KONINKLIJK NEDERLANDS METEOROLOGISCH INSTITUUT

MEDEDELINGEN EN VERHANDELINGEN

No. 89

G. VERPLOEGH

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VOORWOORD

De in de laatste jaren sterk toegenomen belangstelling voor het onderzoek van verschijnselen, die in nauw verband staan met de energie-uitwisseling tussen oceaan en atmosfeer, heeft onder meer geleid tot de noodzaak van het nauwkeurig en vooral gedetailleerd analyseren van het windveld boven zee. Een belangrijke toepassing van deze analyse is bijvoorbeeld de berekening van de door de wind opgewekte golven op de oceaan. De betrouwbaarheid van deze berekening hangt in hoge mate af van de betrouwbaarheid van de windanalyse. Waar deze laatste bijna geheel berust op routinewaarnemingen verricht aan boord van koopvaardijschepen, is het zaak de aard en de grootte van de systematische en toevallige fouten dezer waarnemingen goed te leren kennen.

De onderhavige studie tracht hierin enig nader inzicht te geven. De visuele waarneming, de windmeting en de vergelijking van de gradientwind, die een gemiddelde toestand over een zeegebied van circa 100 km diameter representeert, met de op één punt verrichte waarneming of meting, zijn aan de hand van experimentele gegevens en een groot getallenmateriaal onderzocht. Hierbij werd het aloude probleem van de ontstaanswijze en de opbouw van de schaal waarin subjectieve windschattingen worden uitgedrukt, nu niet alleen analytisch, maar ook synthetisch beschouwd. Op grond van een postulaat over de wijze waarop deze waarnemingen worden verricht, werd een gedachte ontwikkeld over de theoretische opbouw van de windschaal, waarna de verschillende uit de theorie volgende eigenschappen van de schaal werden getoetst aan bekende experimentele resultaten. Dat op deze wijze meer licht kon worden gebracht in een probleem dat ook internationaal weer actueel was geworden, was voor een deel te danken aan de ontdekking van een oude 18e eeuwse Nederlandse windschaal die verrassend grote overeenkomst vertoonde met de schaal die Beaufort 70 jaar later zou opstellen.

De studie besluit met de analyse van enige voorbeelden van het windveld over de Noordatlantische oceaan. Voor een meteoroloog die totdusver gewend was het windveld slechts indirect te „zien" aan de hand van het isobarenpatroon, is de expliciete voorstelling van karakteristieke windpatronen in oceaandepressies bijzonder instructief.

De Hoofddirecteur van het
Kon. Nederl. Meteorol. Instituut,
PROF. DR. W. BLEEKER

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1. THE OBSERVATION

1.1 The Beaufort Scale for wind speed

The force of the wind is estimated, and given in a scale consisting of 13 numbers, from 0 to 12, which was developed by Admiral Beaufort in 1805 (ref. 3). At that time Beaufort commanded a man-o'war, and the steps of his scale are defined in terms of the man-o'war's speed, under a specified sail, and the wind corresponding to that speed.

At the first international Conference on Maritime Meteorology in 1874 it was decided that, in the absence of wind measurement, the estimated force of the wind should generally be given in Beaufort's scale. Until then most seamen used descriptive terms to denote the wind force, others used a so called French Telegraphic Scale with numbers corresponding to the even numbers of Beaufort's scale; the latter scale had however gradually gained wider recognition since its adoption by the British Navy in 1838.

The admittance of wind-force estimates into the meteorological observational program presented a problem which remained the subject of much discussion up to the present time, in particular as regards the reproducibility of the scale and the conversion of its numbers into the normal physical units of metre per second. As regards the first problem, in the past sailors will no doubt have used the performance of their sailing ship as a criterion for wind-force estimates (see for instance R. H. CURTISS (1897), P. PETERSEN (1927)), although they will not have known the particular type of Beaufort's ship. Other criteria may have been used as well. In this regard we may quote G. C. SIMPSON, who remarked when proposing, at the request of I.M.O., a series of equivalent wind speeds for international use in 1926:
'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 everyday conversation. ...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'.

It seems possible, as Beaufort appeared to have shown, to specify a rough scale based on subjective and mostly unknown criteria in an objective and reproducible manner. This fact has been used as a basis for the hypothesis that in the relation between scale numbers and wind speed, the speed should appear as a function of the wind pressure on objects such as, for instance, the sails of a ship. The series of equivalent wind speeds which at present is internationally used was constructed according to this hypothesis; it concerns a set of mean empirical data which was originally computed by G. C. SIMPSON in 1906 and which was modified afterwards to fit an exponential relationship of the form $v = c.n^{3/2}$, where n = scale number, v = wind speed and c = a constant. The exponent was prescribed by theory.

Since then a number of other attemps have been made to explain the construction of the scale from the analytical form of the series of equivalent speeds. Reference is occasionally made to a study by H. ERTEL (1950) whose suggestion that the scale might be based on a psycho-physical relationship may shortly be discussed here. ERTEL hypothesized that the sensation R_n experienced by observing wind effects on nearby objects would linearly be related to the tangential force of the wind, which led him assume $R_n \sim v^{2/k}$ where k should be determined from experiment. He then postulated that not the steps R_n but the steps $R_n^{1/2}$ are spaced equally on the wind scale.

These two assumptions lead to the expression $v_n = c_1 (n + c_2)^k$, where c_1 and c_2 are constants. ERTEL did not discuss, however, whether or not the value $k = 1.5$ which he derived from SIMPSON's equivalents agreed with theories on the tangential force of the wind. Apart from this result he concluded from the postulate on the regular spacing of the steps $R_n^{1/2}$ that 'the interval of each class R_n will be the arithmetical mean of the preceding and the following interval'. It can easily be shown that this cannot be true if we accept his postulate.

As to the principal point of relating scale numbers to wind speeds ERTEL's attempt remained inconclusive. The question in which manner an observation is made is not dealt with, it seems that this question should be answered before it can be decided whether or not a psycho-physical relationship should apply. The current problem is therefore to find a theory which is based on actual observational procedures; up to the present time no such theory has been put forward.

1.2 On sea criteria for wind observations

Lists of criteria for wind observations have been established internationally for use by observers on land and at sea (ref. 29). The criteria for use on board ship are of greater practical importance; they are based on sea criteria which Captain P. PETERSEN published, after careful observation, in 1927. PETERSEN's object was to provide his fellow seamen on steamers with a useful means of observing the wind, as they could no longer use their ship's performance as an indication of the wind speed. The wind effects which are described comprise: the form of the wind waves, the formation and extension of foam patches at the sea surface and, at the higher wind forces, the reduction of visibility due to spray. Due attention was given to the limitation of the applicability of the criteria, for instance in wind sheltered areas.

