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66

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THE EQUIVALENT VELOCITIES FOR THE BEAUFORT ESTIMATES OF THE WIND FORCE AT SEA

1956

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. . . "*Long before Beaufort gave his attention to specifying the strength of the wind, sailors had evolved a rough scale with descriptive terms which were used by them in their everyday conversation. Sailors describe the strength of the wind by such words as calm, air, breeze, gale, storm and hurricane; and use such adjectives as light, gentle, moderate, fresh and strong to qualify them. A sailor could not define these terms; but he has no difficulty in recognizing the difference between an air and a breeze, a gale and a storm and a hurricane. The sailor's estimate of the strength of the wind as used in his ordinary conversation is based on its effect on his surroundings: on the waves formed on the surface of the sea, on the amount of broken water, on the sound produced as it blows through the rigging and on the way his ship can stand up to it. These terms are understood by all experienced sailors and are quite independent of any scientific definitions. The success of Beaufort's Scale is largely due to the fact that, as the result of long experience and careful observation, he was able to attach the name which a sailor would use to each of his thirteen scale numbers.* . . . . . . *The rig of ships has changed, sail has been replaced by steam, but the effect of the wind on the sea has remained, and will always remain, exactly the same. The sailor's description of the strength of the wind being based on effects independent of the rig of his ship has survived all the changes in marine transport and an air, a breeze, a gale and a hurricane mean just the same to a sailor now as they did in Beaufort's time.*" . . . .

G. C. SIMPSON (1926)

THE EQUIVALENT VELOCITIES FOR THE BEAUFORT ESTIMATES OF THE WIND FORCE AT SEA

by G. VERPLOEGH

Summary

In 1950 and '51 anemometer readings were taken on board two Netherlands light-vessels at a height of 7 m above sea level. The measurements have been compared with the routine Beaufort estimates of the wind force. The resulting equivalent wind velocities were found to be identical for both light-vessels, they also agree closely with the corresponding values resulting from observations made on board ship in the South, tropical and North Atlantic Ocean as well as with those made on German light-vessels in the North Sea and Baltic Sea. All these series differ, however, essentially from the equivalents, which have been accepted in 1946 for international use.

These equivalents were drafted by G. C. Simpson in 1906 from observations made at some English coastal and inland stations. With the evaluation of the mean series, which was originally adopted by the Meteorological Office in London in 1906, a comparatively large weight had been attached to the observations of the one observer at Scilly and to a less extent of the one at Yarmouth, so much so, that the adopted mean series represents almost wholly the conception of these two observers, not to mention the influence of the particular circumstances concerning the measuring at these stations. A comparison with the other determinations known, representing the conception of a great number of observers of many nationalities, clearly shows the tendency of the two English observers to overestimate light winds and underestimate strong winds.

Having been drafted originally for the purpose of converting the anemometer readings at land stations into the numbers of a generalized Beaufort scale for use in coded weather reports, in their present use the international equivalents have no more than a provisional significance, since they cannot be considered representative for the mean conception of estimating the wind force at sea.

Therefore, a new set of equivalents based exclusively on observations, made at sea, has been proposed for further international use. The properties of the set, concerning its representative value for estimates at sea, the degree of accuracy of the mean equivalent velocities, the gradation of the scale, the corresponding height of the anemometer and the dependency on the stability of the lower air layers, have been discussed in some detail. The resulting equivalent velocities appear to be well established in the range from 1 *B* to 8 *B*. With light airs the determination is largely influenced by the circumstances concerning the measuring; at the higher wind forces the comparatively large inaccuracy of the estimates sets a lower limit to the accuracy, with which the corresponding equivalents can be established. Additional evidence has been found, however, indicating the right order of magnitude of the proposed equivalents at the higher wind forces.

1. THE VELOCITY EQUIVALENTS OF BEAUFORT NUMBERS BASED ON WIND OBSERVATIONS ABOARD NETHERLANDS LIGHT-VESSELS

1.1. Measurements

In the autumn of 1950 contact-anemometers were mounted aboard two Netherlands light-vessels in order to test the accuracy of estimated wind observations.

The following research is based on two series of observations, made aboard the light-vessels Terschellingerbank and Texel respectively during the periods:

L.V. Tersch.bank (53°30′ N 05°08′ E): Sept. 11th '50–Sept. 1st '51

L.V. Texel (53°07′ N 04°30′ E): Nov. 16th '50–Sept. 1st '51

During these periods the wind force was estimated in Beaufort numbers every three hours in the usual way by means of the Petersen scale, and then converted into knots, using the international equivalents, agreed to at Paris in 1946. At the same time the number of contacts made by the revolving cup-anemometer in a period of ten minutes was read. Both observations were entered into the log-book. In order to achieve the highest possible objectivity in the estimates the standard-measure of the anemometer was not made known to the observers. However, it appeared that in the end the mere presence of an anemometer on board caused the observers to lose confidence in their own observations; by means of some individual measure they tried to match their estimates with the indications of the contact-anemometer. For this reason it was thought advisable to confine both series to periods of not more than one year.

The number of observations thus obtained, i.e. for L.V. Terschellingerbank: 2321, and for L.V. Texel: 1996, is high enough to be used as a basis for some reliable conclusions.

1.2. Elaboration of the observations

First the mean difference was calculated between the measured and the estimated values and arranged for intervals of one knot. These differences are tabulated in Table 1. In this case, according to Köppen (1898), the measured velocities were assumed as having a fixed value with respect to which the deviations of the estimates were computed. The differences obtained by this procedure are independent of the frequency with which the various true wind velocities occurred, as G. C. Simpson (1906) also showed with some examples. The two series of differences from both light-vessels agree well with each other. In both series the estimates appear to be lower than the measured value for

TABLE 1

Mean difference: estimated — measured wind velocity in knots

Light-vessel	Terschellingerbank		Texel	
Measured wind velocity naut. miles/hour	Difference	Number of observations	Difference	Number of observations
0 — 1	+ 0.1	8	+ 0.7	17
1 — 2	— 0.5	28	+ 0.2	31
2 — 3	— 0.3	30	+ 0.1	35
3 — 4	— 0.8	32	— 0.5	54
4 — 5	— 1.1	59	— 0.8	57
5 — 6	— 1.0	63	— 0.7	69
6 — 7	— 1.5	82	— 1.3	79
7 — 8	— 1.7	94	— 1.5	114
8 — 9	— 1.7	112	— 1.5	97
9 — 10	— 2.2	119	— 1.9	106
10 — 11	— 2.5	117	— 2.0	118
11 — 12	— 2.7	119	— 2.0	114
12 — 13	— 2.6	129	— 2.3	121
13 — 14	— 2.4	149	— 2.9	104
14 — 15	— 2.6	147	— 2.2	101
15 — 16	— 2.7	131	— 2.3	82
16 — 17	— 2.2	117	— 2.3	85
17 — 18	— 1.9	112	— 2.0	83
18 — 19	— 2.0	122	— 2.1	88
19 — 20	— 1.7	105	— 2.1	65
20 — 21	— 1.1	93	— 1.4	69
21 — 22	— 0.1	80	— 1.2	60
22 — 23	— 0.4	81	— 0.4	51
23 — 24	+ 0.1	59	— 0.2	43
24 — 25	+ 1.0	50	— 0.6	40
25 — 26	+ 2.0	34	+ 0.3	46
26 — 27	+ 3.7	19	+ 0.5	27
27 — 28	+ 2.0	10	+ 1.9	14
28 — 29	+ 3.3	4	+ 3.8	9
29 — 30	+ 2.2	12	+ 3.5	4
30 — 31	+ 2.0	2	+ 2.1	9
31 — 32	+ 4.0	2	+ 3.3	4
Total number		2321		1996

wind velocities ranging from about 2 to 25 knots. Outside this range the estimates are found to be higher.

To find the cause of this deviation, first the conditions under which the measurements took place will be examined.

1.3. The contact-anemometers

On both light-vessels the cup-anemometer has been mounted 5 feet above the wheelhouse and about 23 feet (7 meters) above sea level. According to the Petersen-scale the estimates are related also to a wind force at about this height. The protection of the contact-box against moisture (with a high salinity) was not altogether satisfactory and it was feared that the resulting corrosion might cause retardation in the rotating parts. It appeared, however, from a later test of the instruments that the retardation during the periods of observation may be considered as negligible.

The instrument was read in the wheelhouse by means of an ordinary telephone counter which was built in a metal box together with the four feeding batteries, each of 1.5 Volts. This box was also unsatisfactorily protected against moisture, which resulted in the batteries being run down more quickly than normally. If the voltage became too low, the counter would miss more and more contacts and so the wind velocity read would be too low. Therefore the batteries were replaced after 7 months in the light-vessel Texel and after 8 months in the light-vessel Terschellingerbank. Thus the error in the reading of the wind velocity has been limited to at the most one knot in the measurements on the last few days, when the voltage had dropped too much.

