Memorandum

HISKLIM 13

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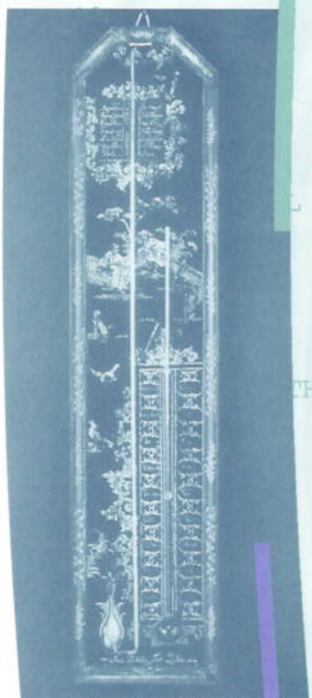
Historical wind speed equivalents of the Beaufort scale, 1850-1950

Hendrik Wallbrink and Frits Koek



De Bilt, 2009

Koninklijk Nederlands Meteorologisch Instituut

KNMI-Memorandum

HISKLIM-13

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The KNMI-program HISKLIM aims at making historical land and sea climate data from Dutch sources physically accessible, with the highest possible time resolution and quality. The program started in 2000 and will run 5 to 10 years.

HISKLIM-1	Het KNMI-programma HISKLIM (HIStorisch KLIMaat) / T. Brandsma, F.B. Koek, H. Wallbrink en G.P. Können. (also KNMI-publication 191)
HISKLIM-2	Gang van zaken 1940-48 rond de 20.000 zoekgeraakte scheepsjournalen / H. Wallbrink en F.B. Koek. (also KNMI-publication 192)
HISKLIM-3	Historische maritieme windschalen tot 1947 / H. Wallbrink en F.B. Koek. (Memorandum)
HISKLIM-4	Onbekende weersymbolen in oude Extract-Journalen (1826-1865). / H. Wallbrink en F.B. Koek. (Memorandum)
HISKLIM-5	CLIWOC, Multilingual Meteorological Dictionary; an English-Spanish-Dutch-French dictionary of wind force terms used by mariners from 1750-1850 (also KNMI-publication 205)
HISKLIM-6	DIGISTAD (DIGitaliseren STADswaterkantoor). H.W. Riepma. (Memorandum)
HISKLIM-7	Parallel air temperature measurements at the KNMI-terrain in De Bilt (the Netherlands) May 2003–April 2005, Interim report. / T. Brandsma. (also KNMI-publication 207)
HISKLIM-8	Hisklim COADS, Final report. / H. Wallbrink and F.B. Koek. (also KNMI-publication 210)
HISKLIM-9	DIGISTAD, Disclosure of the hourly meteorological observations of the Amsterdam City Water Office 1784-1963, Final report. / H. Wallbrink and T. Brandsma. (also KNMI-publication 220)
HISKLIM-10	Report on meteorological observations at Willemstad, Curaçao, during the period 1910-1946. / P.V.J. Girigori (Memorandum)
HISKLIM-11	The US Maury collection metadata 1796-1861. / H. Wallbrink, F.B. Koek and T. Brandsma (also KNMI-publication 225)
HISKLIM-12	Historical maritime wind scales until 1947. / H. Wallbrink and F.B. Koek. (translation and update of Hisklim 3; Memorandum)

Historical Wind Speed Equivalents Of The Beaufort Scale, 1850-1950

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Contents

Introduction

The original Beaufort scale of wind force is a scale that does not present the actual velocity with which the air moves. It is merely a scale of wind conditions that was used by sailors to categorize the different sailing conditions. Over the years, the use of the scale became very popular. Unfortunately, due to the increasing number of types of sailing ships and eventually the arrival of steam boats, exchanging and comparing wind force information became a problem.

Since 1850 many attempts have been made to express the Beaufort scale numbers into physical units by correlating the estimate Beaufort wind force numbers with the measured wind speeds by anemometers. The World Meteorological Organization (WMO) still uses the wind speed equivalents, or WMO Code 1100, of the Beaufort scale adopted in 1946, for operational use (OMI-CMI, 1947). Nowadays it is widely accepted that WMO Code 1100 results in systematic biases when compared to recent anemometer measured winds. Also converting the different anemometer units - i.e. knots or m/s - to Beaufort numbers could lead to unexpected results.

The purpose of this document is to give a historical summary and present metadata to the different equivalent scales developed and used in Europe during the period 1850-1950. The metadata which is often stored very fragmented or is hard to find, is very important to understand old measured wind speed data correctly. Special attention is given to wind speed equivalents used in the Netherlands and to the conversion of the different wind speed units.

Recent equivalent scales developed after 1948, are often officially adopted by the WMO for scientific use, but are not used for operational meteorology. Extensive reviews comparing these scales with the official WMO scale are not discussed in this report but can be found in various other publications (e.g. Verploegh, 1967; Kent and Taylor, 1997; Lindau, 2003).

The Beaufort Wind Force Scale

Initially Commander Francis Beaufort (see Figure a) set up a scale of fourteen wind force categories in 1806. He numbered them from 0 (calm) to 13 (storm) (Garbett, 1926). On 28 December 1838 a slightly modified scale of thirteen wind categories (numbered from 0 to 12) became mandatory for ship logbook entries on all ships and vessels of the British Royal Navy through an Admirality Memorandum by C. Wood (Meteorological Office, 2007). On the British Mercantile Marine fleet the scale was adopted somewhat later. The first Board of Trade publication to mention it was the “Barometer Manual” of 1862 (Garbett, 1926).

Figure a: *A photograph of a 19th century portrait painting of Sir Francis Beaufort (1774-1857). It was copied from the website of the UK National Maritime Museum (www.nmm.ac.uk). The photograph is in the public domain under USA law following the Bridgeman Art Library v. Corel Corp. case*

The Beaufort scale was classified according to the velocity of a full rigged man-of-war (wind forces 2-4), the amount of sail she could carry *in chase, full and by* (wind forces 5-9), or the ship being able to carry few or no sails (wind forces 10-12). In the Netherlands the Beaufort scale became mandatory in 1854 for the use in the Dutch meteorological ship logbook, the so-called *Universeel Extract-Journaal* (Wallbrink and Koek, 2001).

