Since subsynoptic weather factors, and especially localized variations in topography, may influence wind regimes, it follows that wind data may not be extrapolated with any degree of confidence from one region along the Continental Divide to another; unless, in the case of topography, the site differences are first tested and defined.

3. GENERAL WIND CHARACTERISTICS

Research during summer 1980 at AVC indicates that a higher average wind regime occurs in RMNP than has been reported for other alpine areas of Colorado. The results, consistent with those found in the winter study of 1973-74, become especially noteworthy when it is considered that AVC (TR 10) does not represent a site of optimum exposure to all wind directions, such as might be found at TR 15 (12,300 ft; 3,750 m), for example (see Fig. 1).

Table 1 compares the average monthly windspeeds for summer 1980 at AVC to those published earlier for other mountain stations in Colorado, New Hampshire, and the Yukon.

The average windspeeds for one season appear to be higher than those reflected in records spanning several years at Berthoud Pass or Niwot Ridge. The more recent data for Niwot Ridge, as reported by Barry (1972, 1973) suggest slightly higher summer averages for the alpine - perhaps as a result of improved anemometry or shortened averaging base - than were indicated by Marr et al. (1967, 1968a, 1968b).

When compared to averages for summer on Mount Washington, New Hampshire (6,288 ft; 1,917 m), site of the highest average annual windspeed in the United States, AVC values were less by about 5-6 miles per hour (mph) or 2.3-2.7 meters per second (m/s) for the 1941-70 period means. However, June and July 1980 averages at AVC were higher than those for the same months in 1979 on Mount Washington. Significantly, 1979 was a season of "subnormal" airflow for the New Hampshire peak; thus, the importance of recognizing the potential for interannual variability, and the effects of length of record, become clear.

Several months of summer field data were reported for the 17,585 ft (5,360 m) level on Mount Logan, Yukon Territory (Marcus and Labelle, 1970). The average values recorded for July were

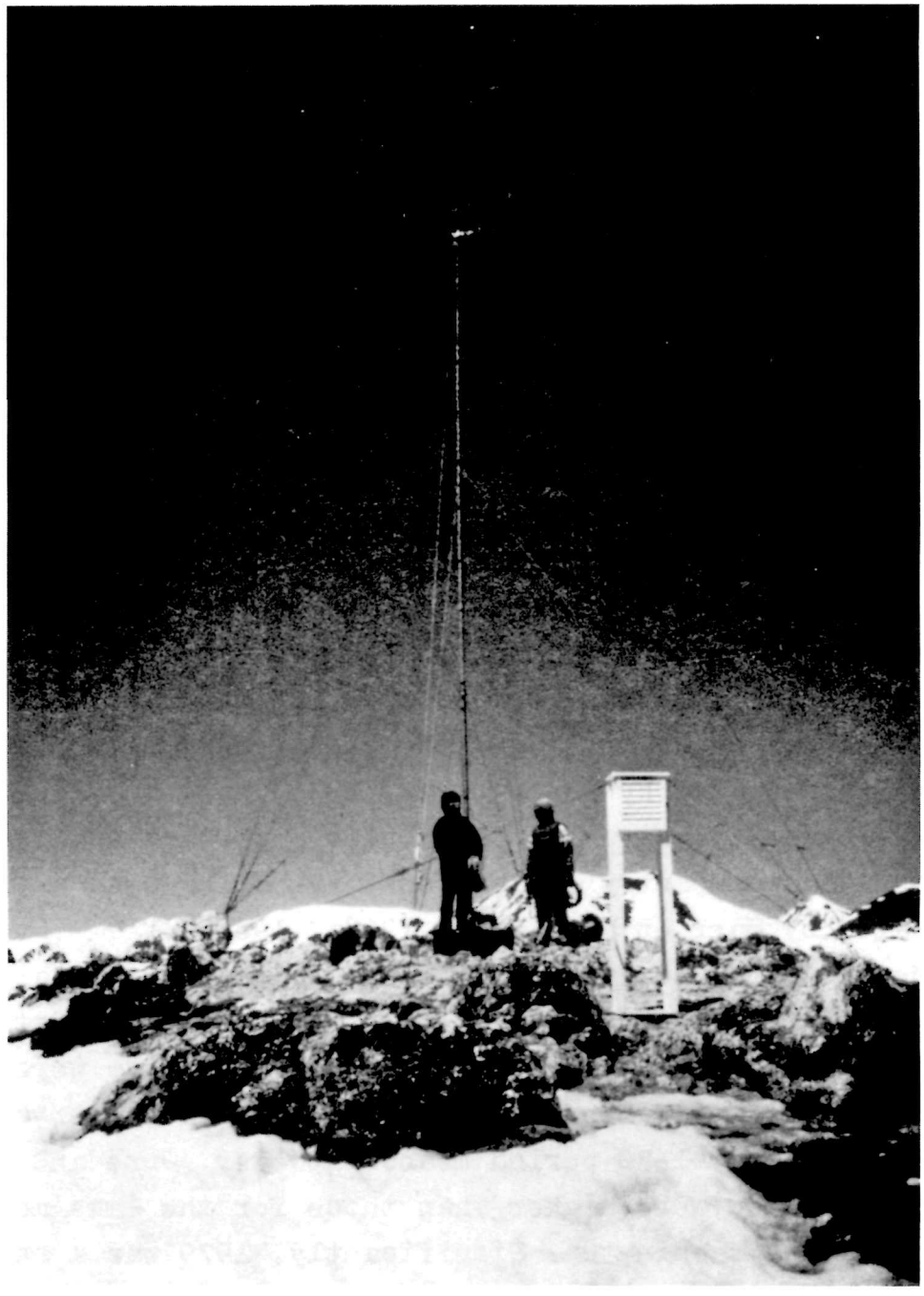


PHOTO 4

The 9 meter mast and instrument shelter at TR 10, Alpine Visitors' Center, summer 1980.

	JUNE		JULY		AUGUST		SUMMER	
	mph	m/s	mph	m/s	mph	m/s	mph	m/s
AVC, RMNP, Colorado (3,596 m)								
1980	21.1	9.4	19.5	8.7	20.1	9.0	20.2	9.0
Berthoud Pass, Colorado (3,621 m)								
1963	10.0	4.5	10.0	4.5	9.0	4.0	9.7	4.3
1964	12.0	5.4	10.0	4.5	11.0	4.9	11.0	4.9
Niwot Ridge, Colorado (3,750 m)								
1953-64	13.0	5.8	10.0	4.5	11.0	4.9	11.3	5.0
1966-69	17.5	7.8	13.0	5.8	12.8	5.7	14.4	6.4
Mount Washington, New Hampshire (1,917 m)								
1941-70	27.1	12.1	24.9	11.1	25.1	11.2	25.7	11.4
1979	20.9	9.3	18.2	8.1	25.5	11.3	21.5	9.6
Mount Logan, Yukon Territory (5,360 m)								
1968	-	-	8.0	3.6	-	-	-	-
1969	-	-	6.0	2.7	-	-	-	-

TABLE 1

The average monthly windspeeds in summer for AVC, RMNP (1980) and other mountain stations (various years).

lower than those at any of the Colorado mountain stations. Monthly wind maxima in July for the 1968-69 seasons were 54 mph (24 m/s) and 20 mph (9 m/s), respectively, although the 1967 reconnaissance party reported "high" winds for long periods of time. Topographic analysis of the site suggests that the station may have been somewhat sheltered from higher winds by surrounding peaks.

Maximum gusts at AVC (TR 10) were 79 mph (35 m/s) in both June and August, and only 60 mph (27 m/s) in July. In September, from partial data collection, superhurricane gusts increased to 88 mph (39 m/s).

Maximum hourly average windspeeds at AVC equalled or exceeded 15 mph (7 m/s) on over 75% of the hours for the summer period; they ranged from 40-45 mph (18-20 m/s) for nearly 18 hours, although this represents only 1.1 percent of the hours with data. Maximum daily one-hour averages equalled or exceeded 40 mph (18 m/s) on 8 days or 9.2% of the summer days.

Extreme maximum hourly speeds during summer at AVC were not far below those reported for winter in early data from Berthoud Pass (Table 2).

Table 2. Maximum one-hour average windspeeds for summer at AVC (1980) and for winter at Berthoud Pass (1950-64).

	J		J		A	
	mph	m/s	mph	m/s	mph	m/s
AVC (1980)	45	20	41	18	49	22
	D		J		F	
Berthoud Pass (1950-64)	53	24	55	25	N/A	

Data on hourly averages for Niwot Ridge were not available in Barry's (1972, 1973) summaries.

Average daily windspeeds at AVC ranged from 12.8-34.0 mph (5.7-15.1 m/s). Daily averages ≥20 mph (9 m/s) occurred on 17 days

in June, 11 days in July, and 14 days in August.

For comparison, maximum hourly and daily windspeeds recorded during winter 1973-74 in RMNP were substantially lower than those for Mount Washington. Maximum 24-hour windspeeds of 129 mph (57.6 m/s) and 109 mph (48.7 m/s) have been recorded at Mount Washington (Pagliuca, 1934) and Port-Martin, Antarctica (Loewe, 1972), respectively. Average hourly values of 173 mph (77.3 m/s) and 149 mph (66.6 m/s) were monitored on Mount Washington and Cannon Mountain, New Hampshire, respectively (Glidden, 1974b).

When extreme windspeeds and their frequency of occurrence are considered, however, winter maxima on Trail Ridge (TR 3) are comparable to long-term values found on Mount Washington. Mount Washington presently holds the world's record high surface windspeed of 231 mph (103.2 m/s), followed by gusts of 207 mph (92.5 m/s) at Thule, Greenland and 199.5 mph (89.2 m/s) on Cannon Mountain, New Hampshire.

A gust of 155 mph (69.3 m/s) was recorded at TR 3 in December 1973. More recently, during winter storm research on Long's Peak Summit in 1980-81 (a period of subnormal regional airflow), two separate storm events produced maxima of 173 mph (77.3 m/s) and 172 mph (76.9 m/s) on the 4,345 m peak.

Data on gust ratios or gust factors (GFs) for the alpine are as rare as that for windspeed. GFs are determined from the ratio of the peak gust (PG) to the average windspeed for some specified period of time. For example, the hourly GF refers to the ratio of the peak gust/average hourly windspeed.