The exposure of the cups was free to a satisfying degree. With following winds, however, the anemometer stood on the lee-side of the big light-structure amidships. Now, following winds on light-vessels only occur at times when the wind velocity is very low; for the anchored vessel, which swings round four

TABLE 2

Terschellingerbank

Frequency per cent of the number of cases in which the wind in the Terschellingerbank came in under various angles of incidence over port and starboard. The wind forces 6 and 7 are taken together

Beaufort	Angle of incidence from the stem (port or starboard)						All directions
	0°–30°	30°–60°	60°–90°	90°–120°	120°–150°	150°–180°	Number of cases
	%	%	%	%	%	%	
1	17	28	9	16	15	15	54
2	28	33	20	9	7	3	98
3	39	30	13	12	3	3	168
4	38	34	17	9	1	1	151
5	49	34	11	5	1		85
6–7	67	20	10	3			70

times a day, assumes a position which is determined by the influence of wind and current together.

Aboard the light-vessels current measurements have also been made and since for this type of measurement the course of the vessel together with the wind direction was needed, both these data could be used to compute a frequency table of the number of cases, in which the wind of a certain force blew under a given angle of incidence from the stem (see table 2). The data are related to the Terschellingerbank and are taken over the months July, August and September 1951.

The influence of the wind on the course of the anchored ship is very well shown by these figures. In general the angle of incidence from the stem is smaller the stronger the wind becomes. Except at very light winds the influence of the light-structure on the mean wind velocity appears to be small. However the anemometer undoubtedly stands in an air stream disturbed by the ship itself. To a small extent winds of 1 and 2 *B* will be accelerated or retarded, depending on the angle of incidence. In general the retardation will have a minimum for cross winds.

The exact value of retardation cannot be found for lack of objective material for comparison. From measurements of this kind, held during the Meteor-expedition in 1925–'27 and elaborated by E. Kuhlbrodt (1936), it was found that the error by the retardation effect amounts to one knot in the mean. At a wind force of 5 *B* this error accumulates and increases to about two or three knots at a wind force of 7 *B*.

With the high wind velocities there is also a tendency for the readings to be too low on account of deficiencies of the anemometer itself. This is illustrated by Table 3, where for some periods with a high wind velocity the measured and estimated values are put next to each other. The anemometer readings appear to have a certain limit, varying for each storm period. This may be due to a very small amount of moisture and salt particles, which have penetrated into the contact box. When the rotation speed of the cups is very high, a small pollution of the contacts will form a resistance too high for contacts to be made in such a short time. Every now and then signals will be missed and the reading of the wind velocity will become too low. This effect has also been noted on other occasions.

Observations under the probable influence of this deficiency were not used for the compilation of Table 1.

From measurements made during the Meteor-expedition, it appears that for the above observations the error caused by the rolling and pitching of the vessel may be neglected.

1.4. Detailed discussion on the estimates

To make a good estimation of the force of the wind from the appearance

TABLE 3

Comparison between estimated and measured wind velocities at high wind forces

Date	Time GMT	Terschellingerbank				Texel			
		Wind velocity knots		Difference (1)–(2)	Wind direction	Wind velocity knots		Difference (1)–(2)	Wind direction
		estim- ated (1)	mea- sured (2)			estim- ated (1)	mea- sured (2)		
1950									
17/9	03	29	28	+1	180				
17/9	06	39	28	+11	180				
17/9	09	38	29	+9	180				
17/9	12	35	28	+7	160				
17/9	15	35	27	+8	220				
17/9	18	34	27	+7	230				
17/9	21	36	27	+9	230				
18/9	00	35	27	+8	240				
18/9	03	34	27	+7	240				
18/9	06	34	25	+9	240				
18/9	09	27	20	+7	250				
18/9	12	27	22	+5	250				
18/9	15	27	23	+4	250				
18/9	18	27	23	+4	260				
18/9	21	26	22	+4	270				
19/9	00	27	25	+2	250				
19/9	03	26	22	+4	260				
19/9	06	26	22	+4	280				
19/9	09	24	22	+2	280				
19/9	12	21	19	+2	280				
30/11	21	30	28	+2	240	32	29	+3	250
1/12	00	37	28	+9	230	33	30	+3	250
1/12	03	37	28	+9	250	33	32	+1	250
1/12	06	37	29	+8	240	33	31	+2	250
1/12	09	37	29	+8	220	31	30	+1	240
1/12	12	39	31	+8	220	38	31	+7	240
1/12	15	09	11	—2	260	19	14	+5	270
1/12	18	17	21	—4	290	23	22	+1	270
1/12	21	22	21	+1	270	24	25	—1	270
2/12	00	25	23	+2	260	27	27	0	270
2/12	03	40	32	+8	250	30	29	+1	260
2/12	06	39	31	+8	270	42	30	+12	270
2/12	09	42	33	+9	290	41	28	+13	270
2/12	12	32	26	+8	290	30	—	—	270
2/12	15	20	19	+1	290	21	19	+2	270
1951									
7/1	06	24	23	+1	220	28	26	+2	260
7/1	09	34	33	+1	240	28	31	—3	280
7/1	12	52	33	+19	240	37	35	+2	270
7/1	15	54	36	+18	260	43	32	+11	290
7/1	18	48	33	+15	250	40	33	+7	290
7/1	21	44	27	+17	270	28	31	+3	280
8/1	00	14	21	—7	260	17	15	+2	310
8/1	03	09	06	+3	230	09	08	+1	250
8/1	06	10	13	—3	180	11	—	—	230

of the surface of the sea requires a great deal of experience; the estimates, however, always retain a personal character. It is advisable, therefore, to involve in a research like this as many experienced observers as possible. In the Terschellingerbank light-vessel eleven observers took turns during the periods of the experiment, while this number amounted to ten in the Texel light-ship. With these numbers the individual influences on the mean result are reduced to a very small amount, though it will never be possible to eliminate them altogether. To demonstrate the personal element in the estimates an investigation has been made to see whether there existed any preference for estimating in even numbers of knots. For each (estimated) Beaufort number the odd and even numbers of knots, into which this number had been converted, were counted. In Table 4 is given the procentual amount of even values that was found more (+) or less (—) than expected at a proportional distribution.

It appears from this table that, apart from a tendency which may possibly be a natural feature of the scale (e.g. a distinct preference for even values at 1, 6 and 7 *B* and for odd values at 3 and 5 *B*), the observers in the Terschellingerbank by preference estimate in even values, while those in the Texel have a marked tendency to estimate in odd values. This result indicates a mutual influence between the observers in one ship.

TABLE 4

Number per cent of even values of wind velocity in knots, that occurred more (+) or less (—) than expected at a proportional division

Beaufort	Even values: residue (+) or deficit (—)		
	Terschellingerbank	Texel	Both
1	+ 17 %	+ 42 %	+ 30 %
2	+ 18 %	— 13 %	+ 2 %
3	+ 5 %	— 15 %	— 4 %
4	+ 19 %	— 8 %	+ 8 %
5	+ 8 %	— 42 %	— 16 %
6	+ 35 %	+ 9 %	+ 26 %
7	+ 57 %	+ 17 %	+ 35 %
Mean	+ 17 %	— 11 %	+ 4 %

For a measure of the accuracy of the estimates the standard deviation of the differences between the measured and estimated wind velocities may be used. These standard deviations, presented in table 5, are given in Beaufort numbers since the estimates are made primarily in this scale.

For both vessels an equal tendency may be noted in the changes in standard deviation up to a windforce of 6 *B*; there the values begin to diverge. Estimating

TABLE 5

Standard deviation of estimates with respect to the mean

Light-vessel	Terschellingerbank		Texel	
Beaufort intervals of measured wind velocity	Number of observations	Standard deviation Beaufort	Number of observations	Standard deviation Beaufort
0-1	66	0.29	83	0.37
2	154	0.47	180	0.43
3	407	0.33	396	0.38
4	792	0.30	640	0.37
5	549	0.52	390	0.52
6	323	0.48	267	0.57
7	30	0.44	40	0.70
Mean	2321	0.40	1996	0.44

the wind force seems to be rather difficult with light breezes (2 *B*) and easiest with moderate breezes (4 *B*). At 5 *B* the spreading in the estimates suddenly increases a great deal; this increase continues at higher wind speeds in the Texel while in the other vessel the values there begin to decrease. The mean standard deviation is 0.4 *B*. This means, that when the measured wind velocities are considered as fixed, the error in the estimates may amount to 0.4 *B* in two thirds of the cases.

This result agrees rather well with the mean standard deviation of 0.3 *B*, which Gallé (1915) has calculated from simultaneous estimations made at various ships in the Red Sea. Since the effect of the wind on the surface of the sea is dependent not only on the wind speed, but also for instance on the fetch and to a certain extent on the stability of the air, besides a certain spreading in the estimates, some systematical errors will also occur. One is the result of the retardation with which the sea follows the changes in the wind field, especially after a period with storms. This retardation effect is clearly to be seen in Table 3. After a stormy period normal wind velocities which usually are estimated 0.5 to 2 knots too low, are now estimated too high.