The First Conference on Marine Meteorology in London in 1874 recommended the Beaufort scale for general use in meteorological reports. To include both observations at sea and phenomena on land as criteria, the meeting of the International Meteorological Committee adopted an altered Beaufort scale for international use in weather telegraphy in Utrecht in 1874 (IMC-PC, 1875). Now the Beaufort scale had become the main scale for specifying the force of the wind and was used in many parts all over the world, both on land and at sea.

The Beaufort scale, however, has no reference to the velocity of the wind. The wind speed during e.g. a gale varies from place to place and from time to time between 34 and 40 knots, but Beaufort’s gale seems to be smoother and continues throughout at force 8 (see Figure b).

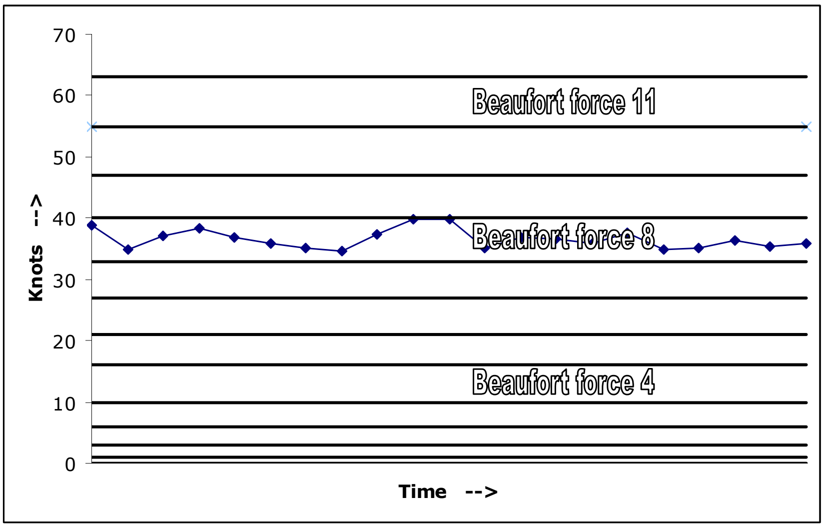

Figure b: *Illustration of the variability in time of the wind speed in relation to the scale of Beaufort*

Wind Speed Equivalents During The 19th Century

After the invention of the Robinson anemometer in 1846, a widespread introduction of anemometers at coastal and inland weather stations took place. At sea, however, on board full rigged ships, anemometers were rarely used. It was discovered that the anemometer measured a higher wind speed when sailing against the wind rather than sailing with the wind (Harding, 1885; Köppen, 1885 and 1897). It turned out that it was not possible to measure proper wind speeds with an anemometer anywhere on a fully rigged ship (Ramage, 1982).

At the Meteorological Conference held in Leipzig in August 1872, the question was raised:

> "What scale should be employed for the force of the wind when it is not determined by actual measurement but only by estimation?"

The reply of a sub-commission which dealt with the question was:

> "The scale of 4 for wind is insufficient according to the experience which has been gained; that of 10, on the contrary, gives too minute distinctions which allow too great latitude for choice when the wind is simply estimated, and therefore the scale of 6 is to be recommended. It is already introduced in large systems of observations, and presents at the same time the advantage of easy reduction of the Beaufort's scale, which will soon come to be adopted generally at sea. ... In agreement with the unit which is taken in all physical works, the velocities should be given in Metres per Second." (MC, 1873)

About twenty years later, at the International Meteorological Conference in Munich in 1891, it was decided:

> "That it is desirable to publish wind velocities in metres per second. The values may be obtained from the instrumental indications by means of a formula of reduction of which the constants have been determined either directly or indirectly." (IMC, 1893)

The Robinson Anemometer

For an anemometer of standard dimensions (9-inch cups with 2-foot arms; see Figure c) originally a factor 3.0 was adopted to convert the *running of the cups* to the *run of the wind*, i.e. the cups will always move with one-third of the velocity of the wind. Although some experiments were done with a whirling machine, the factor was mainly based on theoretical grounds (Robinson, 1855).

- In Japan a factor 3.0 was determined from records taken with an anemometer mounted on a locomotive. The value of 3.0 was in use in Japan until the end of 1924 (IMO-CSWI, 1927, p. 100).

- W.H. Dines set up pressure-tube anemographs alongside the Robinson anemographs and made comparisons between the hourly means of the actual wind speeds of the two instruments. A factor of 2.2 was found for the value of the Robinson factor for all velocities that were observed in the experiment (IMO-CSWI, 1927, p. 100).
- W. Ooisi and later R. Sekiguchi obtained small values (2.1) for the Robinson factor. W. Ooisi compared the velocity of the wind recorded with the Robinson anemograph with the velocity of a pilot balloon which flew in about the same level (IMO-CSWI, 1927, p. 100).
- Also experiments done by Gallé in 1914 on board Dutch steam ships while travelling across the ocean, showed that in practice the factor differed between 2.2 and 2.5 (Gallé, 1915).

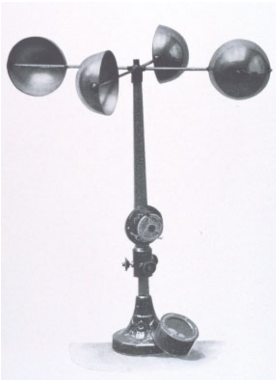

Figure c: *The Robinson anemometer. In: The Aims and Methods of Meteorological Work by Cleveland Abbe. In: Maryland Weather Service, Johns Hopkins Press, Baltimore, 1899. Volume I, p. 316. Image ID: wea00920, NOAA's National Weather Service Collection*

According to G.C. Simpson a factor of 3.0 is certainly too high.