In the Appendix to this paper some lists of specifications to the Beaufort scale are included.

Several of Captain PETERSEN's sea criteria have been discussed in a number of individual studies.

a) the formation of foam

An important series of comparative wind measurements was obtained during the well-known 'Meteor' expedition in 1925-1927. In working these out E. KUHLBRODT (1936) found that observers tended to underestimate the wind speed on entering the region with strong Westerlies in the South Atlantic after having come from the tropical zone where the wind is generally light. KUHLBRODT explains this feature by reasoning that the observers had to get accustomed first to new climatological conditions. H. SEILKOPF pointed out later (1956) that the change of these conditions does not only include the mean force of the wind, but that a difference of plankton content in the surface layers of the ocean also occurs, according to the sampling results of the same expedition. As seawater with a greater plankton content has also a greater tendency to foaming and as the estimates of the wind force depend on the foaming of sea surface-water, there might be a correlation between the plankton content of the seawater and the equivalent speeds of the Beaufort numbers. According to PETERSEN'S criteria wind force 3 is reported when the first foam building becomes visible (small 'white horses'). Comparing the equivalent wind speeds obtained at different 'Meteor' profiles across the Atlantic Ocean SEILKOPF was able to show the following. When the ship sailed through an area where the plankton content was lower than that of the previous area, then at first Beaufort force 3 was still reported even though the wind speed was higher. The speed values ranged from 4.6 to 8.3 m/sec at the various profiles.

In this connection SEILKOPF (1959) also draws the attention to the remarkable phenomenon of 'false spindrift', a foam of small bubbles of air close to the sea surface which appears at wind force 4 or more and gives the impression of a stronger wind than actually is blowing.

The conclusion is that the wind may be underestimated or overestimated (with respect to the average standard) depending on weaker or stronger foam building. The magnitude of the resulting error can be of the order of plus or minus one scale number. According to KUHLBRODT'S findings however, observers gradually arrive at the correct estimate some time after having entered a region of different foam building and this might indicate the fact that other criteria also are used in observing the force of the wind.

b) the form of sea waves

Because seamen are used to watching the wind continuously, they are well aware of the factors which govern the growth of sea waves. The influence of fetch is very marked when the ship steams from sheltered waters out in the open sea or vice versa. On these occasions there is no question of estimating the wind wrongly, as the experienced observer knows that he has to look for other criteria. In the open sea there might be a certain lag of estimates following a continuously rising or falling wind speed as the result of the lag existing in the sea getting up or dying down. The form of the waves is, however, different in the two cases. At rising winds the pressure of the wind is actually seen to form characteristic shell-like impressions on the back of the waves, while at decreasing wind the existing waves soon attain a more smooth appearance as the larger shell-like ripples and impressions disappear rather quickly. The author could observe these phenomena particularly well when standing on the low deck of a light-vessel, but also from the high bridge deck of an ocean steamer the lag of the sea getting up could be inferred from the characteristic form of the wind waves. Because of these visible effects the influence of the lag of the sea following the larger

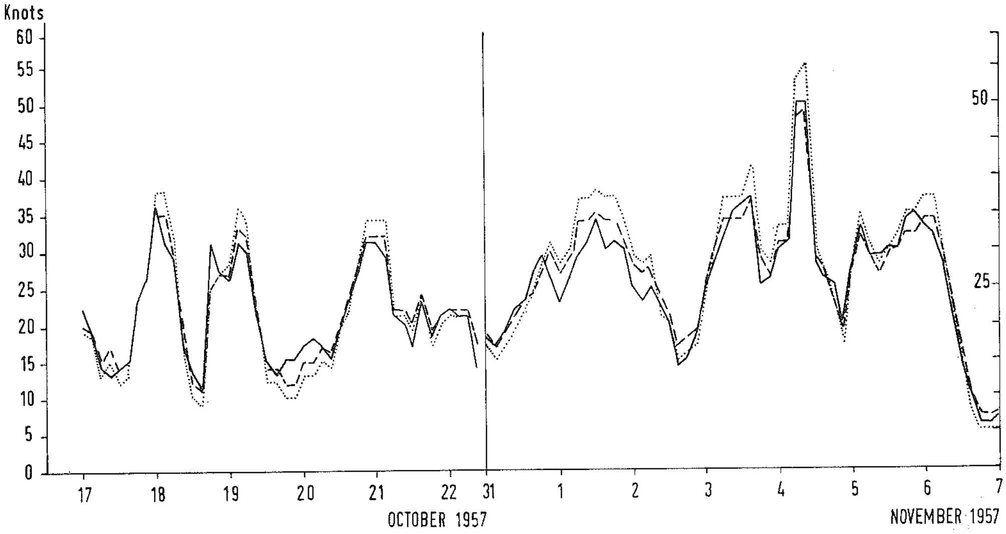

Fig. 1 Wind speed records from 3-hourly observations at light-vessel 'Texel'.
Full line: readings from anemometer at 19 m above sealevel.
Broken line: wind speed estimates, converted by means of equivalents derived by Verploegh (1956).
Dotted line: same estimates, converted by means of international equivalents (1946).
A storm rise is closely followed by wind speed estimates; there is a lag of estimates following a subsequent lull of the storm.

changes of the wind will be suppressed in a series of consecutive wind observations, as is illustrated by the examples in figure 1.

Strong surface currents change the form of wind waves when they are opposed to the wind direction or are running in the same direction. Occasionally reports are received from ships having encountered a strong surface current in the ocean, which was markedly bounded by stream ripples, eddies and floating debris. While steaming across the current a different impression was obtained of the wind force from the effects of the wind on the sea surface. A difference of one or two Beaufort scale numbers (for instance from 8 to 6, ref. 28) could be noted.