Especially during periods of light winds other effects, like tidal currents, swell and the proximity of coastal areas will have relatively a greater influence on the appearence of the sea surface. The large standard deviation at the wind force of 2 *B* is an indication of this. On the average there exists a tendency of overestimating light winds. The reason is found in the statistical features of these estimates: the number of possibilities of underestimating a low wind force is smaller than that of overestimating it. The large spreading in the estimates therefore causes the mean value to be too high.

1.5. Computed relation between Beaufort numbers and wind velocity

The following graph 1 shows for both light-vessels the mean estimated wind force, computed for every knot of the measured wind velocity. For comparison the international equivalency-curve is also drawn. As could be expected from table 1 both the newly found curves do not show any grave departure from their mutual course, in fact they are practically identical. They differ, however, essentially from the international one, which answers to the analytical expression (see G. C. Simpson, 1906):

$$v = 0.836\, B^{3/2} \text{ m/sec.}$$

where v = wind velocity in m/sec and B = Beaufort number.

The derivation of an analogous expression for the experimental curves includes the use of a double-logarithmic diagram, such as is shown in graph 2. In the upper half of the diagram the mean equivalent velocities of the successive Beaufort numbers, derived from both Netherlands light-vessels, have been plotted. For reasons of comparison the wind velocity scale has been converted from knots into m/sec. From 3 B upwards the points lie well on a straight line; through the values for the lower numbers a straight line can also be drawn, which, however, differs from the previous one; the transition occurs at 3 B.

The analytical expressions which have been derived from the graphical presentation are respectively:

for the lower numbers ($\leqslant 3\, B$):

$$v = 1.01\, B^{1.57} \text{ m/sec}$$

for the higher numbers ($\geqslant 3\, B$):

$$v = 1.79\, B^{1.07} \text{ m/sec}$$

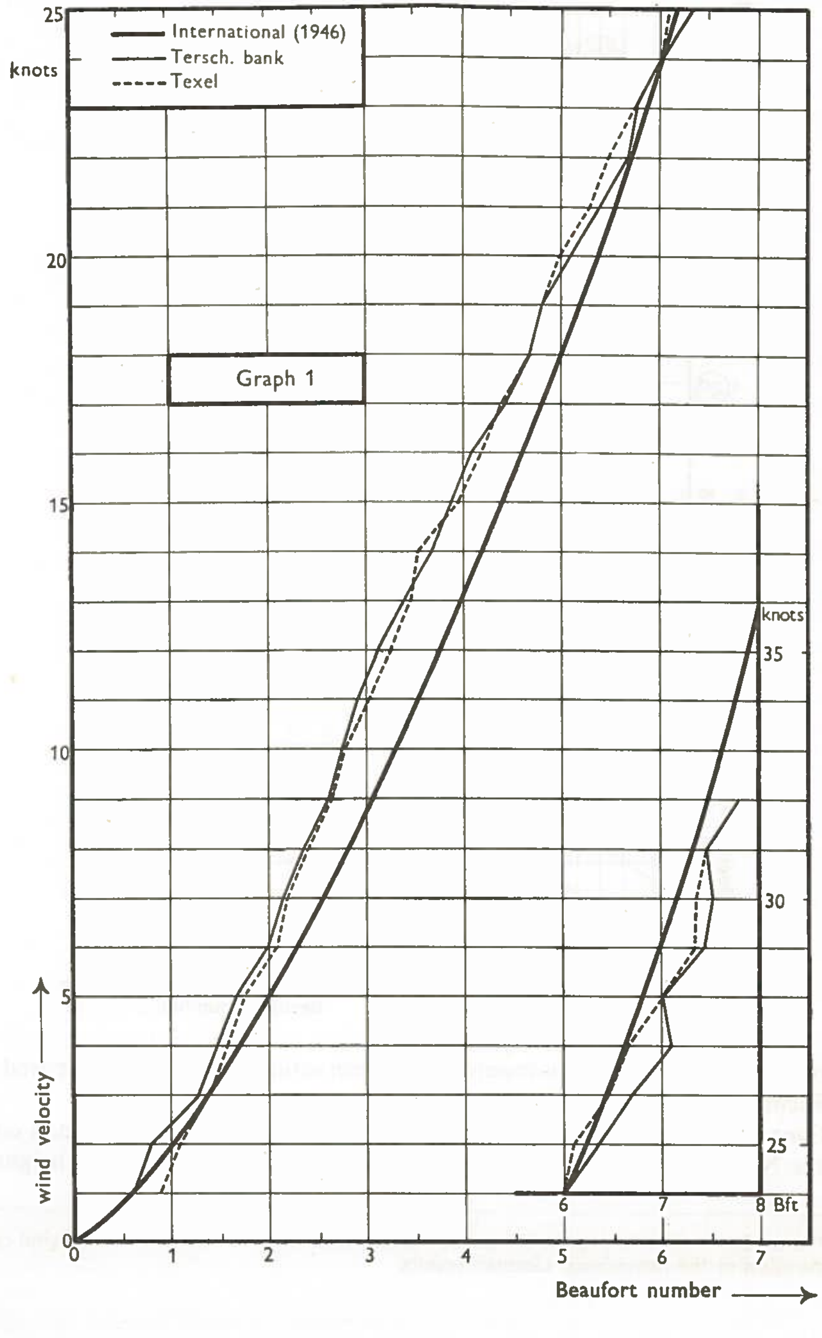
Both sets of equivalents, the experimental and the calculated ones, are compared in the following tables giving a ready survey of the approximations introduced.

In table 7 the series have been extrapolated on to 8 B in order to check the tendency in the differences. It should be noted that it might also be possible to find one analytical expression which covers all the equivalent values within the limits of accuracy; here a rather simple approximating technique has been applied to stress the different behaviour of the equivalencies at the lower wind forces. Especially when comparing the values obtained here with other results, the advantage of analysing the data in this way becomes clear.

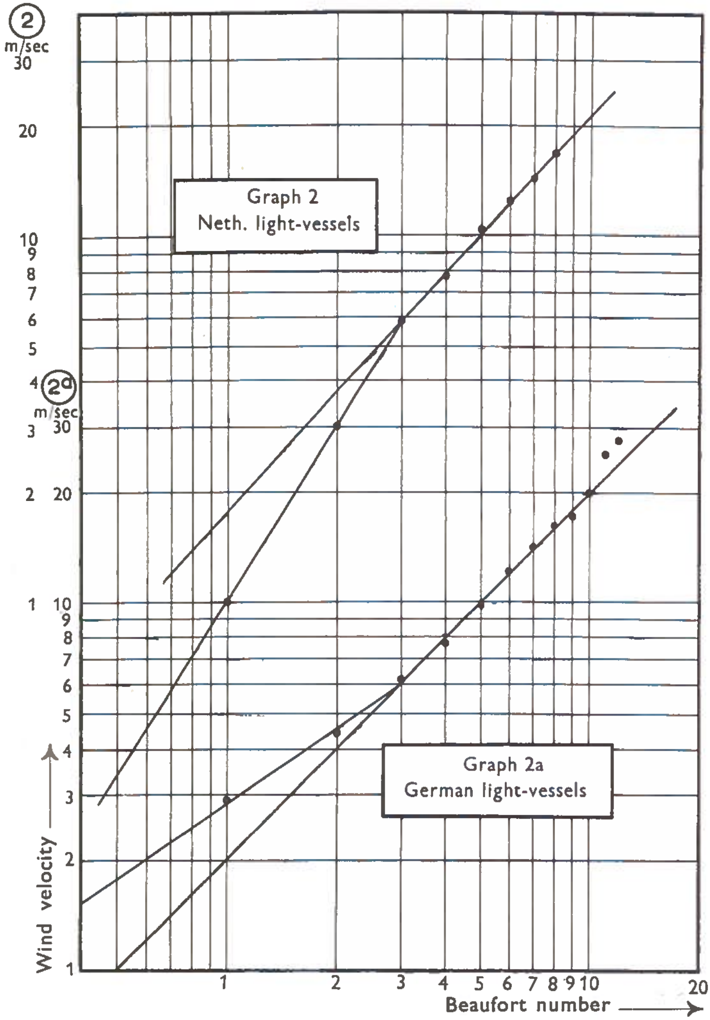
1.6. The influence of the height of the anemometer

After the Netherlands results had been worked out the author learned of some recent measurements having been carried out in rather the same way

Relation between Beaufort numbers and wind velocities in knots



Relation between Beaufort numbers and wind velocities in m/sec



aboard five German light-vessels. The observations have been prepared by J. Richter [1]) of the Seewetteramt, Hamburg.

Four of the light-vessels concerned were stationed along the German coast in the North Sea, the fifth one was lying in the Baltic Sea. The mean height of

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[1]) The author wishes to express his acknowledgements to Dr. J. Richter for the kind communication of the provisional German results.