> "It is clear that the factor for each instrument must depend on the state of lubrication and also on the accuracy of the manufacture of the mechanism." (Simpson, 1906)

Also the turbulent airflow plays an important role in explaining the difference between the above-mentioned factors (IMO-CSWI, 1927, p. 100).

Wind Speed Equivalents Used At The End Of The 19th Century

At the end of the 19th century there was already a great diversity of wind scales in use amongst meteorologists in different countries. The range of the wind velocity was indicated in different scales, ranging from 5 up to 13 numbers. During the period 1845-1894 more than 30 different scales were published and it is very difficult, if not impossible, to make any reliable comparison between them (Curtis, 1897). According to Curtis only three of them, R.H. Scott, A. Sprung and G. Chatterton, (Scott, 1875; Sprung, 1879; Chatterton, 1887) made serious attempts to determine the relation between the estimated wind forces and the velocity of the wind speed as measured by an anemometer (Curtis, 1897).

The values of Scott were mainly based on four months observations, made at the British coastal station in Holyhead during 1860-1870. They were augmented by observations made at the coastal station in Yarmouth, covering a further period of three months. The number of observations used for the comparison was small; for Yarmouth it was 605 and for Holyhead only 433. At that time the accuracy of the Robinson anemometer, with a factor 3.0, was almost unquestioned. However, the correct factor for the standard size instrument was certainly not known (Curtis, 1897).

Sprung's comparison was made with anemometer results from four different stations in northern Germany for the years 1876-1878. It comprised of a total of 3594 observations. Sprung corrected his anemometer results with a factor 2.396, which he found to be the proper factor for the instruments (Sprung, 1879).

Chatterton used anemometer values from three British coastal stations: Holyhead, Falmouth and Yarmouth, for the year 1881. The Holyhead values were compared with estimated wind forces observed at the South Stack lighthouse and at the Carnarvon Bay (or Caernarfon Bay) lightship. The Falmouth values were compared with estimated wind forces recorded at six lightships moored at various distances off the Norfolk coast. Chatterton concluded that the values derived from the comparisons between Holyhead and the Carnarvon Bay lightship, were "probably the most reliable of all" (Chatterton, 1887).

Beaufort Number	Scott, 1874	Sprung, 1879	Chatterton, 1887	Waldo, s.s. Ohio, 1882	Krümmel, Bark Gazelle, 1874-1876	Curtis, 1897	
	Statute miles per hour	Metres per Second	mph	m/s	m/s	mph	m/s
0	0 – 5	2.64	4.9			2	0.9
1	6 – 10	3.99	6.5	2.2		4	1.8
2	11 – 15	5.34	7.8	3.1	3.2	7	3.1
3	16 – 20	6.70	11.6	5.4	4.9	10	4.5
4	21 – 25	8.05	17.0	7.3	6.8	14	6.3
5	26 – 30	9.41	22.9	10.2	9.3	19	8.5
6	31 – 36	10.76	28.3	13.3	11.0	25	11.2
7	37 – 44	12.11	35.4	15.5	14.1	31	13.9
8	45 – 52		41.6	17.0	16.7	37	16.5
9	53 – 60		46.0	19.2	19.9	44	19.7
10	61 – 69		52.1		23.4	53	23.7
11	70 – 80					64	28.6
12	≥ 80					77	34.4

Table 1: *Some 19th century examples of "reliable" wind speed equivalent scales (Curtis, 1897)*

The Curtis Series

In 1897, R.H. Curtis of the Observatory Branch of the London Meteorological Office published a paper that showed the results of an extensive investigation into the relation between the Beaufort numbers and the velocity of the wind measured by anemometers (see Table 1). The data were obtained from the British coastal stations at Yarmouth, Scilly, Fleetwood and Holyhead. No ship observations were involved. The data consisted of estimates of the wind force made by observers for the "Daily Weather Report" and the corresponding hourly velocities of the wind obtained from anemometers situated at the respective stations. The main problem at that time seemed to be the determination of suitable anemometer constants and not the exposure of the instruments (Curtis, 1897).

The Seewarte Series

Around the same time, in 1898 the Russian/German professor Wladimir Köppen (see Figure d) constructed an equivalent scale derived from four independent sets (Groups) of observations made on board ships and at British, Norwegian and German coastal stations (Köppen, 1898).

Figure d: *Wladimir Peter Köppen (1846-1940); source: unpublished collections at UB Graz*

Under "Ocean" Group I Köppen included four sets of comparisons made by sailors on board ships. The first set was made during 1874-1876, on board of the steam/sailing ship *Gazelle*. The second set was made on the *Elizabeth* during four heavy storms in 1877. Two, when she was at anchor in Yokohama and two while she was at sea. The third set was a small number of observations made by F. Waldo in 1882 on board of the American North Atlantic Liner *Ohio* (Waldo, 1888). A fourth small set of observations was made on the steamer *National* during 1889. By far the most important series was the first set, made on board the *Gazelle*. Köppen gave four times the weight to this set when working out the results.

However the *Gazelle* was equipped with a steam engine, the *Gazelle* was a large sailing ship of the type described by Beaufort. During the years 1874-1876 she made a scientific cruise which took her to all oceans. In the process of reducing the number of observations, only those observations were used that were made when the ship was sailing as described by the Beaufort scale. There can be no doubt that these estimates were as nearly perfect as they could have been. The exposure of the anemometer, however, was far from satisfactory; it was held by an observer on the weather side of the ship (Simpson, 1926).

Köppen's Group II consisted of observations made at five meteorological stations maintained by the Seewarte on the coast of Germany: Neufarwasser, Swinemunde, Keitum, Borkum and Hamburg. Group III of Köppen's records included observations made at five Norwegian lighthouses: Torungen, Hellisö, Ona, Prestö and Andenes (Mohn, 1889). In Group IV a number of old determinations from observations made at British coastal stations are combined and discussed by Curtis, Chatterton and Scott. The height of the anemometers above the surrounding obstacles varied from 1 to 10 metres.

Köppen took exception of the Curtis equivalents because of the statistical regression procedure used by Curtis. It was common during that time to sort the data pairs into classes of the same Beaufort force and to calculate the mean wind speed for each of these classes.