Strong tidal currents may produce of course the same effect; L. OTTO (1963) has investigated this on the basis of climatological data from five Netherlands light-vessels over the period 1910 - 1939. A grouping of the wind observations per tide phase showed significant deviations of the numbers of observations of Beaufort force 2 from average. When the maximum current was running against the wind the number of observations was smaller than average, for the opposite case a significantly higher number was found. The effect became less evident for observations of Beaufort force 3. The analysis could not be extended to higher wind forces as the regular current observations were usually discontinued at strong winds.

c) effects of the apparent wind on shipboard

Although visible effects like those on flags and funnel smoke can only serve to estimate the strength of the apparent wind on shipboard, the whistling sound produced by the rigging may enable an estimate of the true wind speed in certain cases; the author became aware of this during an ocean crossing he made in 1959. On this occasion he made the following notes: 'When I arrived at the bridge in the evening it took an appreciable time before my eyes became accustomed to the darkness outside, only then could I discern the white foam patches produced by the bow wave swiftly passing by. In the meantime I listened to the wailing sounds of the rigging whilst standing outside on the wing of the bridge. It was then that I suddenly became aware of the difference between this sound and the whistling tone heard the day before when there was hardly any wind. That tone was a continuous one, hardly varying in intensity or frequency, but this time the individual gusts of the wind could be heard even though the vessel still made a speed of about 14 knots. From a recollection of average gust periods, which I was used to observing at home from wind effects on tree branches, I arrived at a tentative guess of the strength of the true wind. My guess of 6 to 7 Beaufort was somewhat lower than the estimate given on my request by the watch officer who estimated 7 to 8. The officer told me that when the wind was force 5 or more he was usually able to follow the gradual change of the wind force, if it did occur, on dark nights merely by listening to sounds produced by the rigging. Since that night I practised on this method of estimating the wind and after a few days had learned to distinguish between various sounds, and was able to estimate the strength of the true wind rather accurately, except in the case of following winds'.

In the Appendix to this paper a table is included in which certain effects of the apparent wind on shipboard are described. The descriptions were made by H. W. McPhail (1951) from observations made at the Canadian Ocean Weather Station 'B'. As effects of this kind have to be used when the observation of the wind cannot be based on visible effects on the sea surface (e.g. at night or in sheltered waters) it is important to know whether estimates made this way are comparable to those based on sea criteria. As a consequence of discussions held on this subject in the Commission for Maritime Meteorology Captain J. A. Burnett initiated a series of very interesting experiments, conducted in three British Naval ships. The observers were instructed to estimate the relative direction and Beaufort force by 'feel', by its effect on flags, rigging and funnel smoke, then estimate the true wind direction and Beaufort force from the appearance of the sea and finally to read the relative wind speed by fixed anemometer, together with the relative wind direction. In a report to the CMM Working Group on Technical Problems (1964) Captain Burnett gave the following results, which will be compared in the next table with results obtained from earlier observations based on other criteria.

TABLE 1 *Equivalent speeds in m/s*

	Beaufort numbers	1	2	3	4	5	6	7	8
a)	from effects on flags etc. (relative wind, Burnett; WMO, 1964)	1.0	3.1	5.3	7.8	10.7	13.3	16.2	19.6
b)	by sea criteria of WMO (Burnett; WMO, 1964)	2.0	3.4	5.6	7.8	9.7	12.8	15.0	
c)	from formation of foam exclusively (Roll, 1953)	1.8	3.7	5.6	7.8	9.9	12.4		
d)	from effects on terrestrial objects (Simpson, 1906)	1.1	3.4	6.0	8 5	10.7	12.1	13.6	15.7
e)	by sea criteria and by 'feel' at light-vessels (Verploegh, 1956)	1.3	3.2	5.8	7.9	10.2	12.4	14.4	

Up to Beaufort force 7 there is a remarkable agreement between corresponding equivalent speeds. The standard deviations of the measured speeds in experiments a) and b) were given as 1.3 and 1.1 m/sec respectively; the latter value is supported by the standard deviation of 1.1 m/sec which was found in experiment e). The comparison leads up to the conclusion that wind observations based on different criteria eventually give rise to scales with more or less equal intervals, at least up to Beaufort force 7. In a historical sense it might also be inferred from these experiments that the 'rough scale with descriptive terms' which, according to SIMPSON, must have existed long before Beaufort developed his scale of wind forces, may have been shown to have the same equivalent wind speeds if suitable anemometers had existed at that time.

Although the estimates have been made according to different criteria, the various wind scales are not independent as the observers were acquainted with the steps of Beaufort's scale, except perhaps those at the land station Oxford from which the series listed under d) is derived. A decisive proof of the generality of the construction of Beaufort's scale would be obtained from subjective wind observations made without previous knowledge of this scale, and nevertheless resulting in the same length of intervals.

As a remarkable coincidence evidence of this kind had become known in recent years; it shows the development of an old wind scale from its very beginning, centuries ago, up to its calibration in modern times.

1.3 The wind scale of Jan Noppen (1735)

In 1948 A. HAVINGA published a study on wind observations made in the 18th century and their application to studies on the performance of old wind mills. In this work the following interesting story is found.

Around 1735 JAN NOPPEN, surveyor of dikes and sluices at Halfweg (halfway across Amsterdam and Haarlem) started to record weather observations in collaboration with a physician, Dr. Joh. Engelman. The observations which were made three times a day were regularly published since 1743 in the 'Verhandelingen van de Hollandse Maatschappij der Wetenschappen' at Haarlem. They were meant to form a necessary basis for computations in the field of hydraulic engineering. The surveyor's building, a tall mansion, was situated between a large lake, the Haarlemmermeer, to the west and a sea inlet, het IJ, to the east which had an open connection with the North Sea via the former Zuiderzee.

The wind was estimated from a scale consisting of 17 numbers; a calm was noted as 'force' zero, the heaviest storm wind as 'force' 16. The specifications of the scale are lost or have probably never been written. The observational hours were at 7 a.m., at noon and at 10 p.m.

When Noppen was succeeded as surveyor by Christian Brunings in 1765 the observations were carried on mostly by assistants. Brunings did not have much faith in the subjective way of observing the wind; under his guidance a wind meter was constructed on the principle of a so-called pressure plate. A rectangular plate was freely hanging on a horizontal axis and was counterbalanced by a weight on a long string when pushed up by the wind. The inclination angle of the plate from the vertical was taken as a measure of the strength of the wind. During the years 1772 and 1773 the wind meter was placed on the roof of the office building with the plate extending 5 m above the roof and 25 m above the ground. As the wind meter was read daily at 7 a.m., noon, and 6 p.m., comparative data of both an estimated and a measured wind speed was available at two observational hours per day over these two years.