The response characteristics of the instruments (or the capacity of the sensors to respond quickly enough to represent a "true" approximation of the actual gust), and the damping effects which may be introduced by even small amounts of ice on the sensor, are important considerations in the field of anemography.

The mean hourly GF at AVC for summer was 1.58; the average and extreme maxima were 2.20 and 4.28, respectively. An hourly GF of 1.58, for example, indicates that an hourly average windspeed of 20 mph (9 m/s) has a peak gust of 32 mph (14 m/s).

Maximum daily one-hour GFs $\geq$2.0 occurred on 17 days in June, 20 days in July, and 16 days in August.

Based on 1,371 occurrences of 5-minute (min) averages ≥30 mph (13 m/s), the mean 5-min GF at AVC was 1.36. Summer 5-min GFs at AVC appear to be higher than those indicated in a study of 5-min GFs derived from various operational anemometers around the world (including Mount Washington), although statistical methods used in determining GFs, and sample sizes, were different.

When maximum hourly GFs in RMNP were compared on summer and winter days, mean maxima were higher during the latter, although it was also found that mean monthly values were nearly the same for both August (1980) and March (1974).

Average GFs at AVC during summer decreased from midnight to sunrise but increased sharply from sunrise to mid-day maxima. Turbulence generally remained higher near sunset than either the midnight or sunrise periods. As mean hourly windspeeds increased or decreased at AVC, so did the mean hourly GFs.

Reviewing extreme summer windspeeds at all sites, average maxima were highest at TR 3.

As a result of field transects of the variability of maximum windspeeds around the AVC complex, a zone of gust maxima was identified along a high point about 500 ft (152 m) southwest of TR 10.

Following studies of wind variation for three levels above ground at AVC, it was found that, on average, low-level (3 m) exceeded middle-level (6 m) wind maxima slightly, while the highest-level (9 m) values exceeded the lowest with a mean ratio of 1.0605.

Predominant wind direction during summer 1980 was west-southwest, retaining the expected westerly component. Upslope (southeast-northeast) winds occurred infrequently, although several periods of moderate hourly flows exceeding 40 mph (18 m/s) and lasting from 4-6 hours, were recorded. Low GFs, both 5-min and hourly, attended the upslope regimes, and despite the infrequency, the relative steadiness would enhance the operation of a wind turbine.

4. DATA SUMMARY

Table 3 presents the wind regime summary at AVC for the summer period of 1980.

Several years of data would comprise a more representative summary of alpine winds in RMNP. Since a major synoptic weather feature of the southwest during summer 1980 was the persistence of high pressure and heat, data for at least one more summer is needed to increase confidence in the representativeness of the following regime.

	JUNE		JULY		AUGUST		SUMMER	
	mph	m/s	mph	m/s	mph	m/s	mph	m/s
Peak Gust[1]	79	35	60	27	79	35	79	35
Average Daily Maximum	52	23.2	47.5	21.2	43.9	19.6	47.8	21.4
Maximum One-Hour Average[2]	45	20	41	18.3	49	22	49	22
Maximum 24-Hour Average	31.5	14.1	29.2	13.0	34.0	15.2	34.0	15.2
Average Monthly[3]	21.0	9.4	19.5	8.7	20.1	9.0	20.2	9.0
No. Peak Gusts ≥74 mph[4] (Hurricane-force)	2		0		3		5	
Maximum Hourly Gust Factor[5]	3.58		4.28		3.53		4.28	
Average Maximum Hourly GF	2.23		2.22		2.16		2.20	
Mean Hourly GF	1.58		1.54		1.61		1.58	
Average Minimum Hourly GF	1.24		1.19		1.20		1.21	
Minimum Hourly GF	1.00		1.00		1.00		1.00	
Days With Data	28		31		28		87	
Percent of Days With Data	93		100		90		95	

mph = miles per hour
m/s = meters per second

1. Peak Gust - the maximum wind speed measured.
2. The highest average hourly windspeed.
3. Based on 24 hourly average windspeeds for each day.
4. The total number of recorded peak gusts ≥74 mph (33 m/s).
5. Gust Factor (GF) - Based on 24 ratios of the peak gust/average hourly windspeed for each day.

TABLE 3

The wind regime summary for the Alpine Visitors' Center, RMNP (TR 10), summer 1980.

5. FREQUENCY OF SUMMER WINDS

Figures 2, 3, and 4 present a one-season profile of the frequency of occurrence of extreme maxima, one-hour average maxima, and daily average windspeeds at AVC for June, July, and August 1980. Along with the data summary in the prior section, these graphs should be helpful both for environmental research and for determining the overall practicality of operating a wind turbine at AVC.

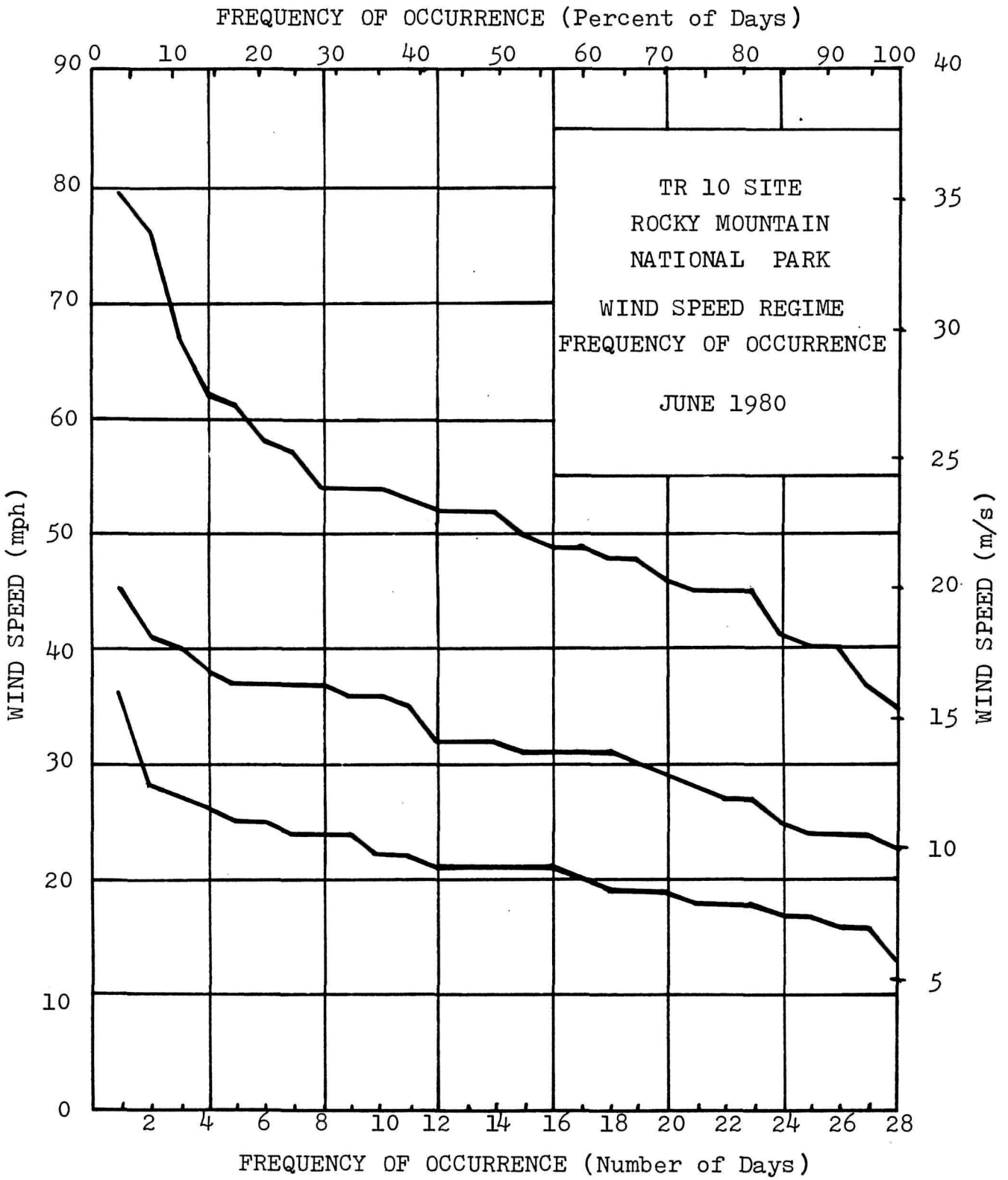
For example, information from Table 4 suggests that a day with at least one gust of storm-force intensity (≥64 mph; 29 m/s) occurred at AVC, on a summer average, less than twice each month.

Table 4. The frequency of occurrence of daily wind maxima ≥64 mph (29 m/s) at AVC, summer 1980.