TABLE 6

Equivalents, calculated with $v = 1.01\ B^{1.57}$ *m/sec*

Beaufort specification		0.2	0.8	1.0	1.3	1.5	1.7	2.0	3.0	4.0
Equivalents in m/sec	calculated	0.0	0.7	1.0	1.5	1.9	2.3	3.0	5.7	8.9
	experimental	—	0.7	1.0	1.5	2.0	2.5	3.0	5.8	7.9
Differences		—	0.0	0.0	0.0	—0.1	—0.2	0.0	—0.1	+1.0

TABLE 7

Equivalents calculated with $v = 1.79\ B^{1.07}$ *m/sec*

Beaufort numbers		0	1	2	3	4	5	6	7	8
Equivalents in m/sec	calculated	0	1.8	3.8	5.8	7.9	10.1	12.3	14.5	16.7
	experimental	—	1.0	3.0	5.8	7.9	10.2	12.4	14.4	16.8
Differences		—	+0.8	+0.8	0.0	0.0	—0.2	—0.1	+0.1	—0.1

the anemometers, which were erected 4 m above the light-structure, was 20 m above sea level. In graph 2, on the bottom side, the mean resulting equivalents have been plotted and for sake of comparison two sets of straight lines have been drawn through the successive points. Again from 3 *B* upwards the points lie approximately on a straight line, except the equivalents for 11 and 12 *B*, which have been left out on account of the small number of the underlying observations (1 and 3 respectively). This set of equivalents has the striking feature that the values at 1 and 2 *B* now lie well above the straight line passing through the other points. This different behaviour between the Netherlands and German series cannot be explained by a difference of the estimating technique. Both sets of measurements have been carried out aboard light-vessels, all lying in an area with equal climatological wind conditions, while on the vessels of both countries a great number of observers had been included in the research programme. It cannot be assumed either that the German personnel would have had another conception of wind force 1 and 2 than their Netherlands colleagues. If this were true we should find larger differences with the higher wind forces also, because a possible difference of the conception of estimating the wind force will not be confined to the lower forces only.

In considering the conditions of measuring we are able to find a possible explanation. Especially at low wind forces the height of the anemometer above sea level becomes a comparatively more important factor, because of the increase of the wind velocity with height. Only a few measurements of the vertical wind profile above the sea surface have been made so far. They indicate (Roll, 1951) that in the mean the relative increase of the velocity with height becomes less with increasing wind speeds. Consequently especially at low winds a high mounting of the anemometer will yield higher equivalent velocities than one would obtain with the anemometer at smaller heights. One may expect, therefore, that in the Netherlands series the observed deviations at the lower wind forces would become less, if the wind velocities were to be measured at greater heights.

This has actually been done on the German light-vessels and since the other circumstances with regard to measuring may be regarded equal, the difference of the corresponding equivalents at the lower wind forces may be attributed mainly to the difference of the mounting of the anemometers.

Apart from a certain connection with the wind velocity itself the vertical velocity gradient depends largely on the thermal structure of the air layer concerned. In the next paragraph some thought will be given to the question to what extent the latter effect influences the determination of the Beaufort equivalents.

1.7. The influence of the stability of the air

This aspect has recently been the subject of a study by H. U. Roll of the Seewetteramt, Hamburg, who in 1953 conducted a series of observations on board the German fishing escorting vessel Meerkatze in the North Sea and the Northern Atlantic, with the purpose of obtaining some sets of Beaufort equivalents under various stability conditions. Because of its fundamental importance for the present investigation some of the results mentioned in this interesting study (Roll, 1953) will be briefly reviewed.

On board the Meerkatze the wind force was estimated in the usual way, while the wind velocity was measured at a height of 19.3 m above sea level. At sea an easy measure of the stability of the lower air layers is obtained by the air – sea temperature – difference $\triangle T$; in this special investigation the readings of the air temperature were taken from a resistance-thermometer, attached to the foremast at a height of 16.5 m above sea level.

From the carefully conducted measurements nine equivalency-curves were computed, each of them referring to a definite interval of $\triangle T$ over a range from $\triangle T = -0.6°C$ to $+ 0.3°C$. The corresponding equivalent velocities showed indeed some significant differences, mainly at the transition from unstable to stable conditions. In unstable air the values are smallest and practically constant up to a difference in temperature of $\triangle T = -2°C$; between $\triangle T = -2°C$ and $\triangle T = + 1°C$ the equivalents increase rather suddenly by about 1 m/sec at light and moderate wind forces. In table 8 some sets have been reproduced.

TABLE 8

Equivalent velocities in m/sec under various stability conditions, determined by H. U. Roll (1953)

	Beaufort	0	1	2	3	4	5	6	7
$T_{air}-T_{sea}$	$-2°$ C	0	1.4	3.1	5.0	6.9	9.1	11.5	(14.8)
	$-1°$ C	0	1.5	3.3	5.1	7.0	9.2	11.8	(14.9)
	0° C	0	1.8	3.7	5.7	7.8	9.9	12.4	(15.0)
	$+1°$ C	0	2.1	4.3	6.3	8.3	10.4	12.8	(15.1)

In connection with this experiment it would be very interesting to see whether the same tendency could be inferred from the observations made aboard the Netherlands light-vessels. The routine estimates of the wind force may not have been conducted so carefully as has been done during the special research programme on board the Meerkatze, but by the larger number of observations it should be possible to find a similar tendency, if the effect existed to a noticeable extent also in the air layer up to 7 m above sea level (i.e. the height of the anemometers on the Netherlands light-vessels).

Therefore, a similar investigation has been carried out using the observations of the Terschellingerbank only, since this light-vessel lies furthest from the coast. In order to eliminate as far as possible the disturbing effects, due to the vicinity of the coast, only the observations with onshore winds were taken. From the 1366 observations made (nearly twice the number used by Roll) also nine equivalency-curves were determined, each of them referring to definite intervals of $\triangle T$. Though the same intervals of $\triangle T$ were adopted, this does not necessarily mean that the equivalency-curves refer also to the degrees of air stability indicated by the Meerkatze measurements, since on the Terschellingerbank the air temperature was measured in the usual way on deck with a psychrometer at a height of approximately 3 m above the sea surface.

This small discrepancy, however, has no influence on the final result, for the mean curves did not show any systematical differences of the corresponding equivalents at unstable and stable conditions. The equivalent velocities derived from the mean curves are represented in table 9.

These figures show that on the average and within the limits of accuracy, the wind velocity measured at a height of 7 m is directly representative of the estimated wind force at sea. At higher exposures of the anemometer the thermal structure of the air influences the readings to a noticeable extent. In a warm air mass the more rapid increase of the wind velocity with height will yield

TABLE 9

Terschellingerbank; Equivalents in m/sec

ΔT (°C)	Beaufort numbers									Number of observations
	0	1	2	3	4	5	6	7	8	
⩽—4.1	0	2.5	6.9	11.6	17.4					17
—4.0 to —2.1	0	2.5	6.0	10.8	15.7	20.0	24.0	28.0	30.5	186
—2.0 to —1.1	0	2.0	5.4	10.6	15.6	19.8	23.8	27.8	31.1	316
—1.0 to —0.6	0	2.0	6.1	10.7	15.6	20.0	24.0	27.2	30.2	204
—0.5 to —0.1	0	3.0	6.8	10.8	15.3	19.6	23.7	27.8		179
0.0 to +0.4	0	2.4	6.5	11.4	16.0	20.0	23.6	27.0	30.1	192
+0.5 to +0.9	0	2.0	6.2	11.2	16.0	20.4	24.4	28.0	30.8	121
+1.0 to +1.4	0	2.2	6.0	10.8	15.7	19.3	23.0	26.0	28.7	86
⩾+1.5	0	2.3	6.2	10.9	16.0	19.9	23.7	26.9		65
									Total	1366

comparatively higher values for the equivalent velocities; according to the measurements on the Meerkatze the mean difference of the corresponding equivalents, determined in an unstable and a stable air layer respectively, may amount at a height of 20 m above sea level to about 1 m/sec.

Reconsidering the equivalents of the German light-vessels it may be assumed on account of the frequency distribution of the ΔT-values in the Dutch coastal area, that the majority of the observations at the German light-vessels are related to a cold air mass. Therefore a transformation of the equivalents to a condition of indifferent stability will enlarge the German values to some extent, while a similar transformation will not affect the Netherlands results. A slight increase of 0.5 m/sec, which could be quite possible according to the findings of Roll, will be enough to bring both the German and the Netherlands series of equivalents into closer correspondence with respect to the different exposures of the anemometers (see table 10).

