BEAUFORT SCALE OF WIND FORCE AS ADAPTED FOR USE ON FORESTED AREAS OF THE NORTHERN ROCKY MOUNTAINS [1]

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INTRODUCTION

The Beaufort scale of wind force, internationally employed by weather agencies, was not designed for use on mountainous and forested areas like those of the Rocky Mountains of northern Idaho and western Montana. The United States Forest Service has used it to estimate wind velocities in this region, but has found that in too many cases the resulting estimates were inaccurate.

In the northern Rocky Mountain region the scheme of forest fire protection demands reliable estimates of wind velocity. Wind exerts an important influence upon the rate at which forest fuels dry and upon the rate at which fire spreads, and the region contains relatively few stations where wind velocity is actually measured. Where measurements are not available, reliable estimates of wind velocity are indispensable in determining potential fire danger, are useful in connection with placing men and camps on going fires, and have an appreciable bearing on the rating of efficiency of control action.

ORIGINAL FORM OF BEAUFORT SCALE, AND REVISED FORM IN GENERAL USE ON LAND

The original Beaufort scale [2] was designed by Admiral Sir Francis Beaufort in 1806 for use on the sea. It is reproduced in table 1.

Table 1.—*Original Beaufort scale of wind force*

Number	Denotation	Specification	Speed and sail required
0	Calm	Just sufficient to give steerageway.	
1	Light air		
2	Light breeze	With which a well-conditioned man-of-war, under all sail and clean full, would go in smooth water, from—	1 to 2 knots.
3	Gentle breeze		3 to 4 knots.
4	Moderate breeze		5 to 6 knots.
5	Fresh breeze	In which the same ship could just carry close-hauled—	Royals, single reefs, topgallant sails, etc.
6	Strong breeze		Single reefs and topgallant sails.
7	Moderate gale		Double reefs, jibs, etc.
8	Fresh gale		Triple reefs, courses, etc.
9	Strong gale		Close reefs and courses.
10	Whole gale	With which she could only bear—	Close-reefed main topsail and reefed foresail.
11	Storm	With which she would be reduced to—	Storm staysails.
12	Hurricane	To which she could show—	No canvas.

[1] Received for publication Mar. 21, 1934; issued July, 1934.

[2] Simpson, G. C. THE VELOCITY EQUIVALENTS OF THE BEAUFORT SCALE. [Gt. Brit.] Air Ministry Met. Off. Prof. Notes no. 44, 24 pp., illus. 1926.

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This historic scale was adopted by the British Admiralty in 1838. From the Navy its use spread to the British mercantile marine and later to those of other countries. In 1874 the International Meteorological Committee, meeting at Utrecht, adopted the Beaufort scale for international use in weather telegraphy.

Since 1838 a few minor changes have been introduced, but the scale has remained substantially the same as Beaufort drafted it. With the development of meteorology there was need for a classification in terms of wind velocity. After many attempts to supply this, the International Meteorological Committee adopted specifications allotting to each number on the scale an equivalent average velocity in statute miles per hour.

The Beaufort scale with specifications for land use, as it is employed today by the United States Weather Bureau, is shown in table 2.

TABLE 2.—*Revised Beaufort scale of wind force*

Number	Specifications for use on land	Wind class, velocity in statute miles per hour	Terms used in Weather Bureau forecasts
0	Calm; smoke rises vertically	Less than 1	Light.
1	Direction of wind shown by smoke drift, but not by wind vanes.	1 to 3	
2	Wind felt on face; leaves rustle; ordinary vane moved by wind	4 to 7	
3	Leaves and small twigs in constant motion; wind extends light flag.	8 to 12	Gentle.
4	Raises dust and loose paper; small branches are moved	13 to 18	Moderate.
5	Small trees in leaf begin to sway; crested wavelets form on inland waters.	19 to 24	Fresh.
6	Large branches in motion; whistling heard in telegraph wires; umbrellas used with difficulty.	25 to 31	Strong.
7	Whole trees in motion; inconvenience felt in walking against wind.	32 to 38	
8	Breaks twigs off trees; generally impedes progress	39 to 46	Gale.
9	Slight structural damage occurs; chimney pots and slate removed.	47 to 54	
10	Seldom experienced inland; trees uprooted; considerable structural damage occurs.	55 to 63	Whole gale.
11	Very rarely experienced; accompanied by widespread damage	64 to 75	
12		Above 75	Hurricane.

NORTHERN ROCKY MOUNTAIN FORM OF BEAUFORT SCALE

A set of wind-velocity indices based on conditions in forested portions of the northern Rocky Mountain region has been developed by the Northern Rocky Mountain Forest and Range Experiment Station, through observations made at the station's Priest River, Idaho, branch as to the visible action of wind upon grasses, shrubs, trees, flags, smoke, dust, scraps of paper, and lake water, and as to physical reactions of the observers. Adapted to regional conditions by the substitution of these indices, the Beaufort scale is as shown in table 3.