	J	J	A	SUMMER
No. Days ≥64 mph	3	0	2	5
% Days ≥64 mph	11	00	07	06

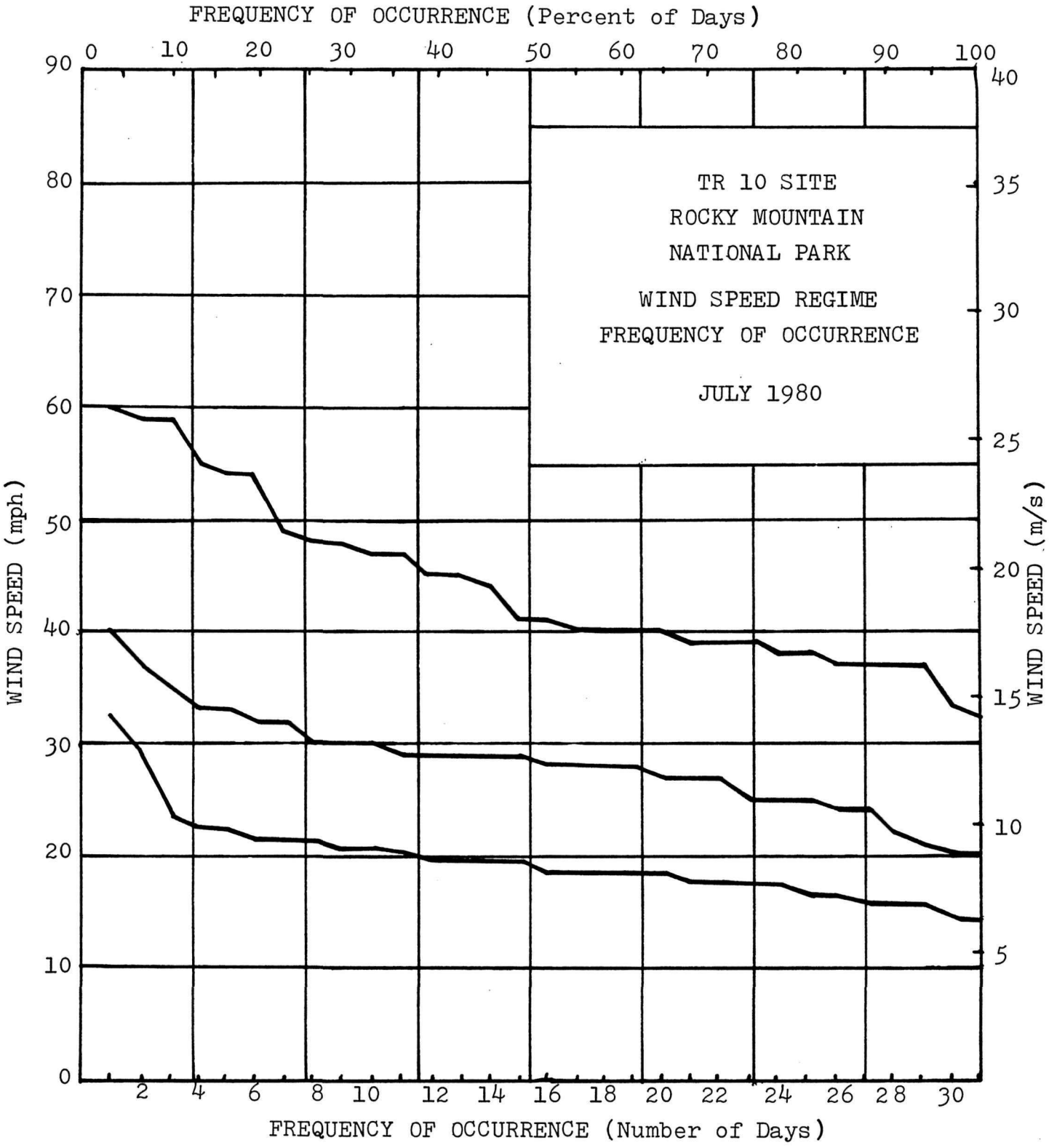
We may accept a value of 40 mph (18 m/s) as a viable shut-down speed for a particular wind turbine. Considering June 1980, we know from Table 3 that the average daily maximum windspeed was 52 mph (23 m/s), or 12 mph (5 m/s) greater than (>) shut-down speed; and from Fig. 2 that daily maxima were ≥40 mph on 26 days. Accordingly, if a turbine were operational during this particular month, it may have experienced at least one shut-down event (depending, of course, on the duration of the gust and the design characteristics of the machine) on each day (Table 3) or on 93% of the days (Fig. 2) in June.

Reviewing the overall summer picture, Table 5 lists the relative monthly occurrences of daily maxima ≥40 mph.



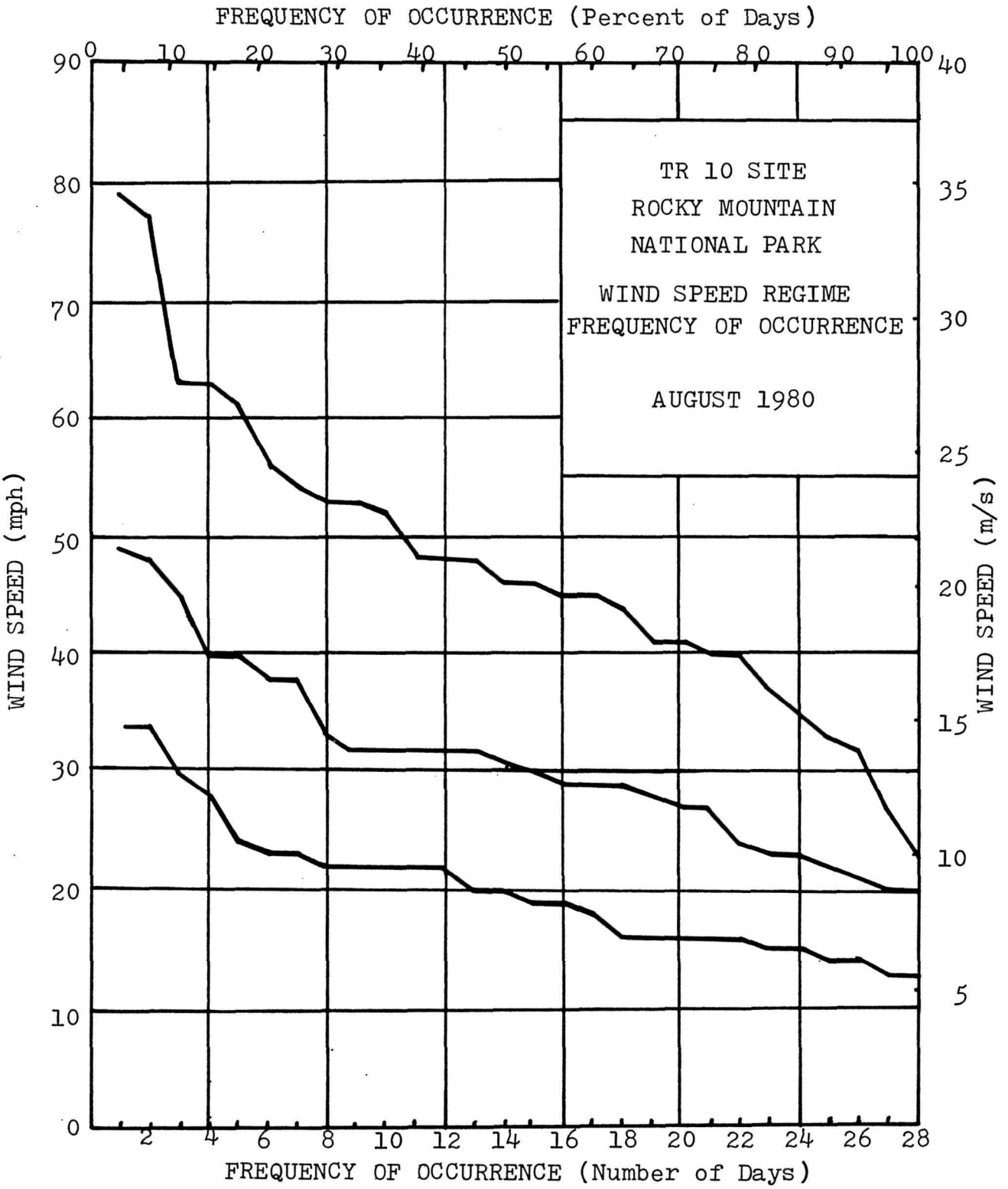
The number of days or percent of days the daily maximum, maximum one-hour average, and average daily windspeeds were equal to or greater than a particular speed.

FIG. 2



The number of days or percent of days the daily maximum, maximum one-hour average, and average daily windspeeds were equal to or greater than a particular speed.

FIG. 3



The number of days or percent of days the daily maximum, maximum one-hour average, and average daily windspeeds were equal to or greater than a particular speed.

FIG. 4

Table 5. The frequency of occurrence of daily wind maxima ≥40 mph (18 m/s) at AVC, summer 1980.

	J	J	A	SUMMER
No. Days ≥40 mph	26	20	22	68
% Days ≥40 mph	93	65	79	79

Thus, accepting the above criteria, a potential shut-down event during summer 1980 could have occurred approximately every 3 out of 4 days.

Since instantaneous gusts of the order of seconds are not always sufficient to cause a turbine shut-down, it may be necessary to look at a longer time scale. If the potential shut-down criteria were made on the basis of hourly maxima, then at least one event could have occurred on 8 days (or 9.3% of the days) of summer 1980 (Table 6). On summer average, this would mean a shut-down ≈2.7 days each month.

Table 6. The frequency of occurrence of daily maximum one-hour average windspeeds ≥40 mph (18 m/s) at AVC, summer 1980.

	J	J	A	SUMMER
No. Days ≥40 mph	3	1	4	8
% Days ≥40 mph	11	03	14	9.3

This information, however, although quite useful from a climatological viewpoint, must be observed in the context of the total number of summer hours with windspeeds ≥40 mph. Discussed in more detail in the next section, such hourly speeds account for only 1.1% of the summer hours with data.

Similarly, of interest perhaps to the field biologist or hiker, gale-force daily average windspeeds (≥32 mph; 14 m/s) were not a frequent event on the alpine near AVC during summer 1980, occurring, on average, 1.3 days each month (Table 7).

Table 7. The frequency of occurrence of average daily windspeeds ≥32 mph (14 m/s) at AVC, summer 1980.

	J	J	A	SUMMER
No. Days ≥32 mph	1	1	2	4
% Days ≥32 mph	3.6	3.2	7.1	4.6

6. DISTRIBUTION OF AVERAGE HOURLY WINDSPEEDS

It is necessary, for both climatological studies of mountain weather and wind power assessments, to determine the percent frequency distribution of average hourly windspeeds for the entire study period.

Table 8 lists this detailed data for AVC for summer 1980. The total possible hours for June, July, and August were 2008; however, 4.1% or 82 hours were missing, which leaves 1,926 hours = 100%.

A broad spectrum of information about winds is available from Table 8. For example, average hourly windspeeds of 25-29 mph (11-13 m/s) occurred on 281.3 hours (or 14.6% of the hours) during summer; average hourly speeds $\geq$15 mph (6.7 m/s) occurred on 75.6% of the hours; hourly speeds $<$5 mph (2.2 m/s) represented only 4.5 hours (or 0.235% of the total hours).

Environmental problems associated with lightning and sensor rime ice accounted for 44 hours of missing data.

Despite the difficulty of achieving an effective ground on the tundra, special grounding precautions were taken at each site. Alpine lightning storms, although usually of short duration, may be both intense and frequent. Generally, we were pleased by the relatively few strikes on equipment, although TR 11 was hit at least 4 times.

Wind sensors were frozen for approximately 7 hours (or 0.35% of the total hours). While rime occurred for a small portion of the time, it nonetheless could be an important environmental consideration in the operation of a wind turbine, particularly early or late in the summer season (when data on rime frequency is not available). A significant accumulation of rime would probably hinder any rotating device and, depending again on design, a combined ice/wind load could cause damage.