TABLE 10

Comparison between the equivalent velocities in m/sec on the Netherlands and German light-vessels

Beaufort number	1	2	3	4	5	6	7
Neth. equivalent velocities	1.0	3.0	5.8	7.9	10.2	12.3	14.3
German equivalent velocities	2.9	4.5	6.1	7.8	9.9	12.1	14.1
Difference	—1.9	—1.5	—0.3	+0.1	+0.3	+0.2	+0.2

1.8. Concluding remarks

With regard to the different behaviour of the German and Netherlands equivalent velocities at the lower wind forces the question arises which one of the two sets is to be regarded as normally acceptable. In this respect we must follow the international agreement on a measuring height of 10 m above sea level. Assuming the differences between both sets are exclusively due to a difference of the mounting of the anemometers and also assuming a logarithmic vertical wind velocity-profile, we are able to deduce from both sets the equivalent wind velocities, valid for a height at 10 m above sea level. The resulting equivalents for 1 and 2 *B* are 1.3 and 3.2 m/sec respectively. For the higher wind forces the correction seems irrelevant.

Finally in table 11 the equivalents in knots are shown for both the Netherlands light-vessels. The mean series may be considered to refer approximately to the standard height of 10 m; to this purpose the observed velocities at 1 and 2 *B* have been converted in the way described.

TABLE 11

Netherlands equivalents in knots

Beaufort number	0	1	2	3	4	5	6	7	8
Texel (7 meter)	—	1.6	5.8	10.9	15.3	20.1	24.0	28.0	(32.8)
Tersch.bank (7 meter)	—	2.5	6.0	11.5	15.6	19.7	24.0	26.9	(32.8)
Mean (about 10 meter)	—	2.5	6.3	11.2	15.4	19.9	24.0	27.8	(32.8)

It is to be noted here, that the mean equivalents correspond rather well with the values derived by Roll for an indifferent atmosphere ($\triangle T = 0$), taking into account the tendency of finding a larger equivalent velocity for light airs and breezes at ships under way compared to the determinations at anchored vessels. In great contrast to the three closely corresponding determinations discussed so far, stands the essentially different international series. Can it be that the observers to day have a different evaluation of the Beaufort numbers? It is hardly conceivable; therefore in order to find an explanation for this phenomenon the origin of the international equivalents will be discussed in some detail.

2. THE ORIGIN OF THE INTERNATIONAL EQUIVALENTS

2.1. Historical notes

In the beginning of this century several equivalent series were in use; in some cases the values differed considerably. About 1913 two series had survived and had come in to general use: firstly the so-called Seewarte series, constructed by W. Köppen in 1898 out of a number of original sets derived from observations made respectively on board ship and at English, Norwegian and German coastal stations; secondly the so-called Met. Office series, which had been drafted by G. C. Simpson in 1906 from observations at English coastal and inland stations and which with a modification, had been officially adopted by the Meteorological Office in London. Gradually the Seewarte series found its way to most of the other countries of the continent, while the Met. Office series was accepted also by Russia in 1915. Both series are presented in table 12.

TABLE 12

Equivalent velocities in m/sec

Beaufort	0	1	2	3	4	5	6	7	8	9	10
Seewarte	0	1.7	3.1	4.8	6.7	8.8	10.7	12.9	15.4	18.0	21.0
Met. Office	0	0.8	2.4	4.3	6.7	9.4	12.3	15.5	18.9	22.6	26.4

Measuring by two standards presented a very unsatisfactory situation in synoptic meteorology, for owing to the rapid development in telegraphic communication, this new science was at that time already organized on a scale of wide-spread international cooperation. Hence a sub-commission was set up in 1912 by the "International Commission for Weather Telegraphy" to investigate the problem. This sub-commission, to which amongst others Professor Köppen had been selected, submitted in 1913 to the "International Meteorological Committee" (IMC) a report, which after lengthy discussions was not accepted, mainly because at the higher Beaufort numbers the equivalent velocity ranges had been made into overlapping intervals. The matter was referred to the sub-commission for further investigation. World War I, however, interrupted this attempt to arrive at an agreement and it was not before 1921, that the IMC accepted a resolution by which Dr. G. C. Simpson was asked to investigate the problem in order to find a satisfactory solution. Simpson's proposal (1926), compromising both his and Köppen's equivalent series, was finally accepted without alteration in the session of the IMC at Vienna in 1926.

To understand the significance of the resolution for the further development of the Beaufort equivalents, it must be realized that in those days the problem had a somewhat different nature than it has today. Though originally the scale of Admiral Beaufort was a measure for the estimated wind force at sea, the Beaufort numbers were gradually being used as a general indication for the wind forces on land too. Some agreement therefore had to be made in order to match the "terrestrial" scale to its "marine" counterpart. Especially so, after the Beaufort indication for the wind was prescribed in coded telegrams, a measure, which implied the necessity for an equal interpretation of the respective Beaufort numbers in all countries and also between land and sea observations.

By the time that the Met. Office and the Seewarte series came into use, at most land stations the wind velocity was being measured with anemometers. For the coded telegrams the velocities had to be converted into numbers of the general Beaufort scale and for this purpose it did not really matter, whether the exact equivalent wind force, which would have been estimated at sea under the same circumstances, was obtained. The general scale for the wind force is an abstraction and for that matter it need not relate to a specific case, in the same way as the original marine scale. For practical purposes, however, a close relationship between both scales is highly recommendable, though it should be remembered that it will never be possible to make the scales wholly identical because of the different nature of the wind at sea and on land.

In constructing the Seewarte series Köppen tried to obtain the best equivalents for estimates at sea, while the Met. Office series had a more intermediate character, being derived from both land and sea observations. With the derivation of the international equivalents in 1926 Simpson had the abstracted Beaufort scale of the wind force in mind.

Concluding that the difference between the Met. Office and Seewarte series was mainly to be ascribed to a difference in the exposure of the anemometers, Simpson recommended in 1926 a mean series, which he obtained by averaging his and Köppen's series in a rather special way and which would be generally acceptable for conversion of the anemometer readings, at an exposure of 6 m, into Beaufort numbers.

His final conclusion is worthwhile being cited here, since it is still of significance nowadays.

> "In conclusion, it should be emphasized that the suggested code is not an attempt to determine the true velocity equivalents of the Beaufort scale. The latter cannot be done without taking into account the exposure of the anemometer. The way is, therefore, still open for further work in finding a better relationship between Beaufort estimates and anemometer readings than that yet reached by the Meteorological Office and the Seewarte."

In 1946 the IMC accepted a resolution at Paris, by which, on the suggestion of the Meteorological Office in London, the former Met. Office series were to replace the equivalents agreed upon in 1926. The background of this resolution was the recommendation that the standard height, for which the surface wind speed is given in coded reports, should be increased from 6 m to 10 m.

This resolution did not change the situation essentially. Being merely a consequence of Simpson's conclusions it meant another evaluation of the abstracted Beaufort scale.

In maritime meteorology the shortcomings of both the international equivalents of 1926 and 1946 were felt in connection with theoretical work and several new estimations have been made on board ship, mainly by German investigators. Some of these resulted in the Seeskala, published by H. Seilkopf in 1939. Most countries, however, used the international scales when converting the estimates at sea into wind velocities, mainly because a satisfactory solution to this problem had not yet been found.

In 1949 the situation in respect to the general usage of the Beaufort equivalents, was changed radically. According to a resolution, adopted at the Directors Conference at Washington in 1947, the Beaufort numbers were abandoned in coded reports and replaced by wind velocities in knots. As a result of this the estimates at sea were generally to be converted into wind velocities in knots. The problem of finding the best equivalents for the estimates of the wind force at sea became relevant also in synoptic meteorology. In connection with the altered situation another resolution was adopted by which further research into the true equivalent velocities at sea was recommended. Up till today, however, no satisfactory general solution has been obtained.

Before discussing the former Met. Office series – the present international scale – a short survey will be given on the construction of the Seewarte series, being the alternative scale before 1926.

2.2. The Seewarte series

Whilst composing the Seewarte series Köppen has dedicated a thorough discussion to the true value of the then existing equivalent series. His article gives a good impression of the many difficulties which were met in the attempt to bring the various earlier measurements together in one corresponding relation. It was Köppen's great merit that by his minute research he elucidated many factors which influence the determination of the velocity equivalents. Consequently he succeeded in correcting many results obtained earlier by his contemporaries. Especially the data from coastal stations were difficult to analyse, since the equivalent values invariably were derived afterwards from long existing, heterogeneous, observational material. The original material to which Köppen had access was rearranged by him, leaving the unreliable observations out. In other cases the original reports were scrutinized and by applying several corrections most of the disturbing factors were eliminated. One of the corrections referred to the anemometer constants, which at the time of the earlier measurements had been known unsufficiently. Köppen also disputed rightly the method used for averaging the data. Originally the measurements were averaged for every Beaufort gradation of the estimates; Köppen on the other hand showed that the estimates, being the greater variables, had to be averaged over intervals of the measured wind velocities. The superiority of his advocated method of averaging was also clearly demonstrated by a statistical investigation by R. H. Curtiss (1897). At Köppen's request some investigators revised their original results.

Finally Köppen obtained 11 basic sets of equivalents which he divided into four groups. The first group consisted of observations made at sea, the second group comprised the observations made at German coastal stations. The other groups contained miscellaneous material. The sets in each group were averaged into mean series, some sets being taken with a multifold weight. By averaging these four mean series with equal weight Köppen obtained the "Seewarte series".