The regression line of the wind speed on the Beaufort wind force can be obtained by connecting these class averages. The second regression line of the Beaufort wind force on the wind speed can be obtained by reversing the sorting and averaging of the parameters. The second regression is suited to predict an individual Beaufort estimate for a given measured wind speed (Lindau, 2003). At the end of the 19th century, however, a discussion began which of the regressions should be used as the equivalent scale (Simpson, 1906).

The Meteorological Office Series

In 1901 the Meteorological Council took up the question of issuing a revised working scale of wind speed equivalents. It was evident that, when using all the available data, the scale of wind speed equivalents and the scale of Beaufort numbers corresponding to given velocities were not reciprocal (Simpson, 1926). The Council thought it desirable to have the discussion of the matter presented in some detail. The preparation of a report was entrusted to George C. Simpson in 1905. Simpson calculated the mean curves for the equivalent wind speeds from the results of five different British stations: the coastal stations Scilly, Yarmouth and Holyhead, and the inland stations North Shields and Oxford. No ship observations were involved. The observations covered the period 1900-1902 and each case included approximately 3000 observations. The analysis was dominated by observations from a lighthouse at St. Mary's, one of the Scilly Islands. However, a total of only 19 observations of wind force 9 and merely 6 observations of wind force 10 were available (Simpson, 1906).

Simpson followed Köppen's statistical argumentation. He averaged the Beaufort wind force for fixed wind speed classes, thus obtaining the second regression line from Beaufort on wind speed. The original calculated "mean" values in Table 3 are not the arithmetical means of the results for each station. The individual observations from all five stations were put together and the whole was treated as the result of one place, made by one observer. Before coming officially into use, the "mean" curve was used to determine the constant *c* in an empirical relation that smoothed the curve. This smooth curve, adopted by the Meteorological Office, was used for extrapolating the equivalent velocities to wind forces higher than 10 Beaufort.

Simpson found a straight line in a double logarithmic plot as the most appropriate relation between the velocity of the wind in statute miles per hour (V) and the Beaufort numbers (B):

$$V = 1.837B^{3/2} \text{ mph} \quad \text{or} \quad B = 0.66V^{2/3}$$

In 1913 the Meteorological Office adopted the smooth curve for metres per second (IMC, 1914). The values are computed from the relation:

$$V = 0.836B^{3/2} \text{ m/s}$$

The upper limits of the velocities for the Beaufort numbers can be obtained by substituting 0.5, 1.5, 2.5, ..., 11.5 for B in Table 3. The numbers derived from above mentioned formulas are still in use in the present WMO, 1946 scale (Table 2).

Beaufort	minimum	average	maximum
0	0	0	0.2
1	0.3	0.9	1.5
2	1.6	2.4	3.3
3	3.4	4.4	5.4
4	5.5	6.7	7.9
5	8.0	9.3	10.7
6	10.8	12.3	13.8
7	13.9	15.5	17.1
8	17.2	18.9	20.7
9	20.8	22.6	24.4
10	24.5	26.4	28.4
11	28.5	30.5	32.6
12	> 32.6		

Table 2: *WMO code 1100, 1946 International equivalents in m/s at 10 metres*

The exposures of the anemometers at the inland stations North Shields and Oxford are not as good as those of the coastal stations Scilly, Yarmouth and Holyhead. For this reason the mean exposure of anemometers is limited to the results of the coastal stations only and may be taken as being around 12 metres above the ground in a perfect open situation (Simpson, 1926).

Later, the results of Simpson were discussed in detail by Köppen, Verploegh and Frost (Köppen, 1916 and 1926; Verploegh, 1956 and 1967; Frost, 1966).

European Wind Speed Equivalents, 1906-1926

In 1912 the Italian Prof. Palazzo asked the International Commission for Weather Telegraphy, which met in London during that year, to reach international agreement on the wind speed equivalents of the Beaufort scale. It had become clear that most of the established wind speed equivalents had been superseded by two determinations resulting from the Seewarte series and the smooth curve of the Meteorological Office (Table 3). The difference between the two series, however, was so great that the commission felt unable to recommend either of the two velocity scales for general acceptance. At the IMC in Rome (IMC, 1914), a combination of both scales, proposed by Köppen, was also not accepted. It did not really solve the problem; the limits of the higher wind velocities had been made in overlapping intervals (Table 3).

In both equivalent series, made by the Seewarte and the London Meteorological Office, respectively, the factors of the anemometers were revised and the correct method for comparing the velocity observations with the Beaufort numbers was used (Table 3).

Beaufort number	Met Office (Simpson, 1906)				Seewarte (Köppen, 1898)			Combined (Köppen, 1913)	
	Original 'mean'	Adopted 'smooth'							
		min	mean	max	min	mean	max	min	max
0	0	0	0	0.2	0	0	0.8	0.5	
1	0.9	0.3	0.8	1.5	0.9	1.7	2.3	0.5	2
2	2.7	1.6	2.4	3.3	2.4	3.1	3.8	2	4
3	4.7	3.4	4.3	5.4	3.9	4.8	5.7	4	6
4	7.2	5.5	6.7	7.9	5.8	6.7	7.6	6	8
5	9.8	8.0	9.4	10.7	7.7	8.8	9.7	8	11
6	12.5	10.8	12.3	13.8	9.8	10.7	11.8	10	14
7	15.4	13.9	15.5	17.1	11.9	12.9	14.0	12	17
8	18.8	17.2	18.9	20.7	14.1	15.4	16.6	15	20
9	22.4	20.8	22.6	24.4	16.7	18.0	19.5	18	24
10	26.4	24.5	26.4	28.4	19.6	21.0	22.7	21	28
11		28.5	30.5	32.5	22.8	24.4	26.2	25	33
12								33	

Table 3: *The British Meteorological Office and the German Seewarte series together with the combined series developed by Köppen in 1913. The Meteorological Office values were converted from mph to m/s from the original sheets, before they were 'rounded'*

The mean values used in Russia (Table 4) were in accordance with the resolution of the IMC-PC Utrecht, 1874 (IMC-PC, 1875). They were based on old comparisons made by Scott in 1874, in which the factor 3.0 is still used for converting the *run of the cups* into the *travel of the wind* (Scott, 1875). Investigations showed that this factor was too high. From 1 May 1915 (De Zee, 1915), the Meteorological Office series and an instrument factor of 2.2 were introduced in Russia.