Climatological and instrumental studies of the nature and

One-hour Average Windspeed		Total Hours of Occurrence	Total Hours of Occurrence	Frequency Distribution		
mph	m/s	%	Number	mph	m/s	%
<5	<2.3	0.235	4.5	≥0	≥0	100
5-9	2.3-4.0	4.67	89.9	≥5	2.3	99.8
10-14	4.5-6.3	19.44	374.4	≥10	4.5	95.1
15-19	6.7-8.5	25.78	496.5	≥15	6.7	75.6
20-24	8.9-10.7	25.21	485.5	≥20	8.9	49.9
25-29	11.2-13.0	14.61	281.4	≥25	11.2	24.7
30-34	13.4-15.2	5.65	108.8	≥30	13.4	10.0
35-39	15.6-17.4	3.32	63.9	≥35	15.6	4.4
40-45	17.9-19.7	0.93	17.9	≥40	17.9	1.1
>45	20.1	0.153	2.9	≥45	20.1	0.31

TOTAL HOURS = 1,926

Total Possible Hours = 2,008

Total Missing Hours = 82

Late start on 2 June = 38 hours

Lightning strikes or failure = 37 hours

Sensor frozen in rime ice = 7 hours

TABLE 8

The frequency distribution of average hourly windspeeds at AVC, RMNP, summer 1980.

frequency of lightning storms in RMNP could serve as a basis for developing localized criteria for short-term prediction. For example, a relationship may be established which showed consistent patterns of wind speed and direction, pressure, temperature, etc. during the three hours preceding cumuli cloud development over the Mummy Range; or there may be a particular set of meteorological conditions which favor storm convection over Long's Peak as opposed to the Alpine Visitors' Center. Eventually such research could lead to early morning predictions of late afternoon storms for different topographic zones in RMNP. Moreover, any prediction criteria derived from these studies may be useful as a tool for visitor protection.

7. GUST RATIOS

A. Gust Factor Regimes

Wind gusts, and their relationship to average windspeeds, are important environmental considerations in mountain climatology. Where AVC is concerned, such factors were studied in detail in view of the potential operation of a wind turbine.

Table 9 summarizes the gust factor (GF) regime at AVC for summer 1980. The GFs are based on 24 hourly ratios for each day with data.

Table 9. The hourly gust factor regime, and associated meteorological variables, for AVC, summer 1980.

	J	J	A	SUMMER
Extreme Maxima	3.58	4.28	3.53	4.28
Average Maxima	2.23	2.22	2.16	2.20
Mean	1.58	1.54	1.61	1.58
Average Minima	1.24	1.19	1.20	1.21
Extreme Minima	1.00	1.00	1.00	1.00
Mean Temperature (Fahrenheit)	45.8	50.9	49.6	48.8
Mean Relative Humidity (%)	39.5	57.8	56.8	51.4
Mean Pressure (Millibars)	1021.0	1022.7	1019.3	1021.0

The extreme maximum hourly GF was 4.28. Average maxima were nearly the same in June and July, but decreased in August. Mean GFs were highest in August.

Table 9 also includes field data on temperature, relative humidity, and atmospheric pressure, which were collected near AVC. It may be worthwhile to relate changes in average GFs to broad changes in these meteorological variables.

For example, it was found that increasing mean GFs were associated with decreasing mean temperature, relative humidity, and pressure, while, conversely, decreasing GFs were associated with increasing levels of these variables.

When the days with extreme maximum GFs for each of the summer months at AVC were compared to the maximum at TR 1 for December (Table 10), mean hourly values were higher in winter.

Table 10. Comparison of extreme gust factors for different alpine sites in RMNP, summer versus winter.

	1980			1973
	June 21	July 25	August 9	December 12
Maximum Hourly GF	3.58	4.28	3.53	4.23
Hour Ending (LST)	0400	1700	1400	0500
Mean Hourly GF	1.66	1.64	1.76	2.26
Hourly Peak Gust (mph)	43	60	53	144
Hourly Average Windspeed (mph)	12	14	15	34
Average for Day (mph)	17.5	17.2	16.3	44.2

Since it was beyond the immediate scope and resources of the summer study, detailed analysis of hourly GFs from the original charts of winter data was not available, although it is hoped that this will be undertaken in the future. Nevertheless, some limited data was reduced for general comparison purposes, and is shown in Table 11.

Table 11. Comparison of gust factors for several heights above ground, elevations, and seasons, RMNP.

Site	AVC	TR 3	TR 6
Month/Year	Aug 80	Mar 74	Mar 74
Maximum GF	2.00	2.10	3.17
Mean GF	1.57	1.58	2.42
Minimum GF	1.17	1.32	1.73
Mean Monthly Windspeed (mph)	20.1	34.1	13.6
Monthly Peak Gust (mph)	79	115	81
Site Elevation (m)	3,596	3,536	2,914
Sensor Height Above Ground (m)	9	3.7	13

It is important to note that the above GFs are not comparable to earlier values, since they are based on the ratio of the peak gust/maximum hourly windspeed for each day (rather than hour) of the months cited.

Despite or because of the differences in sensor height above ground, site elevation, and terrain roughness parameters, mean GFs at AVC for August 1980 were very close to those recorded at TR 3 for March 1974, although the latter monitored higher absolute maxima and minima. It will be interesting to see if this apparent similarity holds following the reduction and use of the hourly winter data. In addition, further summer work, involving a continuous data record for the 3.7 m level at TR 3, is needed to establish a valid relationship with the existing winter data.

Also in Table 11, notice the very high GFs recorded for Lower Hidden Valley (TR 6) and the low average monthly windspeeds. Observe that the minimum GF at TR 6 was higher than the mean GF for both summer and winter alpine sites. The area around TR 6 experienced a severe windstorm in May 1973 which crushed thousands of trees. The atmospheric mechanics responsible for this event may or may not be similar to those in other downslope windstorms, but a better understanding of the Hidden Valley phenomenon is needed in view of both its extreme nature and

potential for recurrence.

Durst (1960), studying a number of early modelling techniques, predicted GFs ranging from 1.48-1.50 with average hourly wind-speeds of 20-80 mph (9-36 m/s). Although Durst's peak gust data approximated that which occurred for a duration of 5 seconds, and AVC data for about 1-2 seconds, a comparison should be made with figures in Tables 9 and 10. It appears that RMNP is an exceptionally turbulent region.

B. Frequency of Occurrence

1. Hourly Ratios

A detailed analysis of gust ratios for each hour of the summer period was performed for the AVC site.

Figures 5, 6, and 7 present the hourly GF frequency regimes for June, July, and August 1980.

Over the 87-day period, the minimum daily one-hour GF was $>$1.00 on over 90% of the days, indicating that there are few days when there is not some component of gustiness to the wind at AVC.

Mean daily GFs $\geq$1.50 occurred on 75% of the days in June, 74% in July, and 82% in August. Maximum daily GFs $\geq$3.0 were recorded on nearly 11% of the days in June and 13% in July; they dropped to 7% in August.

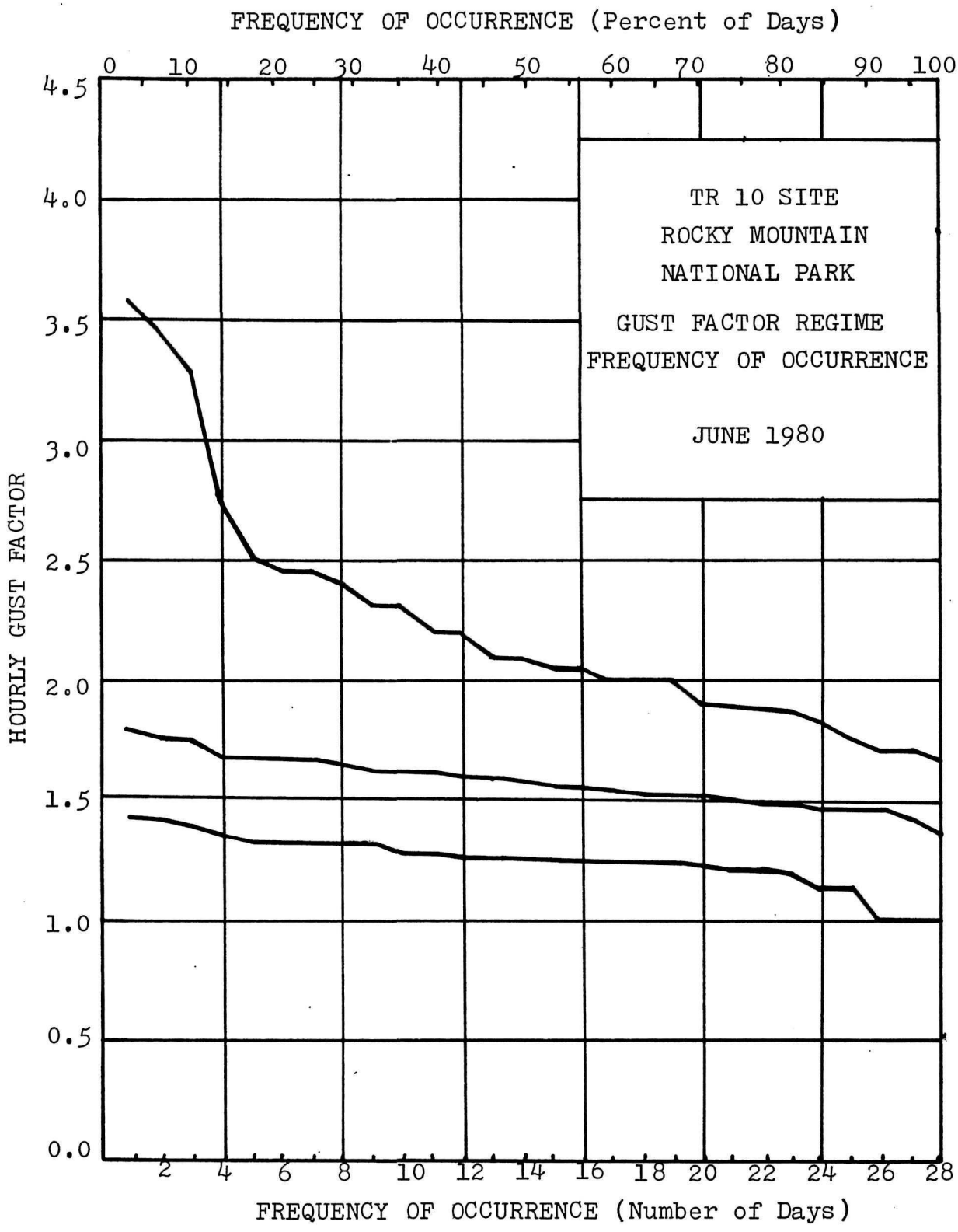
2. Five-minute Ratios

It is important, from both a climatological and engineering standpoint, to ascertain how GFs change as the mean windspeed base is shortened.