About thirty years ago Ir. A. Havinga became interested in these old observations for his studies on the performance of wind mills. He had an exact copy made of Bruning's wind meter from the original blue prints; the wind meter was tested in a wind tunnel and calibrated in the open by means of a cup anemometer. Havinga also studied the aerodynamical influence of the office building from a model placed in a wind tunnel. In this way Havinga was able to compute the speeds equivalent to the numbers of Noppen's old scale as accurately as possible.

By some coincidence the present author was introduced to this interesting study, which revealed the surprising fact that a large similarity existed between the equivalents of Noppen's wind scale and those of the scale which Admiral Beaufort developed 70 years later!

Table 2 *Equivalent speeds in m/s*

Noppen scale	0	1	2	4	6	8	10	12	14
Halfweg (1772-'73)	–	–	3.8	6.2	8.3	10.3	12.0	14.8	–
Neth. lightvessels (1956)		1.3	3.2	5.8	7.9	10.2	12.4	14.4	–
Beaufort scale	0	1	2	3	4	5	6	7	8

When copying the observations from the old registers HAVINGA found that the odd numbers of the scale were gradually less and less used, except number 1. After 1760 they were not used any more[1]. Apparently, as more experience was gained in recognising differences in the 'intensity' of the wind effects observed, and with the human predilection for even numbers, the scale evolved into its final form. An 'absolute calm' could, however, easily be distinguished from a 'light air' so that the first number was maintained. It is possible that also a rough scale of descriptive terms already existed (for instance one used by millers) before NOPPEN began to record his observations; but the development of the final scale of even numbers shows that NOPPEN originally tried to observe the wind speed in as much detail as possible. The criteria he used might have been wind effects on the surface of the extended waters nearby, and on terrestrial objects like trees, reeds, etc.

The surprising result that the intervals of the final scale of even numbers appear to have the same length (according to the equivalent speeds) as the intervals of Beaufort's scale may be considered as an indication of the generality of a subjective wind scale. The generality may be worded as follows:

— *observers who are accustomed to their surroundings, i.e. experienced in observing wind effects on environmental objects, will be able to distinguish mean wind speeds to the same degree of precision whatever wind effects are observed* —.

1.4 The construction of a wind scale

The way in which an observation is made may be best understood by estimating the wind speed regularly from its effects on tree branches. It will then soon become apparent that one actually seeks to evaluate the number of times with which fluctuating motions of certain frequency and intensity occur during the time of observation, in order to find out which motion has the greatest frequency of occurrence. The specifications of the Beaufort numbers for observations made on land already indicate that the gustiness of the wind is used as a measure for the mean wind speed; this suggestion was put forward by M. MINNAERT already in 1940 in his famous book on observing practices in nature: 'De Natuurkunde van 't Vrije Veld'.

At sea an observer watching the sea surface concentrates his attention on those disturbances, caused by the local wind, which constitute a regular feature, i.e. regular in spacing and occurrence; he then seeks to find out which of these features are prevailing.

A possible explanation of the construction of a wind scale may therefore be given on the basis of the statistical theory of atmospheric turbulence. The discussion will be based on the theory of G. I. TAYLOR as recently reviewed and discussed by F. PASQUILL (1962) in his book on atmospheric diffusion. The following definitions will be used hereafter.

1) The author is much indebted to Ir. HAVINGA for his efforts in obtaining supplementary information about these old records.

A measured wind speed constitutes an average of the fluctuating speeds over a certain 'average time' τ,

$$\bar{u}_\tau = \frac{1}{\tau}\int_{t_o - \tau/2}^{t_o + \tau/2} u.\,\mathrm{d}t \tag{1}$$

and

$$u = \bar{u}_\tau + u' \tag{2}$$

Putting the coordinate x along the mean wind direction, two turbulent componentt u'_1 and u'_2 are considered which are measured instantaneously at two points distans x apart, one of the points being fixed. The space correlation coefficient is defined by

$$R(x) = \overline{u'_1\, u'_2} \Big/ \overline{u'^2} \tag{3}$$

in which R (x) and u'^2 are taken to be independent of position (homogeneous turbulence).

In a similar way the autocorrelation coefficient $\mathrm{R}(t)$ is defined, referring to turbulent speeds at a fixed point at instants separated by t. It is generally assumed, that

$$\mathrm{R}(t) = \mathrm{R}(x) \quad \text{when } x = \bar{u}.t \tag{4}$$

PASQUILL concludes from his discussion on the validity of the space-time relationship that 'the available data at least provide some justification for its use as an approximate basis'; the relationship has been verified by experiment for wind velocities up to 6.7 m/s.

The sharpness of the decrease of $\mathrm{R}(x)$ with x can be represented by a length l, commonly referred to as the scale of turbulence and suggested by TAYLOR as a possible definition of the average size of the eddies.

$$l = \int_0^\infty \mathrm{R}(x).\mathrm{d}x \tag{5}$$

In view of wind speed estimates it is of some importance to note that, according to measurements made by GIBLETT et al. at a mean speed $\bar{u}$ = 15 m/s (vide ref. 31), $\mathrm{R}(t)$ reaches a negative minimum at 50 seconds. These findings led to the conclusion that there is a pattern in the wind that tends to be repeated in about 100 seconds or, at this mean speed, over 1500 metres.

If $\mathrm{F}(n).\mathrm{d}n$ denotes the contribution made to the total variance u'^2 by the frequencies between n and $n + \mathrm{d}n$, it is proved and experimentally verified that

$$\mathrm{F}(n) = 4\int_0^\infty \mathrm{R}(t).\cos 2\, nt.\mathrm{d}t. \tag{6}$$

Correlograms in atmospheric turbulence can often be approximately represented by an exponential decay, or

$$R(x) = \exp(-x/l). \tag{7}$$

In this case it follows that

$$n\,F(n) = \frac{2}{\pi\,(a + 1/a)} \quad \text{where } a = 2\pi nl/\bar{u}. \tag{8}$$

Plotting $nF(n)$ against a gives a symmetrical curve with a maximum value of $1/\pi$ at the frequency n_m for which holds $2\pi n_m l = \bar{u}$. This result has also been verified experimentally. The term $n_m l$ may suitably be given the meaning of the 'phase velocity' of the predominant eddy 'of average size'.

If we now try and translate the subjective descriptions of wind speed observations into these analytical terms, we arrive at the statement that the observer, in watching the subsequent gusts (or their distribution in space), tries to estimate which frequency interval makes the greatest contribution to all gusts observed; he thereby tries to gain an impression of, rather, the 'phase velocity' of the predominant eddy. On an average he will arrive at a velocity $n_m l$ which is proportional to the mean speed $\bar{u}$ of the wind. The scale of mean estimated $n_m l$-values will thus in the first instance be linear with respect to $\bar{u}$. The resolution of the scale into specific numbers depends on the sharpness of the maximum of $nF(n)$ and on the possibility of distinguishing specifications for the 'equivalent wave length' l.