The northern Rocky Mountain adaptation, hereafter designated as the "NRM scale", includes no velocities greater than 38 miles per hour because that velocity is seldom exceeded in the forests of the region.[3]

[3] The maximum velocity reported in 1932 by any of the 24 northern Rocky Mountain stations of the Weather Bureau, according to a summary by F. C. Crombie, of the Weather Bureau, was 37 miles per hour, reported from Goat Mountain Lookout, elevation 6,794 feet.

TABLE 3.—*Beaufort scale of wind force as adapted for use on forested areas of the northern Rocky Mountains in western Montana and northern Idaho*

Number	Effects of wind	Wind class, velocity in statute miles per hour	Terms used in Weather Bureau forecasts
0	Smoke rises vertically; no movement of leaves on bushes or trees.	Less than 1	Light.
1	Leaves of quaking aspen in constant motion; small branches of bushes sway; slender branchlets and twigs of trees move gently; tall grasses and weeds sway and bend with wind; wind vane barely moves.	1 to 3	
2	Trees of pole size in the open sway gently; wind felt distinctly on face; loose scraps of paper move; wind flutters small flag.	4 to 7	
3	Trees of pole size in the open sway very noticeably; large branches of pole-size trees in the open toss; tops of trees in dense stands sway; wind extends small flag; a few crested waves form on lakes.	8 to 12	Gentle.
4	Trees of pole size in the open sway violently; whole trees in dense stands sway noticeably; dust is raised in road.	13 to 18	Moderate.
5	Branchlets are broken from trees; inconvenience is felt in walking against wind.	19 to 24	Fresh.
6–7	Trees are severely damaged by breaking of tops and branches; progress is impeded when walking against wind; structural damage, shingles blown off.	25 to 38	Strong.

TEST OF ACCURACY

The revised Beaufort scale and the NRM scale were tested for accuracy at the Priest River branch of the experiment station by recording five men's estimates of wind velocities together with measurements of these velocities made by means of a portable anemometer. Each man made 10 estimates with the revised Beaufort scale and 10 simultaneous estimates with the NRM scale. Special care was taken to avoid the possibility of bias entering into the estimates. The significance of the variation among individual estimators, between scales, and within men's estimates, and sampling error have been determined by Fisher's methods, analysis of variance and z test.[4] Differences between estimates and measurements of velocities were expressed in terms of wind-class units rather than in terms of miles per hour. Table 4 gives the sums of squares, the components of variance attributable to individual sources, respectively, and the Napierian logarithms of the square roots of these components of variance, which were used in making the z test for significance. Sampling error has been divided into four parts, of which three show the interaction between men and scale, men and reading, and scale and reading, respectively.

TABLE 4.—*Sources and components of the variance in estimates of wind velocity, and Napierian logarithms of square roots of the means of component variances*

Source of variance	Degrees of freedom	Sum of squares	Mean square or variance	Napierian logarithm of square root of variance
Differences among men	4	30.34	7.5850	1.0131
Differences between scales	1	110.25	110.2500	2.3514
Differences within men's estimates regardless of scale	9	2.69	.2989	−.6038
Sampling error:				
Interaction, men × scale	4	14.30	3.5750	.6370
Interaction, men × reading	36	19.46	.5406	−.3076
Interaction, scale × reading	9	4.45	.4944	−.3528
Residual	36	13.50	.3750	−.4904
Total	99	194.99		

[4] FISHER, R. A. STATISTICAL METHODS FOR RESEARCH WORKERS. Ed. 4, ch. 7. Edinburgh and London 1932.

It was found that the variance due to differences among men, that due to differences between scales, and that due to interaction between men and scale differed significantly from residual error, and that the variance within men's estimates and that due to interaction between men and reading and between scale and reading did not differ significantly from residual error.

When the components of variation that are found not to be significant are combined with residual error, the data given in table 4 take the form shown in table 5.

TABLE 5.—*Sources of significant components of variance in estimates of wind velocity, and corresponding sums of squares and variances*

Source of variance	Degrees of freedom	Sum of squares	Mean square or variance
Differences among men	4	30.34	7.5850
Differences between scales	1	110.25	110.2500
Interaction, men × scale	4	14.30	3.5750
Sampling error	90	40.10	.4456
Total	99	194.99	

The mean differences in wind-class units for each man and for each scale, together with the standard errors of the means, are given in table 6. The differences of the Beaufort estimates are all shown to be significant as measured by their standard errors, while the deviations of the NRM estimates are shown not to vary significantly from zero. Each standard error includes only the part of the total error that is independent of the personal element, of differences between the scales, and of interaction between men and scale. These standard errors are calculated by the formlua:

$$\sigma_M = \sqrt{\frac{\sigma^2_E}{N}}$$

in which

σ_M = standard error of a mean
σ^2_E = variance due to error
N = number of observations.

In this case $N=10$, because each man made 10 estimates by each scale.