Accordingly, AVC GFs were computed for the ratio of the peak gust/average 5-minute windspeed for June 1980. The criteria involved average 5-minute speeds $\geq$30 mph (13 m/s) for a total of 1,371 occurrences (Table 12).

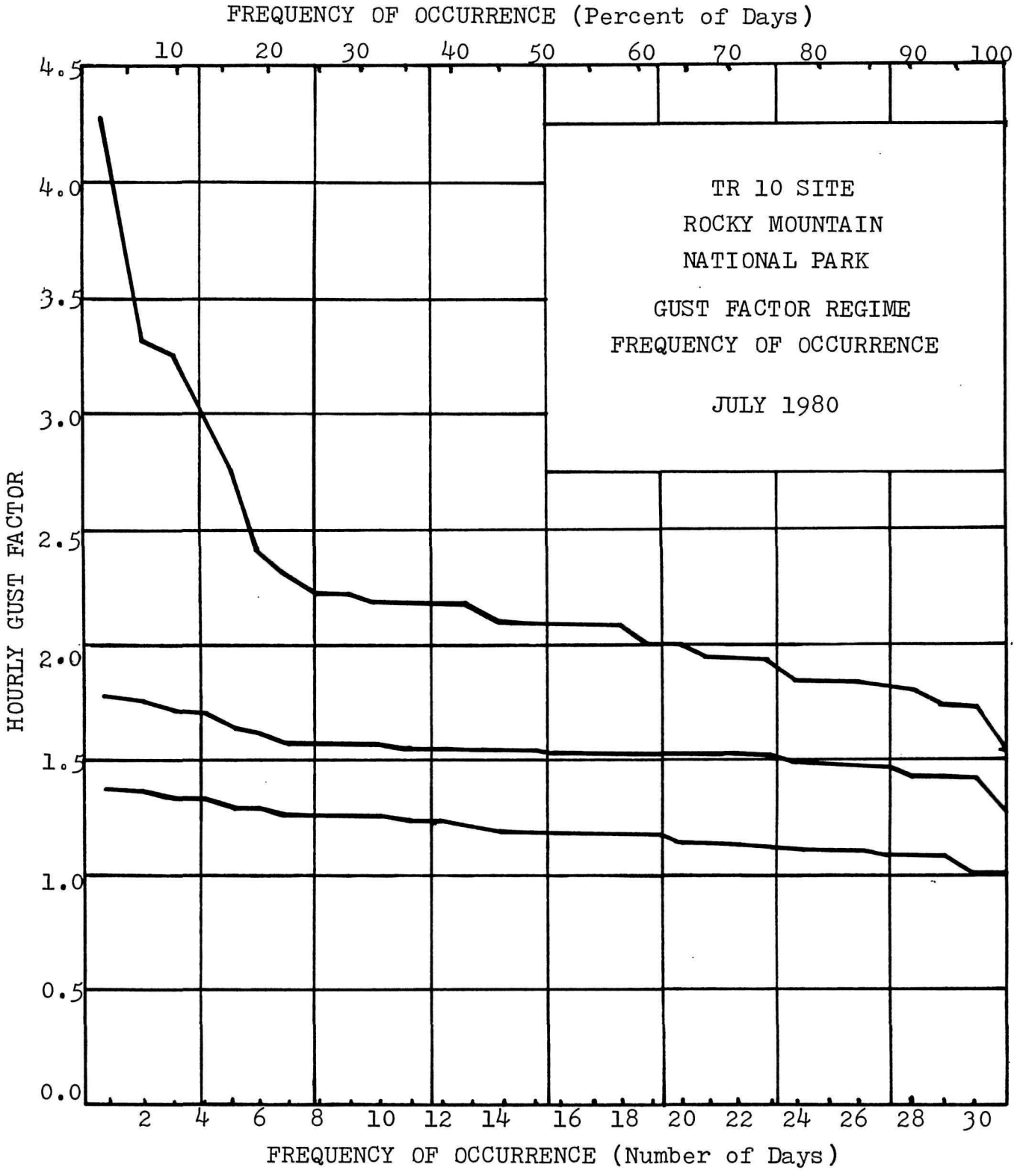
Table 12. AVC GFs for average 5-minute windspeeds $\geq$30 mph (13 m/s), June 1980.

Maximum	2.03
Mean	1.36
Minimum	1.03
n, sample	1,371



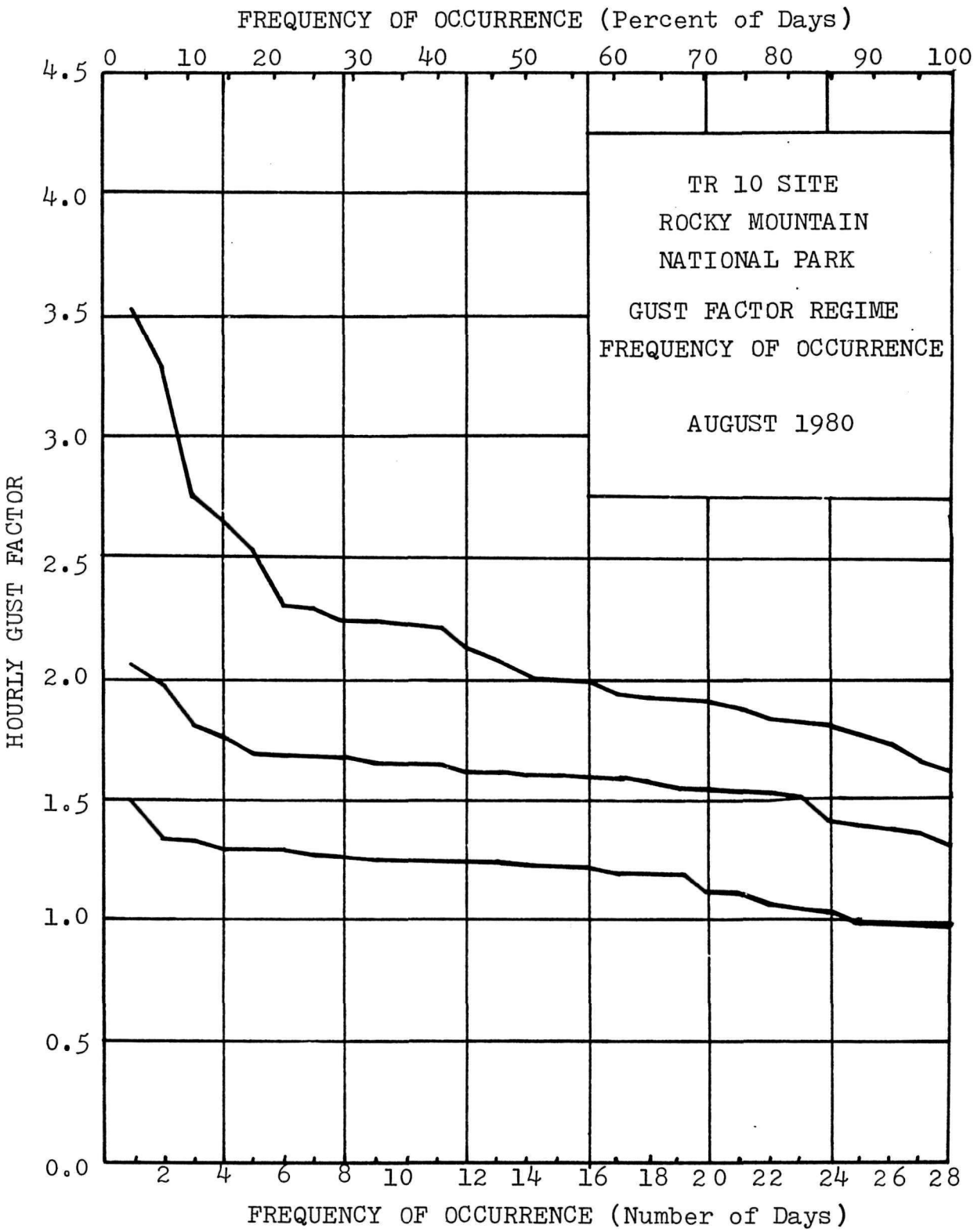
The number of days or percent of days the daily maximum, mean, and minimum hourly gust factors were equal to or greater than a particular value.

FIG. 5



The number of days or percent of days the daily maximum, mean, and minimum hourly gust factors were equal to or greater than a particular value.

FIG. 6



The number of days or percent of days the daily maximum, mean, and minimum gust factors were equal to or greater than a particular value.

FIG. 7

When the hourly mean of 1.58 is compared to the 5-minute mean of 1.36, GFs decreased by about 14% (Table 13).

Table 13. Comparison of hourly and 5-minute GFs at AVC for June 1980.

	Hourly	5-minute	% Difference
Maximum	3.58	2.03	43
Mean	1.58	1.36	14
Minimum	1.00	1.03	03

Tattleman (1975) analyzed 100 hours of wind data from Mount Washington, and found that 5-minute GFs tend to decrease with increasing mean windspeed. However, it is possible that winter GF data for Mount Washington is not always reliable for the above purposes, since sensor response may be dampened considerably (thus producing erroneously low GFs) by even small amounts of rime ice accretion, as well as by surrounding topography, buildings, and towers (Glidden, 1974b, 1976a, 1976b).

As long as the exposure, instrumental, and environmental problems associated with comparing such data are recognized, it is nevertheless interesting to do so. Table 14 offers a comparison of the 5-minute GFs for AVC to those derived from a curve of the Mount Washington data (Tattleman, 1975).

Table 14. Comparison of 5-minute GFs, AVC (summer) and Mount Washington, New Hampshire (100 hours).

	AVC	Mount Washington
Maximum	2.03	1.35
Mean	1.36	1.17
Minimum	1.03	1.09
Sensor Height (m)	9	12

The results of GF change with mean windspeed discussed above should be compared to the observations at the end of Section C, where it was found that, for AVC, as mean hourly windspeeds increased or decreased, so did the mean hourly GFs.