The validity of the space-time relationship $R(x) = R(t)$ may account for the correspondence of wind scales based on observations at sea (mainly $R(x)$) and on land ($R(t)$) respectively at least as far as the lower and medium ranges are concerned, for which the relationship has been verified.

Two important properties of empirical wind scales need to be discussed in some detail: the non-linearity of the scale and the independence of the resolution into specific steps from the wind effects observed.

1.5 The non-linearity of a wind scale

The determination of the mean equivalent speeds corresponding to the numbers of a wind scale involves a comparison of the measured mean speed $\bar{u}_{10}$ (averaging time of 10 minutes) and the estimated mean speed $\tilde{u}$. The difference of sampling gives rise to some statistical effects which will generally affect the linearity of the relation between the two speeds.

1) averaging time

When mean wind speeds $\bar{u}_\tau$ are derived from a record of wind gusts, it may readily be seen that, as the averaging time τ is made larger, the corresponding mean speeds tend to deviate less and less from the overall mean of the entire record. In other words, the gusts will be more and more averaged out.

We may remark that the duration of a visual wind observation is usually less than 10 minutes, except perhaps for storm winds. At sea, for instance, the observer is watching the spatial distribution of wind effects on the sea surface. Since there seems to be a pattern in the wind which tends to repeat itself over 1500 meters or less when the mean wind speed $\bar{u}_{10}$ is 15 m/s (Beaufort force 7) or less, the observer may already get a sufficient impression of the predominant characteristics of the prevailing wind effects by surveying the sea area in the vicinity of the ship. The sea criteria for Beaufort forces 9 and more are less easily distinguishable in practice and it usually takes a much longer time to arrive at a 'satisfactory' estimate. At this range observers may tend to take an average over a longer equivalent period, i.e. a period equivalent to the combination of space and time. When this equivalent period $\tau > 10$ minutes, we will find a higher frequency of cases with $\bar{u}_{10} > u_\tau$ than cases with $\bar{u}_{10} < u_\tau$, so that the series of mean equivalent wind speeds will tend to deviate from linearity, i.e. to larger values. The scale is no more linear, because the situation $\tau > 10$ minutes is only supposed to exist at the upper end of the scale.

2) *lag error*

The mean speed $\tilde{u}$ is an average of certain subjectively distinguishable steps (Beaufort intervals) $\Delta\tilde{u}$ of $\tilde{u}$ which will generally be greater than the changes δu to which an anemometer ersponds. In other words the response time is generally greater for a subjective observation than for the instrumental measurement and consequently the lag error will be greater. This is the cause of the feeling of 'unreliability' which accompanies the subjective observation. A greater lag error generally results in a mean measured value which is less exceptional. When put in subjective wording we may say that, when an observer hesitates between two or three successive numbers of the scale, there is a greater chance that he eventually chooses the number which occurs most frequently; but, as the anemometer only 'hesitates' between values within a scale interval $\Delta\tilde{u}$, the measured speed $\bar{u}_{10}$ will on an average be more exceptional than the observed speed $\tilde{u}$. The effect tends to make the equivalents smaller in the lower ranges of the scale and greater in the higher ranges. The resulting change of the equivalency curve can be described as a rotation around a centre which corresponds to the mode of the wind frequency distribution (normally at forces 4 to 6 for ship observations at the middle latitudes) with a deviation from linearity in that part of the scale where the effect is strongest. We may expect this deviation to occur between forces 2 and 3 where the curve of the wind frequency distribution is normally steepest. It should be noted that the effect of different averaging time works out in the opposite direction at the lower ranges. In the upper ranges the two effects work out in the same direction. The tendencies are schematically indicated in figure 2.

These statistical effects also lead to the phenomenon that observers tend to neglect momentary deviations of the wind speed from generally prevailing conditions. This

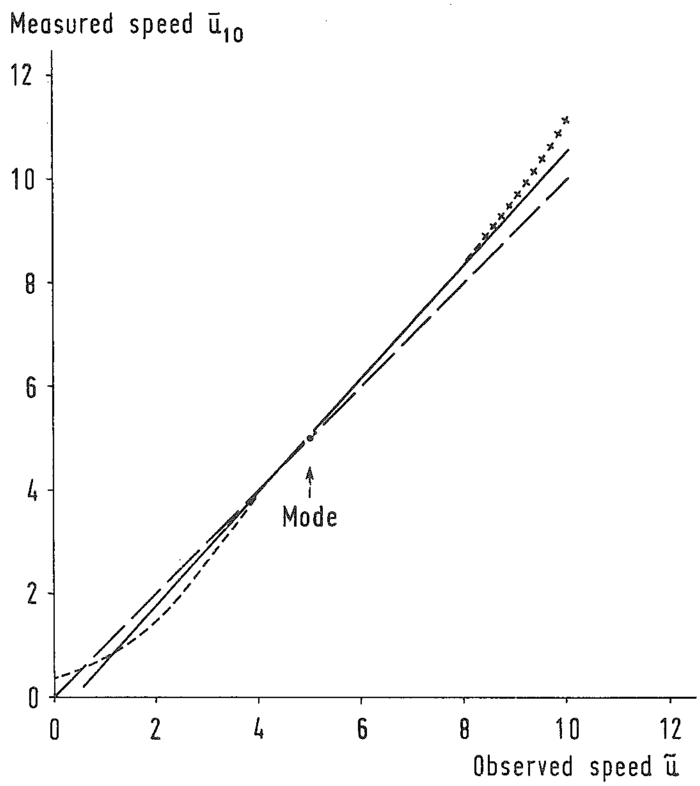

Fig. 2 Scheme, indicating the tendencies of sampling effects.
— — initial identity; assumed
——— differences in lag errors produce a rotation of the initial line and a stronger deviation from linearity at the lower ranges of the scale (-----)
+++ effect of differences in averaging times

makes their series of successive notations of equal wind force generally longer than corresponding series derived from the indications of a wind meter (see table 3).