TABLE 6.—*Mean differences within individual men's estimates with the Beaufort and with the NRM wind scale*

Man	Scale	Mean difference (wind-class units)	Standard error of mean
A	Beaufort	1.3	±0.262
	NRM	−.2	±.144
B	Beaufort	3.4	±.262
	NRM	.2	±.144
C	Beaufort	2.9	±.262
	NRM	.1	±.144
D	Beaufort	1.5	±.262
	NRM	−.2	±.144
E	Beaufort	1.1	±.262
	NRM	−.2	±.144

When the data are summarized as in table 7, it is found that velocity estimates made with the Beaufort scale were more than two wind classes higher than actual velocities. This is a very significant deviation, 17 times the standard error. Estimates made with the NRM scale, on the other hand, averaged 0.06 wind classes too low, a deviation that is less than the standard error and hence is not significant.

TABLE 7.—*Mean differences of Beaufort-scale and NRM-scale estimates from actual velocities*

Scale	Mean difference (wind-class units)	Standard error of mean [1]
Beaufort	+2.04	±0.117
NRM	-.06	±.064

[1] Calculated on the basis of $N=50$, the total number of observations for each scale.

Proof that estimates made with the revised Beaufort scale differed significantly from those made with the NRM scale is obtained by comparing the difference in the means with the standard error of the difference. The latter is computed by the formula:

$$\sigma_{B-NRM}=\sqrt{\sigma^2{}_B+\sigma^2{}_{NRM}}$$

in which

σ_{B-NRM} = standard error of the difference between the means of the Beaufort-scale and NRM-scale estimates
$\sigma^2{}_B$ = variance of the means of the Beaufort-scale estimates
$\sigma^2{}_{NRM}$ = variance of the means of the NRM-scale estimates.

The difference between the means of the estimates made with the two scales, respectively, with its standard error of the difference, is 2.10 ± 0.133. The difference is almost 16 times its error and is therefore significant.

Further investigation of the variation among the means of men shows that the personal error affected the estimates appreciably only when the Beaufort scale was used. Estimates made with this scale by B and C differed significantly from those made with it by A, D, and E. Proof of this is obtained by using the formula for the standard error of a difference, previously explained. An example from table 6 follows:

$$\text{Man } C \text{ mean} - \text{man } E \text{ mean} = 1.8$$

$$\sigma_{C-E}=\sqrt{(.262)^2+(.262)^2}$$
$$=\pm 0.37$$

The fact that the difference of 1.8 is almost five times its standard error indicates that the difference between the means of man C and man E is unquestionably significant. When the NRM scale was used, no man's estimates differed significantly from those of any other man.

The significant variance due to the interaction between men and scale indicates that the difference between Beaufort-scale estimates and NRM-scale estimates made by the same men, respectively, was not consistent. This fact does not affect the validity of any of the conclusions that have been drawn, but corroborates the foregoing tests of differences.

The final source of variation to be considered is sampling error, which equals 0.4456. This variance is within the acceptable limits of accuracy set up for field estimation of wind velocity on forested areas of the northern Rocky Mountains.

SUMMARY

The revised form of the Beaufort scale of wind force that is used by the United States Weather Bureau on land has been specially adapted by the Northern Rocky Mountain Forest and Range Experiment Station to conditions on forested areas of northern Idaho and western Montana. The adaptation consisted in substituting a set of wind-velocity indices devised on the basis of observations made at the station's branch at Priest River, Idaho. These indices are for the most part a classification of the visible action of wind on such objects as grasses, bushes, and trees.

To test the accuracy of estimates made with the scale as adapted, records were taken of wind-velocity estimates made with the revised Beaufort scale and also with the northern Rocky Mountain form of the scale by 5 individual observers on 10 occasions for which were recorded, also, measurements of wind velocity made with a portable anemometer. The significance of the variation among individual estimators, between scales, and within men's estimates, and sampling error, were determined by Fisher's methods, analysis of variance and z test. Sampling error was divided into 4 parts, of which 3 parts show the interaction between men and scale, men and reading, and scale and reading, respectively.

Findings were as follows:

Whereas the average error for estimates made with the revised Beaufort scale was +2.04 wind classes, that for estimates made with the northern Rocky Mountain form of the scale was −0.06 wind classes.

A very significant personal error was associated with use of the revised Beaufort scale; for example, the difference between the estimates of two of the men amounted to almost five times the error of the difference. No significant personal error was evident in estimates made with the northern Rocky Mountain form of the scale; in other words, when the latter was used one man's estimate did not vary significantly from another's.

The differences between the means of estimates made with the revised Beaufort scale and the means of estimates made with the Northern Rocky Mountain scale by the same men, respectively, were significantly different from one another.

The findings show conclusively that for use on forested areas of northern Idaho and western Montana the northern Rocky Mountain form of the Beaufort scale is more accurate than the form of the scale used on land by the Weather Bureau.