C. Diurnal Tides

In order to establish any predominant daily patterns in summer GFs, four hourly data points were analyzed for each day of the study.

Table 15 shows the average maximum, mean, and average minimum hourly GFs for AVC, as determined from 348 hours of data.

Table 15. Hourly averages of GFs and windspeeds at 6-hour intervals, AVC, summer 1980.

Hour Ending (LST)	0100		0700		1300		1900	
	GF	WS	GF	WS	GF	WS	GF	WS
Average Maxima	2.19	32.7	2.27	34.3	2.68	40.0	2.49	36.0
Mean	1.48	19.7	1.45	19.3	1.73	21.8	1.65	21.6
Average Minima	1.13	8.7	1.08	8.7	1.31	13.0	1.31	9.7

GF = Hourly Gust Factor
WS = Hourly Average Windspeed (mph)

The figures represent the one-hour average ending at 0100 (midnight), 0700 (sunrise), 1300 (mid-day), and 1900 (sunset). Average hourly windspeeds are included.

For the summer period, mean and average minimum GFs were higher near midnight than sunrise. While general gustiness, on average, appeared to diminish somewhat toward sunrise, the range of maximum gusts and turbulence increased at dawn (note the jump in average maximum GFs from 2.19 to 2.27).

GFs increased sharply from sunrise to mid-day, as expected, following solar activity and increased heating of the atmosphere. During the afternoon, GFs dropped from mid-day peaks, but overall turbulence remained significantly greater near sunset than at either the midnight or sunrise periods.

Data from Table 15 suggests that, as mean hourly windspeeds increase or decrease, so do the mean hourly GFs. Future research on GFs at the summit of Long's Peak (4,345 m) during winter, 1980-81 may help to better define this relationship.

8. EXTREME SUMMER WINDSPEEDS

A. Site Variability and Climatological Averages

Assuming precise instrument calibration, the recording of extreme windspeeds may be influenced by such factors as small changes in sensor exposure, proximity to irregular terrain or, for long-term comparison, by site orientation to prevailing winds.

Comparing variations in site wind maxima is a form of field study redundancy which is nevertheless necessary in mountain climatology. Table 16, which summarizes the average and extreme maxima for all sites during summer 1980, demonstrates that differences clearly exist.

Average and extreme maxima were higher at TR 3 (which overlooks the northwest-southeast trending Forest Canyon) than they were at any of the AVC sites (which overlook the southwest-northeast trending la Poudre Valley. TR 3 appears to be more directly exposed to high winds from the southwest. The difference in topographic orientation may account for the lower maxima observed near AVC, which presents an oblique interception to southwest flow.

Owing to frequent lightning strikes, data from TR 11 were missing for a significant portion of the time. One may presume, on the basis of average maxima for June (when data is complete), that actual summer values at TR 11 would have been higher with more complete data.

The summer means for average and extreme maxima for all alpine sites were 50.0 (22.3 m/s) and 74.7 mph (33.4 m/s), respectively.

	JUNE				JULY				AUGUST				SUMMER 1980			
	Average Maxima		Peak Gust		Average Maxima		Peak Gust		Average Maxima		Peak Gust		Average Maxima		Peak Gust	
	mph	m/s	mph	m/s	mph	m/s	mph	m/s	mph	m/s	mph	m/s	mph	m/s	mph	m/s
TR 10-01	52.0	23.2	79	35	47.5	21.2	60	27	43.9	19.6	79	35	47.8	21.4	79	35
TR 10-02	49.5	22.1	64	29	46.0	20.6	62	28	49.5	22.1	68	30	48.3	21.6	68	30
TR 3	53.9	24.1	71	32	49.6	22.2	71	32	58.8	26.3	82	37	54.1	24.2	82	37
TR 11	55.2	24.7	70	31	44.5	19.9	69	31	M		M		49.9	22.3	70	31
Extreme Maxima													54.1	24.2	82	37
Mean, all sites													50.0	22.3	74.7	33.4
Extreme Minima													47.8	21.4	68	30

mph = miles per hour
m/s = meters per second

TABLE 16

Average daily maximum and extreme (peak gust) windspeeds for all sites, RMNP, summer 1980.

PHOTO 5

Field Assistants Kim Maher and Betsy Jewet at the TR 3 research site, which overlooks the Continental Divide.

B. Variability Around AVC

The variability of windspeeds with varying topography is evident in both the summer and winter studies. Therefore, under a predominantly zonal (or westerly) airflow, it was considered important to quantify any variation in wind maxima around the AVC complex.

Azimuthal transects were drawn to five compass points, each extending in an arc approximately 500 ft (152 m) out from TR 10. This configuration sampled the slope exposures which most readily intercepted the westerly component. After each site (transect) was identified with a marker for future location, a series of comparison tests were made. A portable anemometer was operated in turn at each site, and the data compared to that which was recorded on the 3 m sensor at TR 10. The calibration of each system was checked.

Precise measurements of 600-second maxima (made possible by the use of NPS radios) were performed at the southwest, west, northwest, north, and northeast sites. Each timed event was compared with data from TR 10. Maxima from TR 10 during these tests ranged from 11-39 mph (5-17 m/s), and each event was conducted on days representing clear, overcast, and night skies. Table 17 summarizes the transect results as a percentage of occurrence.

Table 17. Comparison of 600-second wind maxima at TR 10 (3 m) with five Transects around AVC.

TRANSECTS	SW	W	NW	N	NE	MEAN, ALL TRANSECTS
% Transects > TR 10	66.6	20	33.3	20	25	33
% Transects < TR 10	16.6	80	66.6	60	75	60
% Transects = TR 10	16.6	0	0	20	0	07
Events, n	6	5	6	5	4	26 (Total)

% Transect ≷ TR 10 = The percent of test events in which the Transect site had higher, lower, or the same wind maxima.

Several trends become apparent. On 66.6% of the test events for the southwest transect, maxima were higher at the field site (about 152 m southwest of TR 10) than they were at TR 10. However, maxima were higher at TR 10 on 60-80% of the events for all other transects. The maximum difference in maxima between a transect and TR 10 was 11 mph (4.9 m/s) with the west azimuth.

Maxima at each transect were divided by maxima at TR 10 to establish ratios. Table 18 lists the results.

Table 18. Ratios of wind maxima for five transects and TR 10 (3 m height).

TRANSECT	SW	W	NW	N	NE
R_{max}	1.30	1.41	1.18	1.05	1.41
R_{mean}	1.08	0.93	0.95	0.95	1.03
R_{min}	0.86	0.69	0.84	0.80	0.87
Events, n	6	5	6	5	4

$$R = \frac{vt}{v_{10}},$$

where R = ratio of the maxima at transect/ the maxima at TR 10
vt = wind maxima at transect
v_{10} = wind maxima at TR 10

On average, maxima were higher at the southwest transect than they were at TR 10, as indicated by the mean ratio of 1.08, while west, northwest, and north sites all reflected lower values. Maxima increased again along the northeast slope, although in three out of four test events they were still less than those recorded at TR 10 (see Table 17).

Further test data was not acquired for these sites, although a greater sample would be necessary for a statistical analysis.

C. AVC Height Profiles

Formulae for theoretically estimating the expected increase in windspeed with height, over various types of terrain, are available for general wind power calculations. None appears to be universally applicable in mountainous terrain, and each is subject to correction factors, depending upon a variety of micrometeorological criteria.

Since wind power calculations vary with height, and in recognition of the importance of on-site measurements, the variation of maxima with height above ground at AVC was studied for short periods on the 9 m tower. Wind sensors were located at the 3, 6, and 9 m levels with leads to separate recorders. The prevailing winds during these tests displayed a westerly component, ranging from 250°-285°.

Seventeen (17) events, with maxima ≥20 mph (9 m/s), were selected. Events ranged from 15-120 minutes and extended over four days of clear, partly cloudy, overcast, and night conditions. The results are listed in Table 19.

Table 19. Ratios of wind maxima for three levels above ground at AVC.

Events, n=17	$\frac{V_b}{V_a}$	$\frac{V_c}{V_a}$
R_{max}	1.35	1.30
R_{mean}	0.9976	1.0605
R_{min}	0.92	0.96