One of Simpson's objections to the generality of this series was that the increase of the successive equivalent velocities was not a regular one. Some of the 11 basic sets only referred to wind forces up to 6 *B*, others started from 6 *B* onwards. Consequently the mean series showed a rather discontinuous jump at the transition from 5 to 6 *B*.

The height of the anemometers above the surrounding obstacles varied with the basic experiments from 1 to 10 meters.

2.3. The Met. Office series

Simpson's original series is also constructed from rather heterogeneous observations. In contrast to Köppen's series two of the five basic sets were drafted from observations at inland stations, i.e. at North Shields and Oxford. Here for instance the wind force had also been estimated from the rotation speed of the anemometer cups. Also at Holyhead the estimates referred normally to the appearance of certain objects on land; only when the wind force surpassed 5 *B* the observer went out to the shore to base his estimates on the appearance of the sea surface. The other two sets were derived from observations at Scilly and Yarmouth. R. H. Curtiss found that the estimates at these stations depended to a certain extent also on the wind direction; for instance a comparison of the estimates from Yarmouth with those from the light-vessel St. Nicholas Gat, about two miles away, showed that with westerly winds there was no difference in the estimates, while with easterly winds at Yarmouth the wind was underestimated by about one Beaufort number in respect to the observations from the light-vessel. Also at other coastal stations a certain dependence of the estimates on the wind direction has been noticed (see for instance G. Pogade, 1937).

In the following table the five original sets are given, together with the total number of the observations.

TABLE 13

Simpson's equivalents in m/sec

Beaufort numbers	1	2	3	4	5	6	7	8	9	10
Scilly	1.0	2.1	3.7	6.0	8.9	12.3	15.6	19.2	22.6	25.5
Yarmouth	0.6	1.6	3.6	5.8	8.9	12.3	15.6	19.0	22.3	—
Holyhead	2.2	4.5	6.7	8.2	10.1	11.8	14.1	17.9	22.8	—
North Shields	1.0	2.9	6.7	10.3	13.4	15.4	17.2	19.0	—	—
Oxford	1.1	3.4	6.0	8.5	10.7	12.1	13.6	15.7	—	—
Mean	0.9	2.7	4.7	7.2	9.8	12.5	15.4	18.8	22.4	26.4
Total number of obs.	1888	3288	3759	2306	1202	588	357	170	19	6

The mean values have been obtained "by putting the observations from the five stations together and treating the whole as the result from one place"; the estimates were averaged according to the method Köppen had recommended.

Before coming officially into use the mean values had been smoothed by a mean curve, based on the formula: $v = 0.836\, B^{3/2}$ m/sec in which $v =$ velocity in m/sec and B the Beaufort number. This curve had been drawn mainly to fit the equivalent values at the higher wind forces; it shows a consistent deviation from the empirical values in the range from 1 to 6 B despite the larger number of the observations at these forces. Some discussions on the smoothing formula seem to show that in those years some importance has been attached to the simple figure of 3/2 as an exponent. Some suggestions were made as to whether this figure could be linked with a law connecting the wind velocity v with the true wind force W on objects. Apart from the fact that the underlying heterogeneous observations are not very suitable for deducing such a relationship, for these theoretical deductions one should also know something about the functional relationship $W = f(B)$, if such a function could be derived at all. The only condition one may impose on an equivalent series is the regularity of the differences between the successive values and with most empirical sets of equivalent velocities it appears that for a first and simple approximation a power formula, such as has been used by the Met. Office, can be adopted for smoothing the small statistical deviations. But as long as the function $W = f(B)$ is not known in all instances, the constants appearing in one analytical expression are as good as those appearing in another.

2.4. Discussion on the validity of the Met. Office series constituting the present international scale

The mean curve adopted by the Meteorological Office has been used for extrapolating the equivalent velocities to wind forces higher than 10 B. For this purpose, however, it is important that the mean curve approximates the empirical values in the whole range of the scale. For the sake of the argument we have constructed another analytical curve, based on the formula $v = 1.02\,B^{1.40}$ m/sec, which answers better to this condition. A comparison with the officially adopted formula shows that the latter tends to exaggerate the span between the equivalents at both ends of the scale.

TABLE 14

Approximating equivalent velocities in m/sec

Beaufort	1	2	3	4	5	6	7	8	9	10	11
Simpson, mean	0.9	2.7	4.7	7.2	9.8	12.5	15.4	18.8	22.4	26.4	
I: $v = 0.836\,B^{3/2}$	0.8	2.4	4.3	6.7	9.4	12.3	15.5	18.9	22.6	26.4	30.5
II: $v = 1.02\,B^{1.40}$	1.0	2.7	4.8	7.1	9.7	12.5	15.5	18.8	22.1	25.6	29.3

This correction, however, is not very important in itself. It only serves to eliminate the exaggerating effect, introduced by the officially adopted formula. Köppen (1926) has also pointed to this effect.

The possible explanation why the Met. Office values differ from practically all other equivalency sets must be sought elsewhere. The main cause cannot be a difference in exposure of the anemometers, like Simpson (1926) stated in respect to a comparison between his and Köppen's results. Simpson checked his statement by comparing the corresponding equivalents at 8 B only. Using Hellmann's empirical formula for the increase of the wind velocity with height, he found that the resulting corresponding exposures of the anemometers agreed rather well with the actual situation. Simpson agreed, however, that he could not find an appropriate explanation for the larger values of the Seewarte at the lower wind forces.

It will be shown next, that also at the higher wind forces the situation is more complicated. Some experiments have been made indicating that the proportional factors between wind velocities at different heights vary with the wind velocity itself. C. Braak (1929) has derived some factors from measurements made by Lako (Gelderse Vallei, 1908) and by Köppen (radio-masts Eilvese near Hannover, 1915), giving the ratio between the wind velocity at 10 m to the velocity at 6 m. He found a decrease in the ratios from 1.08 at 2 m/sec to 1.04 at 20 m/sec. These results agree with those found by Roll (1951) and mentioned in chapter 1, i.e. that the relative increase of the velocity with height becomes smaller with increasing wind speed. The ratios between Simpson's equivalents to the corresponding values of the Seewarte increase with the wind force in the whole range of the Beaufort scale, indicating the more complicated character of the difference between both equivalent series.

In considering the five basic sets, tabulated in table 11, we note a striking difference between the sets from Scilly and Yarmouth on one hand and the other three sets on the other hand. The first two sets have much smaller equivalent values in the lower range of the Beaufort scale up to 5 *B*. As to the possible cause of this feature we can only speculate; in this respect it may be noted here that other determinations from the observations from Scilly and Yarmouth (made by Curtiss, 1897) show larger equivalent values at these Beaufort numbers.

The descriptions of the local situation at the five stations indicate that, for each station, the free exposure of the anemometer above sea level and above the surrounding grounds, the structure of the wind from the various wind directions and the estimating technique were different to such an extent, that it may be questioned here, whether Simpson was right in averaging the results in the way he did, i.e. "in treating all the estimates as though they had been made at the same place and by the same observer". In our opinion it would have been better to take only the simultaneous estimates and anemometer readings together, which refer to the same local wind conditions.

Consequently a better mean will be obtained by averaging the corresponding mean equivalent velocities from the five stations arithmetically; moreover, in this way a series is obtained, which does not show, like Simpson's series does, the predominant influence of the estimates by the one observer at Scilly (and to a smaller extent by the one at Yarmouth). The fact is that, at the Beaufort numbers 4 and higher, the Scilly and Yarmouth observations outnumber those from the other stations to a large degree.

The objection to the predominant influence of one observer in the whole series of equivalents led Köppen in 1926 to the same corrected method of averaging the five basic sets. Köppen also corrected the values for, what he calls, the omission of the frictional constant in the English anemometer formula. This correction would amount to 0.6 or even 0.9 m/sec at all wind forces. By the frictional constant Köppen could not have meant the influence of the material friction in the rotating parts of the cup-anemometer, for this influence becomes apparent only at wind velocities smaller than about 3 m/sec. Some anemometers with spherical cups, however, show a slightly bended calibration curve, indicating that by the substitution of a linear anemometer formula in these cases some (slight) corrections will be made necessary But Simpson states that at Scilly and Holyhead the readings of the Robinson anemometers showed no material differences with the recording of a Dines pressure tube anemometer, to which they had been compared. Taking these circumstances into account the correction, recommended by Köppen, seems to be of a rather problematical nature, the more so because of the impossibility of its determination even approximately.

In the following table the three equivalent series, discussed so far, are compared; they are the Seewarte series, the Simpson series, corrected by taking the arithmetical mean of the five basic sets and the Netherlands series.