For the Austrian, Hungarian and Egyptian equivalents, force 10 was regarded the same as force 12 of the Beaufort scale (Table 4). The official Austrian values were based on a compromise of values given by Curtis, Köppen, Waldo, and others. They were derived from a twelve-numbers Beaufort scale that was reduced to a ten-numbers scale via a graphical method (Hann, 1906). The official Hungarian values were from Jelinek (Jelinek, 1876) and the values used in Egypt were also graphically derived from the twelve-numbers scale used by the Meteorological Office, London. The numbers given were converted from the original values, given in km/h. Comparisons with anemometers at several stations in Egypt and Sudan showed that the observer's estimates were generally too high (IMC, 1914).

Wind force	Austria	Hungary	Egypt		Russia
	mean	mean	min	max	mean
0	0 – 1	0 – 1	0	0.5	1.5
1	2	3	0.6	1.1	3.5
2	4	5	1.1	2.2	6.0
3	6	8	2.3	7.2	8.0
4	9	11	7.3	10.5	10.0
5	12	15	10.6	13.9	12.5
6	15	19	14.0	17.0	15.0
7	19	24	17.0	22.5	18.0
8	24	29	22.5	27.0	21.0
9	33	34	27.0	32.0	25.0
10	40 – 50	40		> 32.0	29.0

Table 4: *Mean velocity equivalents in m/s for the numeric scale of wind force 0-10 (IMC, 1914)*

Table 5 shows the values of seven different countries. The values used in Norway, Sweden, France, Spain and Portugal are all based on the German Seewarte series (Köppen, 1898). The values used in Denmark are based on observations made at Danish lightvessels. It was impossible to trace the origin of the scale used in Italy (IMC, 1914).

No known velocity equivalents of estimated wind forces were used in Switzerland. The scale in general use was the half-Beaufort scale of six numbers. For the purpose of international weather telegrams, the numbers were doubled so that the results were comparable with those of other countries. This same practice prevailed in Belgium (IMC, 1914).

Beaufort number	Norway, Sweden		France, Portugal, Spain		Denmark		Italy	
	min	max	min	max	min	max	min	max
0	0	1	0	1	0	1	0	0.3
1	1	2	1	2	2	3	0.3	0.8
2	2	4	2	4	4	5	0.8	1.7
3	4	6	4	6	6	7	1.7	3.0
4	6	8	6	8	8	9	3.0	4.0
5	8	10	8	10	10	11	4.0	7.0
6	10	12	10	12	12	13	7.0	10.0
7	12	14	12	14	14	15	10.0	13.0
8	14	17	14	16	16	18	13.0	17.0
9	17	20		> 16	19	21		> 17.0
10	20	24			22	25		
11	24	30			26	30		
12		> 30				> 30		

Table 5: *Velocity limits in m/s for the Beaufort scale 0-12 (IMC, 1914)*

International Wind Speed Equivalents, 1926

After World War I, at he Eleventh Ordinary Meeting of the IMC in London, 1921, and at the IMC of Directors in Utrecht, 1923, a resolution was adopted by the former and re-affirmed by the latter, that Simpson should be asked to look again into the matter and to propose a definite scale of equivalents between the Beaufort numbers of wind speed in miles per hour and in metres per second (IMC, 1922; IMCD, 1924).

According to Simpson, the difference between the equivalents found by the Seewarte's and the Meteorological Office's series could be explained by considering the exposure of the anemometers. He based his tentative conclusion on a comparison of equivalent wind speeds at Beaufort force 8 (Simpson, 1926). Köppen, on the contrary, referred to the friction of the anemometers that, for the earlier measurements, had been known insufficiently in England (Köppen, 1898 and 1916).

As a compromise Simpson averaged the two series in a rather peculiar way. He plotted the differences between the successive equivalent velocities of the Seewarte and the Meteorological Office's series on the same diagram, and then he drew a smooth curve by the eye, to be the best fit of the two curves. From this new curve the successive steps for the new scale were read, thus ensuring that the steps increased regularly over the whole scale. Next the scale itself was determined. These values were plotted and a smooth curve was drawn through the points. From this curve the limits for each number were read halfway between each whole number (Simpson, 1926, p. 20-21), see Table 6.

Beaufort number	Statute miles per hour			m/s			km/h		
	min	mean	max	min	mean	max	min	mean	max
0	0	0.5	1	0	0.2	0.5	0	0.5	1
1	2	2.5	3	0.6	1.1	1.7	2	4.0	6
2	4	5.5	7	1.8	2.5	3.3	7	9.5	12
3	8	9.5	11	3.4	4.3	5.2	13	15.5	18
4	12	14.0	16	5.3	6.3	7.4	19	22.5	26
5	17	19.0	21	7.5	8.6	9.8	27	31.0	35
6	22	24.5	27	9.9	11.1	12.4	36	40.0	44
7	28	30.5	33	12.5	13.8	15.2	45	49.5	54
8	34	37.0	40	15.3	16.7	18.2	55	60.0	65
9	41	44.5	48	18.3	19.9	21.5	66	71.5	77
10	49	52.5	56	21.6	23.3	25.1	78	84.0	90
11	57	61.0	65	25.2	27.1	29.0	91	97.5	104
12			> 65			> 29.0			> 104

Table 6: *International velocity equivalents of the Beaufort scale. The wind speed refers to a height of 6m (Simpson, 1926; ZMG, 1926)*

Simpson's proposal, combining both the Meteorological Office's and the Seewarte's equivalent series, was finally accepted in 1926 without change by the Commission for Synoptic Weather Information (formerly Commission for Weather Telegraphy), in Zurich (IMO-CSWI, 1927, p. 24) and by the IMC in Vienna in the same year. Resolution 22d:

> "The velocity equivalents of the Beaufort-Scale should be the values in Table VI of Dr. Simpson's report with the addition of a note that these values for the Beaufort-Scale correspond on land with the speeds at a height of approximately 6m above a level surface free from all obstructions. Such an exposure of an anemometer would be called the standard exposure for synoptic purposes." (see Table 6; Simpson, 1926; ZMG, 1926)

However, the International Commission for Air Navigation has taken the wind measured at a height of 10-15 metres above ground as the surface wind (ZMG, 1926).