TABLE 3 *Number of periods of equal wind force (successive observations in pro mille of total number)*

No. of successive obs (at 3-hours interval)	1	2	3	4	5	6	7	8	9	10
observed	236	111	51	32	17	8	7	3	3	2
measured	291	122	59	29	14	5	4	2	2	2

From observations at the Netherlands light-vessel 'Texel' in 1957-58 (see page 22; total number 4141 observations).

3) difference of measuring site — air stability

At sea the observed wind effects refer to wind speeds at a lower level than the speed measured by the anemometer which was, at the various trials, usually exposed at a height of 20 - 30 metres above sea level. The series of resulting mean equivalents should therefore also reflect the variation of the vertical profile of the wind speed with increasing wind force. The stability of the lower air layers is mainly involved in this effect of physical nature, since the variation of the wind speed with increasing height depends on this stability and individual measurements are not generally corrected for such a variation.

The magnitude of this effect was first investigated experimentally by H. U. ROLL (1953) from observations made by himself on board the German fishing escort vessel 'Meerkatze' in the North Sea and the North Atlantic Ocean. The observations, total-

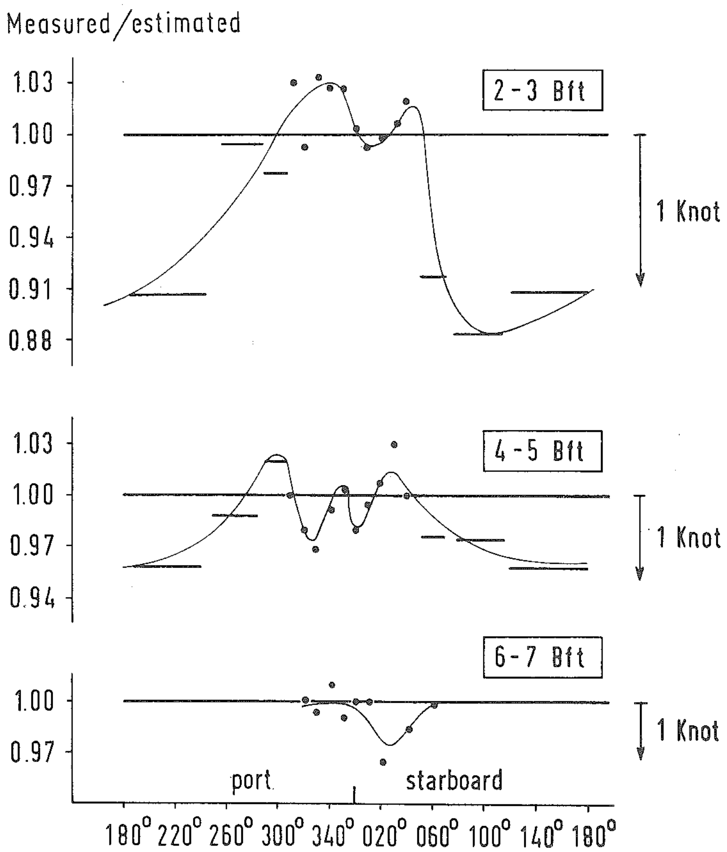

Fig. 3 Variation of the ratio between measured and estimated wind speeds with relative wind direction (zero is head wind) at light-vessel 'Texel' (1957/58).

ling about 700, indicate a change of corresponding equivalents from lower to higher values at the transition from unstable to stable conditions. In the range of wind forces 2 to 6 a difference of approximately 1.3 m/s was found.

The comparative wind observations made in 1951 on board two Netherlands' light-vessels have been investigated by the author (VERPLOEGH, 1956) to determine whether a similar effect occurred or not. At these trials the anemometer was exposed at a height of 7 metres above sea level. The observations (about 1300) did not show a systematic difference of corresponding equivalents at stable and unstable conditions.

The experiment was repeated in 1957 and '58 on board the light-vessel 'Texel'; over 4000 observations were made. This time the cup anemometer was installed on top of the light tower on a special yard-arm extending one metre above the hood and one metre to starboard from the center. The height was 19 m above sea level and about 15 m above the upper deck of the vessel. The disturbing influence of the ship's upper-structure on the air flow at anemometer level appeared to be small as was already indicated by the results of comparative rainfall measurements which were made during the same period (VERPLOEGH, 1962). However, insofar as the effect depends on the relative wind direction, it can directly be investigated on the basis of a comparison with estimated wind speeds which are independent of this direction. The equivalent speeds are graphically shown in figure 3 for certain intervals of relative wind direction; small differences, not exceeding 0.5 m/s, are found at the lower wind forces only.

The measured wind speeds were corrected accordingly; the data were then grouped in intervals of air-sea temperature difference. The equivalent speeds of the boundaries between the Beaufort scale intervals, which are shown in figure 4, were graphically interpolated. In the range between 2 to 8 Beaufort a consistent difference varying from 0.2 to 0.8 m/s is indicated between stable and unstable conditions.

CH. F. and E. S. BROOKS (1958) also found a difference of 0.5 m/s between equivalent speeds at force 5, corresponding to Δ T (air-sea) $\geqslant 2°C$ and Δ T (air-sea) $\leqslant -4°C$ respectively, from observations made on U.S. ocean weather ships and compared to wind speeds measured at heights of 20 and 30 metres.

Recent measurements made on British ocean weather ships (anemometer level at 20 metres) and worked out by H. LUMB (WMO 1964) show a similar difference. This data had not been differentiated according to a greater or lesser degree of stability, which might explain the smaller values of the mean differences.

The results obtained to date are reproduced in table 4.

TABLE 4 *Mean maximum differences of equivalent speeds in m/s between stable and unstable conditions*

Beaufort	1	2	3	4	5	6	7	8
Meerkatze'	0.6	1.2	1.3	1.4	1.3	0.7	0.3	
'Texel'	0	0.2	0.4	0.4	0.8	0.6	0.6	0.2
British O.W.S.	0.6	0.1	0.1	0.6	0.2	0.4	0.6	0.1
U.S. O.W.S.					0.5			