TABLE 15

Beaufort	1	2	3	4	5	6	7	8	9	10
Seewarte	1.7	3.1	4.8	6.7	8.8	10.7	12.9	15.4	18.0	21.0
Simpson, corrected	1.2	2.9	5.3	7.8	10.4	12.8	15.2	18.2	22.6	25.5
Neth. light-vessels	1.0	3.0	5.8	7.9	10.2	12.4	14.4	(16.8)		

In order to investigate whether the differences of the corresponding values are mainly due to differences of exposure of the respective anemometers, we use the following proportional factors, given by Köppen (1926) and resulting from measurements at Nauen and Eilvese:

free exposure:	2 m	4 m	6 m	8 m	10 m	12 m	15 m
factor:	1.00	1.14	1.24	1.31	1.36	1.40	1.46

The ratio between the corresponding equivalents of the first two series is almost constant at the wind forces between 4 and 10 *B*, the small deviations being statistically founded. The mean value of 1.20 of this ratio indicates that, with a mean free exposure of the English anemometers at a height of 12 m, the resulting mean free exposure of the anemometers used by the Seewarte amounts to a height of 4 m. These values are the same Simpson obtained when comparing the equivalents at 8 *B* only, but with the corrected series the ratios agree much better with each other at the various wind forces.

The ratios between the corresponding Netherlands and Seewarte equivalents decrease with the higher numbers from 3 *B* onwards; this feature corresponds with the experimental results of Braak and Roll. Establishing the free exposure of the Seewarte anemometers at a height of 4 m, from these ratios it follows that the resulting free exposures at the Netherlands light-vessels would amount to a height of 8 m, Since the actual height of the anemometers on the Netherlands vessels amounted to 7 m, the result may be called very satisfactory.

There is not much point in carrying this investigation on to the lower wind forces, since the statistical errors in these mean equivalents influence the proportional factors too much. Moreover the whole result obtained so far is rather surprising, considering the complexity of the Seewarte and the Simpson series.

Thus, the discrepancy between the former Met. office series and the Seewarte values on one hand, and the present international scale and the Netherlands results on the other hand is solved to a satisfactory degree.

In the next chapter the corrected series of Simpson will be used together with other determinations to construct a set of new equivalent velocities valid for observations at sea. In doing so it is fully realised that, strictly speaking, the English equivalents cannot be considered representative for sea observations only, since they are based also on observations from inland stations. The estimates made at these stations are of an entirely different nature, though they yield, together with the observations at the three coastal stations, equivalent values which do not differ materially from the Netherlands results at wind forces up to 7 *B*.

Series, however, which extend up to 10 *B* or even further are rare and since the equivalent velocities at 9 and 10 *B* are based on the coastal observations only, these values make a welcome contribution to the final mean set of equivalents. But the admission of the equivalents implies the inclusion of the whole series in order to avoid irregularities in the final mean result. Thanks to the "convenient" equality (reasoned in the same strict sense) of the equivalents at the lower forces with other determinations made on board ship, the inclusion of the whole series seems fully justified.

3. EQUIVALENT WIND VELOCITIES VALID FOR OBSERVATIONS AT SEA

3.1. Original determinations

In 1939 H. Seilkopf published a mean set of equivalent velocities – the "Seeskala" – meant for use at sea and composed of several original determinations made on board ship. One of these originated from observations at the German light-vessel Borkumriff; the resulting equivalent velocities, however, appear to be exceptionally high with respect to all other determinations known. In consequence of this the Seeskala values are also rather large at the lower and moderate wind forces.

In the present study, use will be made also of the original sets considered by Seilkopf, except, however, the Borkumriff values. Since the circumstances with regard to measuring are not known, these equivalents cannot be evaluated to their real merit. It is thought advisable, therefore, to replace them by the recent determinations on board German light-vessels, which have been kindly communicated to the author by Dr. J. Richter of the Seewetteramt and which have been discussed in some detail in chapter 1.

In table 16 several old and new determinations have been put together. Some of the circumstances concerned in the measuring will be reviewed briefly, and for a more comprehensive study reference will be made to the original publications.

The first series, representing the corrected equivalent velocities of Simpson, has been discussed in detail in chapter 2.

Both the following series contributed to the former Seewarte equivalents. The first originated from observations made on the Gazelle during a cruise for scientific purposes in the years 1874–1876, which took her into all oceans. The Gazelle was a large sailing ship of the type specified by Beaufort; since the conditions described by Beaufort could be controlled by the ship itself the estimates are of particular value. For the determination of the wind velocity a hand-anemometer was used; the readings with this instrument are likely to be lower than those obtained with a more fully exposed anemometer on the mast. From a choice of the most reliable observations Krümmel (see Köppen, 1898) drafted equivalent velocities, which for the Beaufort numbers 1–4, had been inferred from observations made while the ship was lying still. These equivalents are given here.

The other series was drafted by F. Waldo in 1888 from observations, made on the s.s. Ohio while crossing the Atlantic Ocean in 1882. Three anemometers were used, but for the computation, only the readings from the one on top of the wheelhouse (9 m above sea level) and the one on the main mast (26 m) had been taken. The original equivalents were recomputed later at Köppen's request.

In 1914 P. H. Gallé made comparative observations on two crossings over the Atlantic Ocean. On the first voyage the anemometer was erected 12 m above sea level, on the second one the exposure was brought down to 7 m. From both determinations Gallé computed one mean series of equivalent wind velocities.

During the well-known Meteor expedition in 1925–1927 (E. Kuhlbrodt 1936), the estimates of the wind force were compared with readings of an anemometer at 32 m above sea level. Because of the high exposure of the anemometer the resulting equivalent velocities computed from the observations made in the tropical seas, have been reduced by 0.5 m/sec, while those, referring to the higher Southern latitudes have been reduced by 1.0 m/sec [1]). From the observations it was found that, coming from the tropical zone with generally light winds, on entering the region with the strong Westerlies in the Southern Atlantic the wind was usually underestimated at first. This feature indicates clearly the subjectivity of the estimates with regard to the observers getting accustomed to certain climatological conditions. Kuhlbrodt points to the generality of this effect. The introduction of the Petersen-scale in 1947, however, tends to reduce the subjectivity of the estimates a great deal, but the influence of climate on human nature can never be wholly cancelled out.

H. Regula (1937) reports of investigations carried out on the Schwabenland in 1936 and on the Friesenland in 1937. Here the estimates have been compared with anemometer readings at heights of 35 m and 40 m respectively; at the Friesenland a distinction is made between the observations in a cold and in a warm air mass. The latter gave rise to comparatively higher values for the resulting equivalent velocities. Regula computed mean equivalents from these observations by averaging the corresponding values for a stable and an unstable air mass with equal weight. In table 16 the mean result of both the Schwabenland and Friesenland observations are given; the values have been reduced by Regula by 0.3 m/sec [1]).

Both the last two series of table 16 have been discussed in chapter 1; the equivalent velocities for the Beaufort numbers 1 and 2 have been reduced to a reference height of 10 m above sea level according to a method described in 1.7.

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[1]) The application of a constant reduction for all wind forces does not agree with the empirically founded conception, that the velocity-height-profile varies with the wind velocity itself. Too little is known, however, about the form of this profile above the sea surface under the varying circumstances; therefore, for a first approximation a constant reductional factor for all wind forces will suffice, considering the accuracy of the mean equivalents, which is of about the same order of magnitude.

3.2. The final mean series of Beaufort equivalents

The essential data needed for a final discussion, are compiled in table 16. From the original determinations a mean series has been computed by averaging the corresponding equivalents arithmetically. The values in brackets, which have been considered unreliable by the respective authors, have not been used in the averaging process.

The equivalent velocities for force 1 *B*, derived on board ships under way, show consistently larger values than those, derived at the anchored light-vessels and the coastal stations. The main cause for the discrepancy will be the comparatively large degree of inaccuracy, with which the true velocity of these light airs can be computed on a ship that is moving. Since the statistical deviations are limited to one side only – i.e. to zero wind velocity – the mean value is likely to become larger than the "true" equivalent velocity. For a first approximation the equivalents from vessels under way have not been included, therefore, in the mean value.

On the Meerkatze the equivalent velocity for force 1 *B* was found to be 1.8 m/sec for an atmosphere with indifferent stability and 1.5 m/sec for unstable conditions. According to Roll special care was taken with the computation of the true wind velocity on board this vessel. Taking this into consideration these smaller values seem to confirm the reasoning given in the explanation of the observed discrepancy. It also follows that the adopted mean of 1.5 m/sec will be not far from the exact value.

Considering all the effects, which may influence the determination of mean equivalent velocities, the individual sets show a remarkable coincidence, notwithstanding the large number of years between the successive determinations. This feature demonstrates clearly that the general evaluation of the wind force at sea has not changed during all those years despite the changes of marine transport and the accompanying changes of specification of the Beaufort numbers. In this connection we may refer to the quotation at the beginning of this paper, where Simpson vividly describes the real background of the Beaufort scale.

The systematical differences between the original sets are due to a cooperation of many factors, like for instance the differences of exposure of the anemometers used, the air stability, the influence of a changing of the climatological conditions on the estimates and the number of observers taking place in the experiment. Because of the complexity of these influences no attempt will be made here to relate in general the observed differences to definite causes.