International Wind Speed Equivalents, 1946

Prior to 1948 the velocity equivalents of 1926 were used to convert measured wind speeds to Beaufort numbers in the synoptic records (WMO, 1970). Because of the high wind speeds measured on land, a need for higher Beaufort numbers arose. At the 12th meeting of the Commission for Synoptic Weather Information in 1946 in Paris (OMI-CSWI, 1947), the Beaufort scale was extended to 17 numbers (Table 7).

At the same meeting it was decided that the wind speed in coded reports should be given in knots, or half-metres per second. Moreover it was decided, on the suggestion of the London Meteorological Office, to replace the international series of equivalent wind speeds of 1926 by the series in use at the British Meteorological Office, i.e. the smooth curve introduced by Simpson in 1906. The reason was that the standard anemometer height was raised from 6 to 10 metres and the 1926 equivalents, approved at the conferences in Zurich and Vienna, corresponded to a height of 6 metres (WMO, 1970). The following Resolution 9 was adopted:

> "The commission recommends that the standard height for which the surface wind speed is given in coded reports should be 10 metres and the table of equivalents should replace the table mentioned in Vienna's Resolution 22 (1926). Provision is required in the scale for forces higher than 12. The values up to force 12 are consistent with the values for a height of 6 metres of the Vienna's Resolution 22 (1926)."

A remarkable decision if one realizes that the wind speed for the lower Beaufort values at 6 metres is stronger than the wind speed at a height of 10 metres. The minor differences of 1 decimal between the midpoint values of the 1906 and the 1946 equivalent series for 1, 3 and 5 Beaufort were caused by the truncation to one decimal of the limits of the 1906 smooth series. The midpoint value for 1946 is the truncated average (one decimal) of the limits of the 1906 series.

Beaufort number	m/s			km/h			knots			miles/hour		
	min	mean	max	min	mean	max	min	mean	max	min	mean	max
0	0	0	0.2		0	< 1		0	< 1		0	< 1
1	0.3	0.9	1.5	1	3	5	1	2	3	1		3
2	1.6	2.4	3.3	6	9	11	4	5	6	4	5	7
3	3.4	4.4	5.4	12	16	19	7	9	10	8	10	12
4	5.5	6.7	7.9	20	24	28	11	13	16	13	15	18
5	8.0	9.3	10.7	29	34	38	17	18	21	19	21	24
6	10.8	12.3	13.8	39	44	49	22	24	27	25	28	31
7	13.9	15.5	17.1	50	55	61	28	30	33	32	35	38
8	17.2	18.9	20.7	62	68	74	34	37	40	39	42	46
9	20.8	22.6	24.4	75	82	88	41	44	47	47	50	54
10	24.5	26.4	28.4	89	96	102	48	52	55	55	59	63
11	28.5	30.5	32.6	103	110	117	56	60	63	64	68	72
12	32.7	34.8	36.9	118	125	133	64	68	71	73	78	82
13	37.0	35.2	41.4	134	141	149	72	76	80	83	88	92
14	41.5	43.8	46.1	150	158	166	81	85	89	93	98	103
15	46.2	48.6	50.9	167	175	183	90	94	99	104	109	114
16	51.0	53.5	56.0	184	193	201	100	104	108	115	120	125
17	56.1	58.6	61.2	202	211	220	109	114	118	126	131	136

Table 7: *The WMO code 1100 wind speed equivalents of the Beaufort numbers. The wind speed refers to a height of 10 metres. (OMI-CSWI, 1947; OMI-CMI, 1947)*

The 'Washington Code', 1949

Because of a complete change of the Paris meteorological code, after two conferences in Canada (OMI-CIMO, 1949) and one in Washington, USA (OMI-CD, 1949), the wind speed equivalents were officially adopted on 1 January 1949 in the Dutch meteorological ship logbook. According to this so-called 'Washington Code', at sea the Beaufort wind force is estimated but should be converted to nautical miles per hour (knots) for the synoptical records. For maritime use the Beaufort numbers 13-17 of the 1946 Paris scale were abolished again in 1960.

At the meeting of the Commission for Instruments and Methods of Observation held in Toronto, 1947, there was discussion about the standard height of 10 metres above the ground for the exposure of the anemometers, as approved by Resolution 9 in Paris. The feeling was that this resolution should be revised so as to make it more specific, but there were very decided objections to reducing observations to an effective height of 10 metres. There are so many factors involved that it would be very difficult to formulate any accurate method of reducing the wind speed to this particular height. It was the opinion that at present the only way to "measure" the wind on board ships and at floating stations was by estimating according to the Beaufort scale (OMI-CIMO, 1949).

The Commission for Maritime Meteorology, also held in Toronto, 1947, questioned the applicability of the older equivalents to ship observations because the observations on which the scale was based were from land or coastal stations; none came from ship comparisons. The commission recommended:

> "That further investigations should be made from observations taken aboard weather ships and well-exposed lighthouses, etc., to confirm the accuracy of Tables A and B of Resolution 9 that were adopted by the IMC in Paris, 1946." (OMI-CMM, 1949)

This recommendation was adopted by the IMC's Conference of Directors, Resolution 54 (OMI-CD, 1949).

Prior to 1949 the Beaufort scale numbers were used as a code to report estimated (by ships) wind forces as well as measured (on land) wind speeds. The measured wind speeds from land stations should be converted to Beaufort numbers for the use in meteorological reports. Nevertheless, from 1 January 1949 the wind speed equivalents have been used the other way around, i.e. from Beaufort estimates at sea into wind velocities in knots (nautical miles per hour).