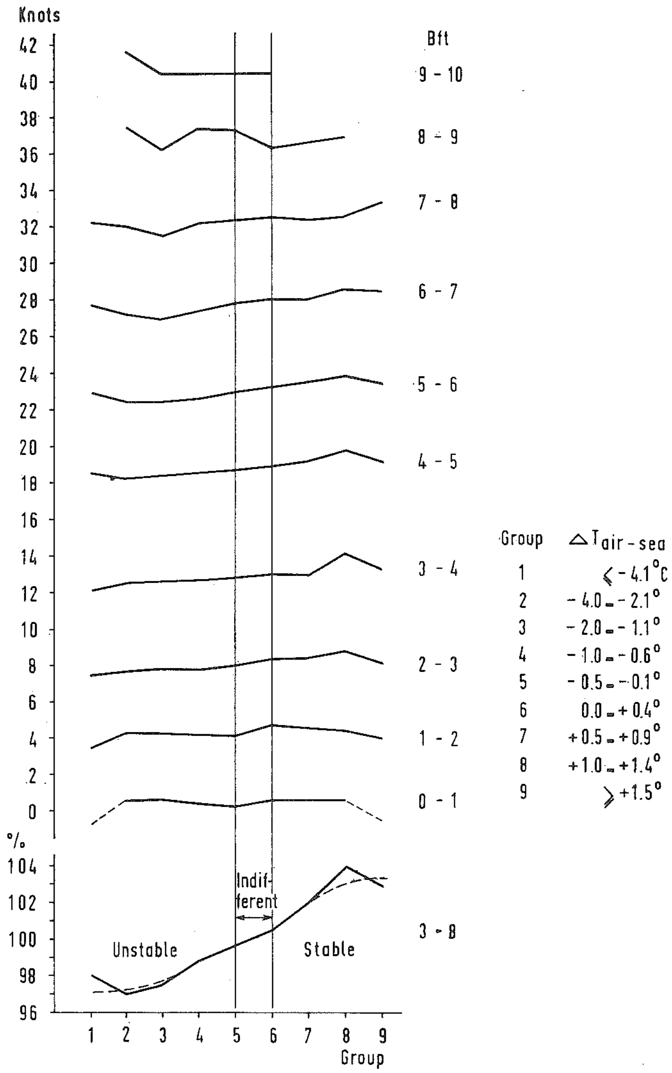

Fig. 4 Equivalent wind speeds to boundaries between Beaufort Scale intervals, for different values of air-sea temperature difference. Lower curve: mean deviation in per cent of equivalents at varying air stability in the range of Beaufort forces 3 — 8.

The sign of the differences corresponds to the variation of the vertical profile of the wind speed with increasing air stability. At higher wind forces we may expect to find smaller differences because of the largely increased vertical exchange of momentum both at stable and at unstable conditions.

H. U. ROLL (1952) also demonstrated numerically that with wind of equal force and within the range of forces 3 to 8, waves will become somewhat higher and steeper in case of unstable conditions of the lower air layers than they will become at stable conditions. It has been suggested by CH. F. and E. S. BROOKS that this phenomenon might also influence the estimates of wind forces in the sense that the wind will be underestimated at stable conditions and overestimated at unstable conditions. According to the comparative measurements described in this paragraph the effect, if it does exist, should be very small on an average, presumably less than 0.2 m/s (which is equivalent to about $^1/_{20}$th interval of the Beaufort scale), since it could not be found from measurements with the anemometer at 7 m height. The other comparisons with wind speeds measured at about 20 m height should still show the effect of the variation of the vertical profile of the wind speed.

As far as the linearity of an empirical wind scale is concerned the influence of the air stability may cause small deviations, predominantly at the medium ranges. In an average scale the deviations will be small, because of the combination of observations made at stable and unstable conditions.

1.6 The resolution of the scale

In the observing practice, the identification of each of the steps of a wind scale which grows from experience, seems possible only when, at the centre of a scale interval, the frequencies of features belonging to adjacent steps are so small that their occurrence can easily be recognized as being marginal. In order to make the scale reproducible for further use it needs to be 'calibrated' in some subjective way, which can only be done on the basis of an easier characterisation of certain steps. The first of the two calibration points which are generally needed may be identified with the distinction between an 'absolute calm' and a 'light air', which determines the lower limit of the scale. As regards the other 'point' the criterion should be that the steps which are frequently used ought to be easily distinguishable from each other. The resolution of the scale at the range of maximum wind frequency should therefore be such that the standard error of estimates is, at the most, half a scale interval.

The scale may thus be thought to have been built up from interpolation between scale number zero and the range of relatively large wind frequency (which varies at sea from 4 to about 7 Beaufort and on land from 3 to about 6 Beaufort) and then from extrapolation on to higher numbers. The extrapolation may become less secure as the higher wind speeds become rarer.

An estimate of the standard error of wind speed estimates may be made from comparative wind measurements, if differences resulting from the heterogeneity of the data compared (the measured $\bar{u}_{10}$ versus the estimated $\tilde{u}$) can sufficiently be eliminated. Two sets of measurements are known which may serve for this purpose. Firstly, the wind meter installed in the light-vessel 'Texel' in 1957 has proved to be sufficiently free from disturbing aerodynamical effects; the possible errors may be considered less than about 3 per cent of the measured mean speed. The influence of the air stability can be eliminated by separating the data at stable conditions from those at unstable conditions. The computed standard deviation refers to the deviations of Beaufort estimates from the mean estimated value in a range of measured wind speeds; this range was chosen as an interval around the mean equivalent speed of the corresponding mean Beaufort interval.

TABLE 5 *Standard deviation of estimates in units of a scale interval; from data at 'Texel' 1957/58*

Beaufort	0	1	2	3	4	5	6	7	8	9	
unstable	0.34	0.44	0.49	0.39	0.32	0.53	0.57	0.51	0.67	0.62	scale units
no of obs.	18	96	316	430	413	481	368	157	53	22	
stable	0.54	0.50	0.50	0.43	0.44	0.47	0.49	0.49	0.46		scale units
no. of obs.	20	84	238	422	482	326	109	52	23		

The computed values show little variation from the overall mean value of 0.50 scale units. It should be noted that the standard deviations at the lower wind forces have been influenced to some extent by the effect of tidal currents on the observation.

A mean standard deviation may also be derived from the investigation into the reliability of wind observations made by 'feel' and from effects on shipborne objects in three British Naval vessels (BURNETT; WMO 1964). The speeds measured by the fixed anemometer in these vessels may be considered to be directly representative for the speeds which were estimated. The results of these measurements have briefly been reviewed on page 14; from the standard deviation of 2.6 knots and a mean scale interval of 5.1 knots the mean value 0.51 in units of a Beaufort scale interval, is obtained.

If the speed $\bar{u}_{10}$ which was measured at these two trials is now identified with the 'prevailing wind speed' which is to be estimated, the standard deviation may be given the meaning of a 'standard error' of estimates. At least up to force 8 the standard error appears to be close to half a scale interval. Its magnitude determines the number of steps of the wind scale in the range where wind effects are still distinguishable, i.e. up to force 12 at sea and up to about force 10 on land.