$$R = \frac{V_b}{V_a}, \frac{V_c}{V_a}$$

where R = ratio of maxima

V_a = maxima at 3 m

V_b = maxima at 6 m

V_c = maxima at 9 m

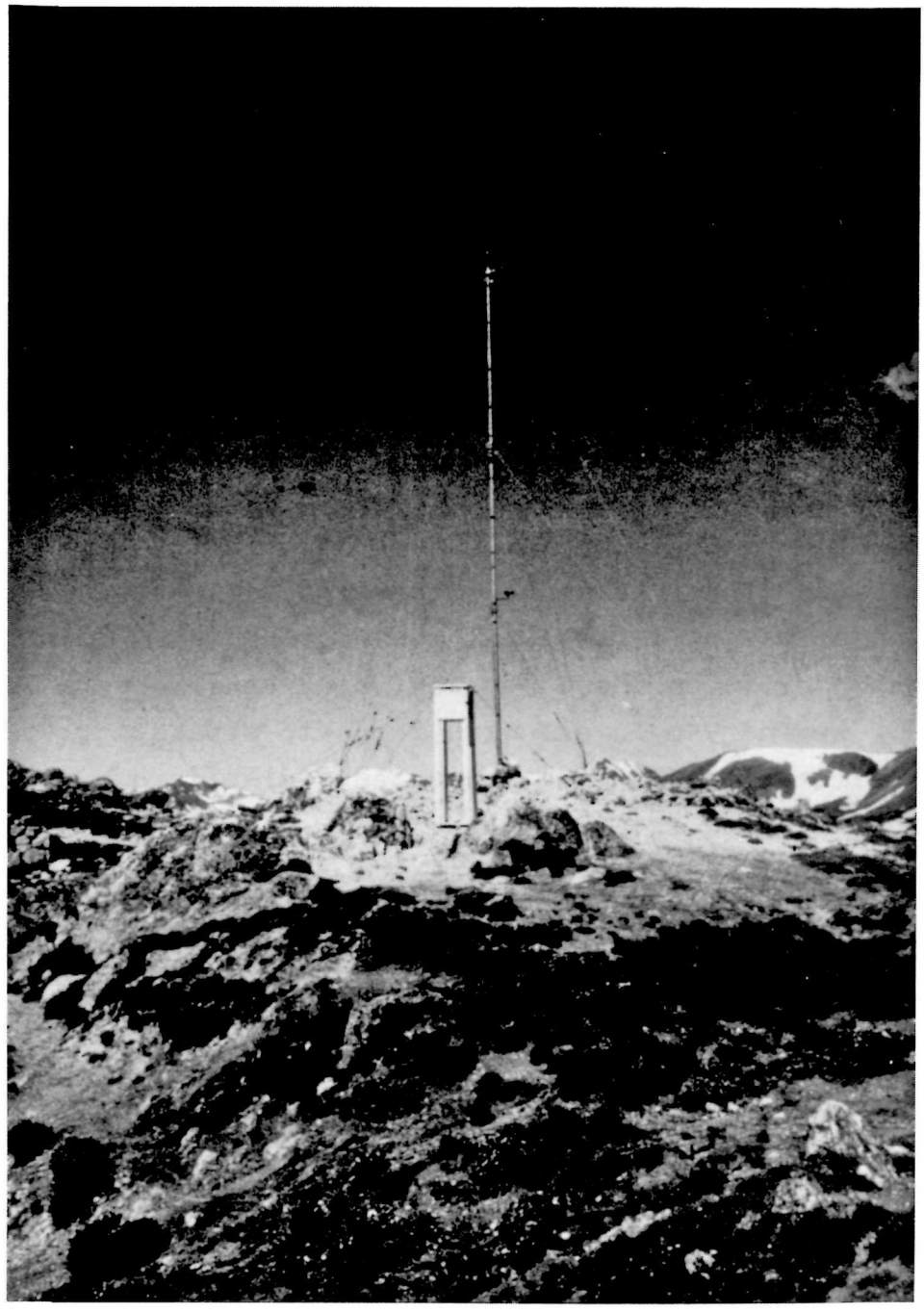


PHOTO 6

The main instrument tower at AVC (TR 10), showing wind sensors at the 3, 6, and 9 m levels.

The mean ratio of V_b/V_a was 0.9976. This suggests that, although maxima were quite close between the 3 m and 6 m levels, on average they were higher at the lower level. Terrain roughness and topographic acceleration of airflow over Fall River Pass may have masked any true differences this near the boundary layer.

However, the expected increase with height is realized in the V_c/V_a mean ratio of 1.605. This indicates, for example, that on average a maximum windspeed of 30 mph (13.4 m/s) at 3 m would increase to 31.8 mph (14.2 m/s) at 9 m.

Further research involving detailed hourly data for 3 levels up to 15 m, as well as quantitative studies of surface roughness and airmass stability characteristics - beyond the scope of the summer project - would be required to demonstrate a more complete profile of the variation of wind with height above ground at AVC.

9. CHARACTERISTICS OF UPSLOPE WINDS

Upslope winds, as used in this study, were defined as those which possessed an easterly component, and included southeast or northeast flow.

Although the importance of upslope winds at AVC is diminished by the predominance of the westerlies, it is worthwhile to understand some characteristic differences between them.

Figure 8 reproduces a trace of a strong summer upslope (southeast) wind at AVC, which occurred on August 25, 1980 and lasted for perhaps six hours.

Following the initiation of a typical upslope pattern at AVC, a weak westerly flow dropped to near-calm at 1100 LST. A windshift to southeast marked the beginning of a steadily increasing hourly flow and the formation of fractocumulus clouds around the facility. Note the high hourly averages, which ranged from 20-40 knots (23-46 mph; 10-20 m/s), and the low hourly GFs, which ranged from 1.15-1.25. This type of airflow would be more compatible with the operation of a wind turbine, for example, than a moderate westerly wind (Fig. 9), which could produce hourly GFs >3.0 or five-minute GFs >1.50.

The prediction, birth, and propogation of storm cells in RMNP are poorly understood. During summer, the dynamics of formation may often produce dramatic increases (>58 mph; 26 m/s) in westerly winds over a period of minutes, as seen in Fig. 10. No such turbulent events were recorded under upslope conditions at AVC.

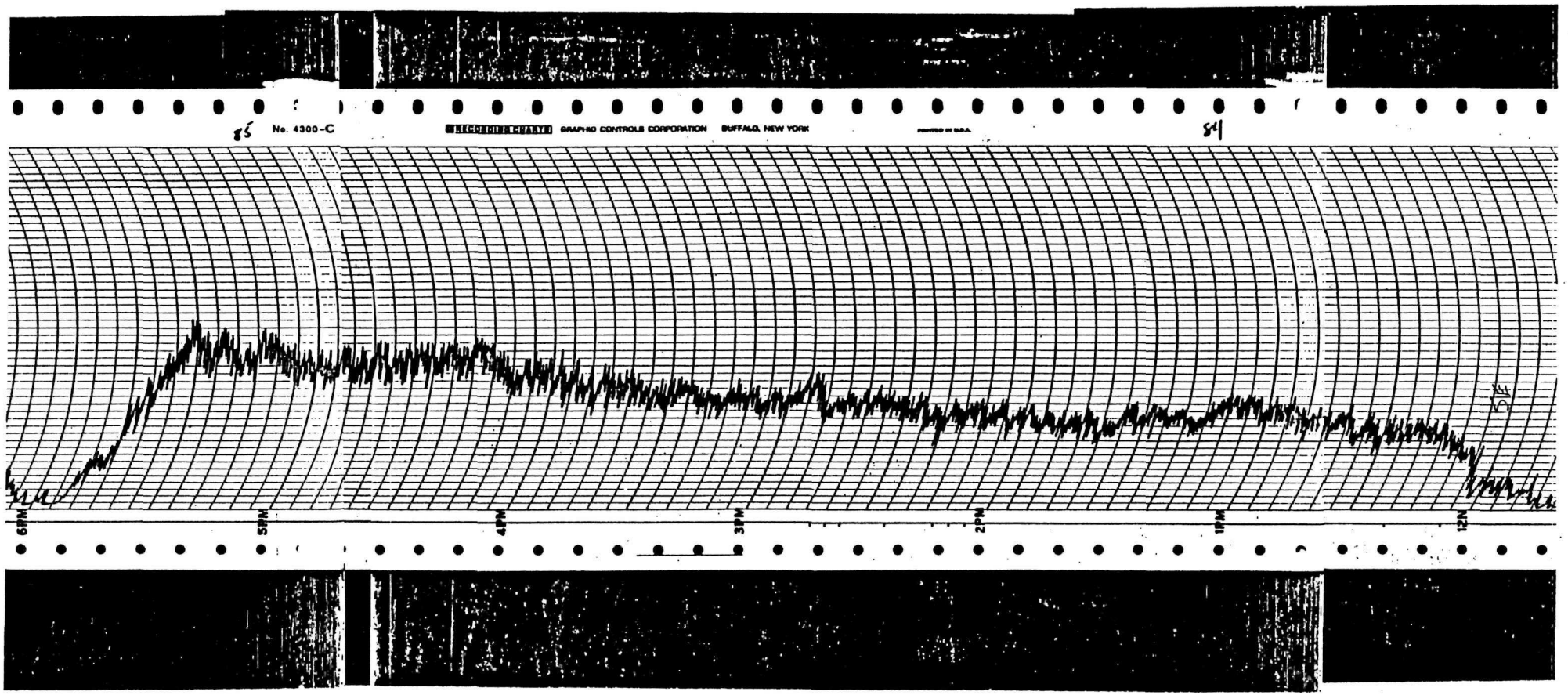


FIG. 8

Anemograph of strong summer upslope (southeast) wind at the Alpine Visitors' Center (TR 10), August 25, 1980. Note sudden cessation of flow from 5:30-6:00 PM.

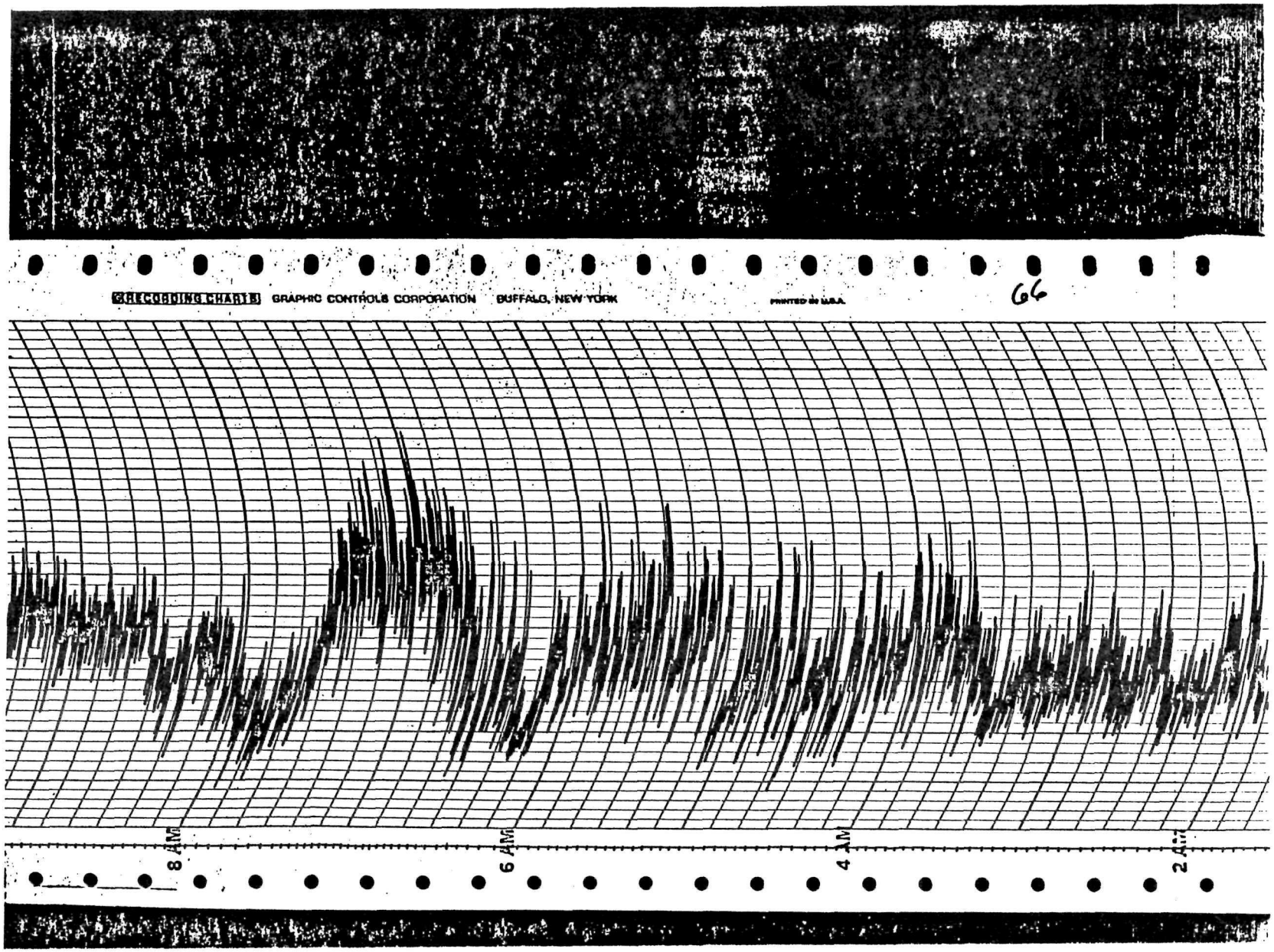


FIG. 9

Anemograph of strong and gusty westerly winds at the Alpine Visitors' Center (TR 10), August 20, 1980.