Wind Speed Equivalents Used In The Netherlands

Although the Beaufort scale was recommended in the Netherlands for use in the meteorological ship logbooks at sea, i.e. the *Universeel Extract-Journaal*, the Beaufort numbers were applied for inland use as well. From 1854 onwards, the Dutch meteorological land stations often were equipped with Robinson anemometers that gave the wind speed in metres per second. For use in the synoptic records the wind was converted to a Beaufort number. In 1855 the Dutch land stations Leeuwarden, Assen and Nijmegen were not equipped with anemometers and therefore the wind force was estimated and logged according to the marine Beaufort scale, i.e. according to the sail setting of a full rigged ship (KNMI, 1855).

Dutch marine wind speed equivalents of the Beaufort scale were published for the first time in 1865 (Table 8). On board ships the use of this table was recommended instead of using anemometers (Mossel, 1865). It is not known how the wind speed equivalents were calculated.

In 1898 the wind speed equivalents in metres per second appeared in the meteorological logbooks on Dutch ships for the first time. The published values were adopted from R.H. Scott, internationally accepted at the First International Meteorological Congress in Vienna, 1874. The equivalents are certainly too high because an incorrect anemometer factor (3.0 instead of 2.2) was used. Therefore the equivalent wind speeds are probably 22% too high (Gallé, 1915).

In 1900 the equivalents in the Dutch meteorological ship logbooks were replaced by the Seewarte equivalents, developed by Köppen in 1898 (Table 3; Köppen, 1898). The equivalents used for the Dutch telegraphic and climatological stations were also adopted from these same equivalents.

The equivalent values for knots (nautical miles per hour) were calculated according to:

1 knot = 0.896 statute miles per hour or 1 knot = 1.944 metres per second
1 km/h = 1609 statute miles per hour or 1 knot = 3.6 metres per second

Beaufort number	Dutch expression for the wind force according to the sail setting	Wind speed in "Dutch ell per second"
0	Stilte	0
1	Flaauwe koelte, als het schip stuur heeft	0.97
2	Flaauwe bramzeils koelte	1.38 – 1.68
3	Bramzeils koelte	1.94 – 2.37
4	Stijve bramzeils koelte	3.06
5	Marszeils koelte	5.31
6	Stijve marszeils koelte	6.86
7	Gereefde marszeils koelte	9.70
8	Dubb. gereefde marszeils koelte	13.75
9	Digt gereefde marszeils koelte	16.80
10	Onderzeils koelte	19.40
11	Storm	25.67
12	Orkaan	30.70

Table 8: *Wind speed equivalents in use on Dutch sailing ships in the 19th century. Wind speed in Dutch ell per second (Mossel, 1865); 1 Dutch ell = 0.694 metre*

The Royal Dutch Navy used the 1874-Scott equivalents until 1908. In 1908 the equivalents were replaced again by the British equivalents developed by Simpson in 1906. These equivalents are from table XVII, p. 40 of the Meteorological Publication M.O. No. 180 (Simpson, 1906). In the ship logbooks the values of Simpson, originally given in statute miles per hour, are converted from miles per hour to metres per second according to 1 mile/hour = 0.4470 metre/second, and rounded to 1 decimal (Table 9). Note that in the Netherlands a different scale of equivalents was applied during the period 1908-1925 compared to the UK. There the smooth curve of Simpson, 1906, was used until 1948 (IMC, 1914).

In Batavia/Jakarta (the capital of the former Dutch colony *Dutch East Indies*) the same equivalents as for the Dutch merchant ships in 1908 were used during the period 1908-1925 (Niblack, 1926).

The wind speed equivalents in the Dutch meteorological ship logbooks were replaced again in 1926 by the international wind speed equivalents developed by Simpson, based on a compromise between the Seewarte and the Meteorological Office series (Table 6; Simpson, 1926). The mean values were rounded to 1 decimal. The equivalent values are valid for land stations at a height of 6 metres.

The international equivalents of Paris, 1946, were already adopted in 1947 for the Dutch ship logbooks, edition 1947. However, both the wind speed in knots (nautical miles per hour) and the Beaufort number were logged.

Beaufort number	1898 (Scott, 1875)	1900 (Köppen, 1898)	1908 (Simpson, 1906)	1926 (Simpson, 1926)	1947 (OMI-CMI, 1947)
0	1.5		0-1.3	0.2	0
1	3.5	1.7	2.2	1.1	0.9
2	6.0	3.1	3.6	2.5	2.4
3	8.0	4.8	4.9	4.3	4.4
4	10.0	6.7	6.7	6.3	6.7
5	12.5	8.8	8.7	8.6	9.3
6	15.0	10.7	11.0	11.1	12.3
7	18.0	12.9	13.4	13.8	15.5
8	21.0	15.4	16.1	16.7	18.9
9	25.0	18.0	19.7	19.9	22.6
10	29.0	21.0	23.7	23.3	26.4
11	33.5			27.1	30.5
12	40.0				> 32.6

Table 9: *Mean wind speed equivalents of the Beaufort scale 0-12 in use in the Netherlands during the period 1850-1950*

Around 1916 many Dutch sailors used to log meteorological observations in both American and Dutch or British logbooks. They also consulted different weather charts that were issued by different countries. Although these countries used the same units, i.e. knots, for the wind speed equivalents, they used quite different scales (Table 10). This was, however, not common knowledge among sailors, so the use of wrong scales cannot be excluded for this period (De Zee, 1916). For clarity an explanation of the scales is given.

In the Dutch ship logbooks the equivalents of table XVII of Simpson (1906) were used and converted to knots, using a factor of 0.514. According to Gallé the 1906-Simpson equivalents were the most reliable in that time (De Zee, 1916).