Up to 6 *B* the mean equivalents are accurate to a satisfactory degree; at the higher wind forces the accuracy decreases gradually until with strong gales and storms the equivalent velocities become rather uncertain. It is not to be expected, however, that within a reasonable number of years sufficient data will become available for a more accurate determination. In order to establish with more confidence the equivalents at the higher wind forces, the series extending to at least 9 B have been extrapolated graphically and together with the extrapolated values new equivalent velocities for the numbers 10 and 11 B have been computed. In the following the corrected values will be adopted.

Additional information on the probable order of magnitude of the limiting equivalent velocity of force 12 was given by Köppen in 1898. On land this scale-number is specified according to the severity of the destruction wrought on houses, trees, etc. On basis of the measured wind velocities and the destruction observed during storms in England and in N.W. Germany Köppen deduced that, on the average, wind force 12 is reached at a wind velocity of 28 m/sec.

The adopted mean series yields for 11.5 B an equivalent velocity of 28.2 m/sec, which agrees well with the figure given by Köppen. From the good agreement between both data, the right order of magnitude of the mean equivalents at the higher wind forces is ascertained.

Although the mean values at the upper end of the scale are based on about half as many data as those in the lower half, in the entire range of the scale the gradation is very regular. The small statistical deviations have been smoothed with help of a mean curve, represented by the formula: $v = 1.51\, B^{1.18}$ m/sec.

It remains to be discussed to which exposure the adopted mean equivalent velocities would correspond, thereby taking into account the variation of the vertical wind velocity-profile with the various conditions of the air stability.

To this purpose the mean equivalents have been compared with the values, which have been deduced by Roll for various stability conditions on the Meerkatze and which correspond to an exposure at 19.3 m (see also table 8). It appears, that for all wind forces concerned the corresponding equivalents are practically identical with the set for an indifferent atmosphere; this set has been reproduced in table 16. Finally, the exposure of the mean series may be determined at a height of 10–15 m.

Thus, a mean series of equivalent velocities has been found, which has the following properties:

a. It has been built up from nine original determinations, made in various parts of the Atlantic Ocean and in some of its adjacent seas under various climatological conditions and over a wide range of years. The individual series are not essentially different, though comparatively small systematical differences occur. These may be attributed to the varying circumstances concerned with the measuring.

b. Up to force 6 the mean equivalents are accurate to a large extent (within 0.2 m/sec); for force 6 and 7 the accuracy is slightly less. From then onwards

TABLE 16

Survey of old and new determinations of the equivalent velocities (in m/sec) to the Beaufort estimates of the wind force at sea

Beaufort number	1	2	3	4	5	6	7	8	9	10	11	Exposure (m)
I. Simpson 1906, corrected	1.2	2.9	5.3	7.8	10.4	12.8	15.2	18.2	22.6	25.5		10—13
II. Krümmel (*Gazelle*; 1874—76)		3.2	4.9	6.8	9.3	11.0	14.1	16.7	19.9	23.4		± 6
III. Waldo (1888)	2.2	3.1	5.4	7.3	10.2	13.3	15.5	17.0	19.2			9 and 26
IV. Gallé (1914)	2.2	3.5	5.5	7.8	10.1	12.2	14.4					7 and 12
V. *Meteor* (tropics) (1925—27) corr. with —0.5 m/sec		3.6	5.6	7.7	9.9	11.9	(13.8)					32
VI. *Meteor* (higher S. Lat.) corr. with —1.0 m/sec		(3.0)	6.5	9.0	11.6	14.4	17.3	20.1	22.5			32
VII. *Schabenland—Friesenland* (1936—37) corr. with —0.3 m/sec	2.6	4.3	6.1	7.9	10.0	11.7	(13.5)					
VIII. *Texel—Tersch.bank* (1951)	1.3[1])	3.2[1])	5.8	7.9	10.2	12.4	14.4	(16.8)				7
IX. German light-vessels (1950)	1.3[1])	3.2[1])	6.1	7.8	9.9	12.1	14.1	16.3	17.9	20.1	25.8	20
Mean	(1.3)[2])	3.4 ±0.15	5.7 ±0.15	7.8 ±0.2	10.2 ±0.2	12.4 ±0.3	15.0 ±0.4	17.7 ±0.7	20.4 ±0.9	23.0 ±1.6	25.8	
Adopted mean $v = 1.51\, B^{1.18}$ m/sec	1.5	3.4	5.6	7.8	10.2	12.6	15.1	17.7	20.4	(23.1) 23.3[3])	(25.8) 26.5[3])	10—15
Meerkatze (1953) Indifferent atm.	1.8	3.7	5.6	7.8	9.9	12.4	(15.0)					19

[1]) Reduced to an exposure at 10 m. [2]) Light-vessels and coastal stations only. [3]) Computed with help of a graphical extrapolation of the series extending to at least 9*B*. The values in brackets of the constituting series have not been used in the averaging process.

the accuracy of the equivalent velocities decreases rapidly; however, they are still of the right order of magnitude as could have been ascertained from an independent investigation by Köppen into the velocity which would be equivalent to the limit of force 12.

c. The gradation is regular throughout the entire scale. Some minor statistical deviations, not exceeding 0.2 m/sec, have been smoothed with help of a mean curve.

d. The equivalents relate to an atmosphere with indifferent stability.

e. The corresponding exposure amounts to 10–15 m above sealevel.

In other words, the new scale possesses the properties required for a standard measure by which the Beaufort estimates at sea are to be converted generally into wind velocities, referring to the air layer at 10–15 m above the sea surface. The error which is introduced when the estimates are made in a stable or in an unstable air mass will probably not be as large as the differences found by Roll, because of the smaller height of the exposures to which the proposed equ valents refer.

It is not to be expected that the mean values will have to be altered in the future by more than 0.1 m/sec for wind forces up to 8 *B*; for the higher wind forces some larger alterations may appear necessary, although probably they will not exceed 1 m/sec at 11 *B*, since the present equivalents have already been found to be of the right order of magnitude. In this respect it is to be remembered that the rather large uncertainty of the estimates of gales and storms sets a lower limit to the accuracy that can ever be obtained .

In table 17 a final survey is given on the adopted mean equivalents together with the velocity limits of the successive Beaufort numbers. With the conversion into knots, the values have been rounded off; the equivalent values in knots are easy to remember for daily use.

This year, 1956, it is the golden anniversary of the international equivalency-scale, being identical with the former Met. office series. In the first 40 years of its existence it has served in Great Britain for the conversion of the measured wind velocities (at an exposure of 10 m and more) into coded Beaufort numbers, then for three years it was used that way internationally and during the last seven years it has been serving as a conversion the other way round, i.e. from the Beaufort estimates at sea into wind velocities in knots.

Having been drafted originally for the purpose of converting the anemometer readings at land stations into the numbers of a scale, which we have called earlier in this paper the "abstracted" Beaufort scale, in their present use the international equivalents can have no more than a provisional significance. Therefore it would be quite a natural consequence of the historical background, if one of these days the international equivalents were to be scrutinized to ascertain their validity for the present conversion.

TABLE 17

Beaufort number	A. *Maritime Conversion Scale* — meters per sec		A. *Maritime Conversion Scale* — n. miles per hour			B. *International* 1946 — n. miles per hour	
	mean	limits	mean [1]		limits	mean	limits
0	0	≤0.6	0		<1	0	<1
1	1.5	0.7— 2.3	3	4×B−1	1— 4	2	1— 3
2	3.4	2.4— 4.4	7	4×B−1	5— 8	5	4— 6
3	5.6	4.5— 6.6	11	4×B−1	9—12	9	7—10
4	7.8	6.7— 8.9	15	4×B−1	13—16	13	11—16
5	10.2	9.0—11.3	19	4×B−1	17—21	18	17—21
6	12.6	11.4—13.8	24	4×B	22—26	24	22—27
7	15.1	13.9—16.4	29	4×B+1	27—31	30	28—33
8	17.7	16.5—19.0	34	4×B+2	32—36	37	34—40
9	20.4	19.1—21.8	39	4×B+3	37—42	44	41—47
10	23.3	21.9—24.8	45	4×B+5	43—48	52	48—55
11	26.5	24.9—28.2	52	4×B+8	49—55	60	56—63
12	—	>28.2	—		>55		>63

Though actually the present investigation has been initiated on account of the erroneous nature of the international values, the resulting proposal for a new set of equivalents, valid for Beaufort estimates made at sea, may be regarded as an answer to the recommendation for further research into the true equivalent velocities as laid down in a resolution of the Directors Conference at Washington in 1947.

The 50th anniversary of the former Meteorological Office series may probably be celebrated no better than by presenting a new series of equivalents like the present one, which comprises the thoughts and the experimental results of many investigators in past and recent times, thus concluding an epoch of basic research.

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[1]) In order to obtain regular intervals also for the scale in knots, the mean equivalent velocity at 5 *B* has been rounded off from 19.8 to 19 knots, thus introducing a small inaccuracy in the conversion from meters per sec to knots.

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