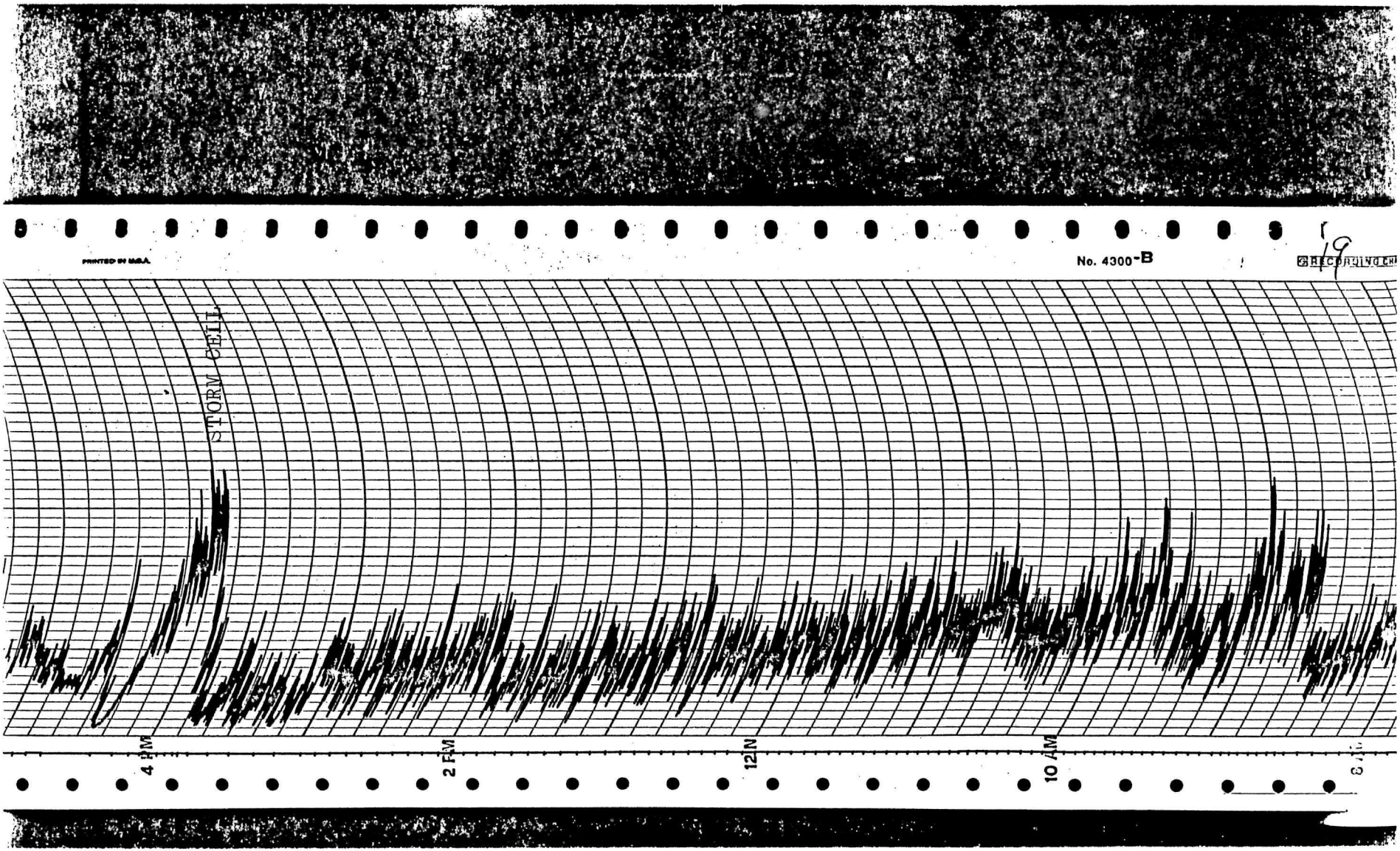


FIG. 10

Anemograph showing the dynamic passage of a thunderstorm cell at the Alpine Visitors' Center (TR 10), formed under a moderately turbulent westerly windflow. August 5, 1980.

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APPENDIX A

Instrumentation and Calibration

Wind

All sensors and meters were manufactured and calibrated by Maximum, Inc., Dover, Massachusetts.

Specifications:

Sensors

- cup rotation versus true wind speed nearly linear; 100 mph = 1,760 rpm.
- distance constant: 10 ft.
- error due to angle of attack above and below the plane of the cups is always positive, reaching a peak of 9% at 46° off level.
- dynamic response: acceleration from full stopped condition to full speed rotation in steady 40 mph (18 m/s) wind is achieved in 0.45 sec without overshoot.
- calibration tests: Wright Brothers wind tunnel, MIT; Air Force Cambridge Research Laboratory 200 mph (89 m/s) wind tunnel.

Meters

- meter movement: 300 microamps, full scale; meter resistance: 450 ohms.
- response rate: 180°/ sec.
- gust register response rate: 75% delta V / 5 seconds.
- overall system accuracy: ±3% full scale, 0-200 knots (230 mph; 103 m/s).

Recorders

- type: Esterline-Angus, 1.0 milliamp.
- response rate: ½ sec, full scale.
- overall accuracy: ±1%, full scale.

Temperature and Relative Humidity

Taylor maximum/minimum sixes (calibration: ±1° F)

Bendix-Friez Hygrothermograph

Specifications:

Temperature accuracy: ±3° F
Relative Humidity accuracy: ±5%

Pressure

Bendix microbarographs

Specifications:

overall accuracy: ±1 millibar

APPENDIX B

WIND RESEARCH IN ROCKY MOUNTAIN NATIONAL PARK: SITE HISTORY AND INSTRUMENT EXPOSURE[1]

SITE[2]	INSTALLED	REMOVED	ELEVATION	SENSOR HEIGHT
Wind			Meters	
TR 1	10/12/73	12/15/73	3,669	3.6
TR 2	10/21/73	5/10/74	3,365	4.3
TR 3	12/16/73	6/1/74	3,536	3.6
	6/6/80	9/23/80	3,536	3.6
TR 4	1/3/74	1/8/74	3,498	3.5
TR 5	1/18/74	5/4/74	3,469	4.3
TR 6	1/23/74	6/1/74	2,913	12.8
TR 7	12/25/73	6/2/74	2,377	12.2
TR 8	2/28/74	6/1/74	2,810	3.6
TR 10-01	6/2/80	8/28/80	3,602	9.0
TR 10-02	6/2/80	9/19/80	3,602	9.0
TR 11	6/6/80	9/18/80	3,658	6.0
Atmospheric Pressure				
TR 6	1/24/74	5/26/74	2,913	-
	6/3/80	9/21/80	2,913	-
TR 7	1/1/74	5/31/74	2,377	-
	9/22/80	-	2,377	-
TR 12	6/3/80	9/21/80	3,243	-
Temperature and Relative Humidity				
TR 6	2/10/74	5/28/74	2,913	-
TR 7	1/21/74	5/31/74	2,377	-
TR 10	6/3/80	9/19/80	3,602	-

1. Does not include temporary field study sites, such as TR 9, 13, 14, and 15.

2. See Figure 1 for location of research sites.

APPENDIX C

SUPPLEMENTARY METEOROLOGICAL DATA

1980

	J	J	A	SUMMER
TR 10 (AVC)[1]				
Temperature (F)				
Extreme Maxima	65	68	69	69
Average Maxima	50.3	60.1	57.6	56.0
Average	45.8	50.9	49.6	48.8
Average Minima	37.7	42.2	41.2	40.4
Extreme Minima	28	38	28	28
Average Range	16.1	18.0	16.6	16.9
Relative Humidity (%)				
Extreme Maxima	74	91	86	91
Average Maxima	50.3	76.4	73.0	66.6
Average	39.5	57.8	56.8	51.4
Average Minima	28.7	40.2	40.4	36.4
Extreme Minima	18	30	26	18
Average Range	21.6	35.2	29.9	28.9
TR 6 (Hidden Valley)				
Atmospheric Pressure[2] (Millibars)				
Extreme Maxima	1028.8	1028.4	1025.1	1028.8
Average Maxima	1023.0	1025.1	1021.7	1023.2
Average	1021.2	1024.0	1020.3	1022.0
Average Minima	1020.0	1022.7	1019.0	1020.7
Extreme Minima	1015.6	1019.3	1011.2	1011.2
Average Range	2.94	2.03	2.37	2.45
TR 12 (Milner Pass)				
Atmospheric Pressure[2] (Millibars)				
Extreme Maxima	1024.4	1026.1	1024.0	1026.1
Average Maxima	1021.7	1023.7	1020.3	1021.9
Average	1021.0	1022.7	1019.3	1021.0
Average Minima	1020.0	1021.7	1018.3	1020.0
Extreme Minima	1016.9	1019.3	1012.9	1012.9
Average Range	1.83	1.69	2.03	1.85

1. Temperature and Relative Humidity readings were recorded in a screen 1.52 meters above ground, and absolute values were probably greater than those indicated.
2. Reduced pressure readings are correct for comparing relative changes between sites; absolute values should not be used for comparison elsewhere.

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