For the calculation of the American equivalents to knots the US Weather Bureau apparently still used the very old 1874-Scott equivalent scale (De Zee, 1916). Because of the incorrect Robinson anemometer factor of 3.0 instead of 2.2, the American values deviate strongly from the others. The US Weather Bureau began to use a 12-point Beaufort scale in 1905, switching to a 7-point scale from 1909 to 1914, after which it reverted to the 12-point scale again.

In the British *Brown's & Pearson's Nautical Almanac* (the 'Seaman's Bible') the smooth curve of Simpson (1906) was used for the conversion to knots.

It is certainly not so that the abovementioned problem has any impact on the marine climatology. The sailors had to report the estimated Beaufort numbers in the logbooks and not the equivalent wind speeds.

Beaufort number	KNMI (knots)	US Weather Bureau (knots)	UK, Brown's Almanac (knots)
0	0 – 2.5	0 – 2.6	0
1	4.3	6.9	1.7
2	7.0	11.3	4.3
3	9.5	15.6	8.7
4	13.0	20.0	13.0
5	16.9	24.3	18.2
6	21.4	29.5	23.4
7	26.0	34.7	30.4
8	31.3	41.6	36.5
9	38.3	48.6	43.4
10	46.1	56.4	51.2
11		65.1	59.0
12		78.1	65.1

Table 10: *Mean wind speed equivalents of the Beaufort scale 0-12 in use in three different countries around 1916*

Accuracy Of The Wind Speed In Knots

Because the estimated wind force had to be converted to knots (OMI-CD, 1949) the observer is given the opportunity to distinguish between a number of sub-intervals of a Beaufort interval. This number varies in the Beaufort scale from three at Beaufort 1, to eight at Beaufort 11. Some experienced observers estimate for example a *low 4* or a *high 3*, suggesting a higher precision. According to Verploegh, this will not give a greater precision of the estimated wind force.

> "When an observer is given the possibility to mark wind speeds within a Beaufort interval, he usually tends to consider three possibilities: a lower, higher or an upper interval. The middle one will contain 58% of the observations, the other two an equal number of 21%. By subdividing a Beaufort interval the bias towards a distinct preference for even numbers and towards the centre value of the interval will largely diminish any gain in precision. It would be sufficient for all practical purposes in climatology and synoptical meteorology to have the estimated wind speed reported by means of the mean equivalent wind speed of a Beaufort number." (Verploegh, 1967)

Unit Conversion

The Nautical Mile

The knot is the world wide universal unit of speed, used by seamen and in air navigation. One knot is equal to one nautical mile per hour. In order to compute the correct length of a nautical mile, the international spheroid is used in most countries.

The First International Extraordinary Hydrographic Conference, Monaco 1929, ordered the standard length of the *International Nautical Mile* to be 1852 metres (= 6076.10333 English feet). The average length of a meridian minute of the international spheroid was 1852.201 metres, rounded 1852 metre. This standard length was adopted by Argentina, Belgium, Brazil, Denmark, Finland, France, Germany, Greece, Iceland, Italy, Japan, the Netherlands, Norway, Poland, Portugal, Spain, Turkey and Sweden. The USA uses the spheroid of Clarke (1866) in their calculations until 1 July 1954, making 1 nautical mile = 1853.248 metres (Judson, 1976).

In the beginning of the 20th century the Royal Dutch Navy defined the nautical mile as the length of one minute of arc along the equator:

$$40070368/360/60 = 1855.1 \text{ metre.}$$

The Dutch merchant marine however, defined the nautical mile as the length of one minute of arc along the meridian:

$$40003432/360/60 = 1852 \text{ metre (l'Honoré Naber, 1901).}$$

Equivalents Of Knots

Exact equivalents of 1 knot according to WMO Code 1100 (Daking, 1947):

1 knot = 1.15 statute mile per hour
= 1.855 km/h
= 0.514 m/s
= 1.013 ft/min
= 1.685 ft/s

Conversion Of Anemometer Winds To Beaufort Numbers

There is a curious phenomenon in the official WMO Code 1100 velocity equivalent table. If velocities expressed in m/s are used to determine the Beaufort wind force, the result sometimes differs from the wind force when the equivalent value expressed in knots or miles per hour was used. Originally, in 1906 G.C. Simpson calculated the wind speed equivalents in statute miles per hour with the formula:

$$V = 1.87B^{3/2}$$

To find the limit of the wind speed classes that define the various Beaufort numbers, he used the values 0.5, 1.5, 2.5, ..., 11.5 Beaufort in the formula and from these values the knots were calculated. To find the limits in metres per second, the WMO used the smooth formula:

$$V = 0.836B^{3/2}$$

from W. Napier Shaw (IMC, 1914), and from these values the km/h values were calculated.

To find the exact Beaufort numbers from the different wind speed units:

m/s	→	Beaufort = $(m/s / 0.836)^{2/3}$
km/h	→	Beaufort = $(km/h / 3.01)^{2/3}$
mph	→	Beaufort = $(mph \times 0.535)^{2/3}$
knots	→	Beaufort = $(knots \times 0.615)^{2/3}$

Abbreviations

IMC ....International Meteorological Committee;
IMCD.............International Meteorological Conference of Directors;
IMC-PC...........International Meteorological Congress, Permanent Committee;
IMO-CSWI ....International Meteorological Organization, Commission for Synoptic Weather Information;
JCOMM..........Joint WMO-IOC Technical Commission for Oceanography and Marine Meteorology;
KNMI ....Koninklijk Nederlands Meteorologisch Institute (Royal Netherlands Meteorological Institute);
MC..................Meteorological Conference;
MO.................Meteorological Office;
OMI-CD ....Organisation Météorologique Internationale, Conference of Directors;
OMI-CIMO ....Organisation Météorologique Internationale, Commission for Instruments and Methods of Observation;
OMI-CMI........Organisation Météorologique Internationale, Comité Météorologique International;
OMI-CMM .....Organisation Météorologique Internationale, Commission for Maritime Meteorology;
OMI-CSWI .....Organisation Météorologique Internationale, Commission for Synoptic Weather Information; WMO World Meteorological Organization;
ZMG..............Zentralanstalt für Meteorologie und Geodynamik.

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