It should perhaps be stressed that in deriving this 'standard error' of estimates we have purposely restricted the discussion to the case of one observer developing a wind scale from the observation of effects produced by the local wind, or a group of observers doing the same in close collaboration. The reversed and more general question of the reliability of a given wind observation made by an arbitrary observer, at an arbitrary place, is a problem which has, of course, practical importance, but one should then also take into account the question of the representativity of the observation for the purpose needed. We shall return to this question later in chapter 3.

1.7 The interrelation of scale intervals as found empirically

Equivalency curves based on empirical sets of mean equivalent wind speeds may deviate from a straight line in the upper and lower ranges of the scale, as explained in paragraph 1.5, with the effect that they will be slightly bent upwards in these regions. Such bent curves seem to approximate a straight line on a double log. diagram, although it will usually be found that in particular the equivalent speed at Beaufort force 1 and the speeds at the upper end of the scale (at forces 11 and 12) may not coincide with the line of best fit. This feature has in earlier times induced a number of authors (as for instance G. C. SIMPSON and H. ERTEL) to explain the construction of the wind scale on the basis of an exponential relationship.

Although the approximation becomes rather poor as the scale is extended to equivalents above force 8, the slope of the line of best fit which is represented by the exponent k in $v = c.n^k$ (v = wind speed, n = Beaufort number, c = a constant), may be used as an easy and approximate measure to indicate in a comparative way the extent of the departure from a linear relationship. In table 6 the slopes are indicated for a number of empirical series.

Short series extending up to force 7 or 8 show a comparatively small deviation from linearity. The larger slope of the series resulting from wind speed estimates by 'feel' (BURNETT; WMO 1964) may be explained from a larger 'average time' as this method of observation should require more time to arrive at a satisfactory estimate.

The series extending to higher wind forces have generally a larger slope; exceptions are the series derived from light-vessels and from stations inland. On board the 'Gazelle' the wind speed was measured with a hand anemometer; it may very well be that the wind fluctations to which the wind meter responded were not entirely representative for the observing conditions; the resulting difference of response time may be held partly responsible for the relatively large slope.

The great exception is the series originating from Scilly; as compared to the other observations the observer apparently overestimated the smaller wind forces (the equivalents are too small) and underestimated the higher forces (the equivalents are too great). The observation tends therefore to less exceptional values as compared to the speed measurement. According to descriptions given by R. H. CURTIS (1897) and G. C. SIMPSON (1926) the anemometer was sited at the highest point of the small island St. Mary's and had a perfectly free exposure. The observer estimated the wind from effects on the sea surface, but contrary to the practice on board ship he had to watch distant effects while standing 30 to 40 metres above the surrounding sea. This manner of observing may easily lead to values of the estimated speed that are less exceptional than those normally obtained on board ship, since, in fact, an average is being taken of the wind speed over a greater area.

Another interesting analysis can be made as regards the span of the wind scale between its lower limit at force 0 and its centre point at 'force' 5.5 (because the class interval of force 12 is unlimited[1], the last step is in fact 11 and consequently the centre point of the scale relating to marine observations should be taken at 5.5).

1) Before 1948, when the Beaufort scale numbers were used as code figures to report also measured wind speeds, the scale had been extended for this purpose beyond number 12. As the present coding practices render the extension meaningless, it has internationally been dropped.

TABLE 6 *Summary of main properties of empirical series of equivalent wind speeds*

year	origin of series	height wind meter (m)	range of wind forces	exponent k (see text page 26)	equivalent of 5.5 Bft (m/s)
1874/76	'Gazelle' (Krümmel)[1]	6	2–10	1.26	10.0
1888	(Waldo)	9, 26	1–9	1.19	11.8
1897	Scilly (Curtis)	6	1–9	1.41	9.7
1906	Scilly (Simpson)	10	1–10	1.68	11.0
1906	Holyhead (Simpson)	13	1–9	1.00	11.0
1906	Oxford (Simpson)	13	1–8	1.00	11.4
1914	(Gallé)	7, 12	1–7	1.15	11.1
1925/27	'Meteor' - tropics	32	1–7	1.00	11.9
	(Kuhlbrodt) - S. Atl.	32	2–9	1.10	14.0
1936/37	'Schwabenland' - 'Friesenland' (Regula)	15	1–6	0.94	11.0
1953	'Meerkatze' (Roll)	19	1–7	1.10	11.2
1956	German light-vessels (Richter)	20	1–11	1.00	11.0
1956	Dutch light-vessels (Verploegh)	7	1–7	1.07	11.3
1956/57	'Willem Barentsz'[2]	40	1–10	1.30	12.3
1957/58	'Texel' (Verploegh)[3]	19	1–10	1.13	11.8
1963	Canadian O.W.S. (Allan)[4]	20	1–7	1.13	11.8
1963	British O.W.S. (Lumb)[4]	20	1–12	1.21	11.5
1963	'Louis Sheid' (Dury-Verploegh)[4]	25	1–10	1.17	11.1
1963	Relative wind by 'feel' (Burnett)[4]	20	1–8	1.32	12.0
1772/73	'Halfweg' (Havinga, 1948)	25	1–7	1.03	11.3

[1]) see ref. 4; [2]) see page 29 of this paper; [3]) see page 22 of this paper; [4]) see ref. 34.

It was assumed, and the empirical results seem to confirm this, that the statistical effects of the comparison between $\bar{u}_{10}$ and $\tilde{u}$ affect the linearity of the scale only in the lower and upper ranges, leaving the medium range, and of course the lower limit at force 0, practically unaltered. The assumption implies that the equivalent speed of the scale's centre point only depends on the measuring conditions of the anemometer used for the comparison. Considering perfectly free exposures, the conditions to be reckoned with are the height of the anemometer level and the stability of the lower air layers.

The equivalent speeds shown in table 6 should reflect therefore the mean variation of the wind speed with increasing height. However, since the exposures of the wind meters may generally not have been 'perfectly free', we may expect a rather large spread. The deviations due to the influence of the air stability on these mean values may be considered rather small, presumably not exceeding 0.3 m/s, as most maritime observations have been made at more or less equal conditions, i.e. in areas where the sea surface temperature is on an average slightly higher than the temperature of the adjacent air.

In the graph of figure 5 the equivalent speeds are compared to curves representing the mean variation of the wind speed with increasing height, according to a number

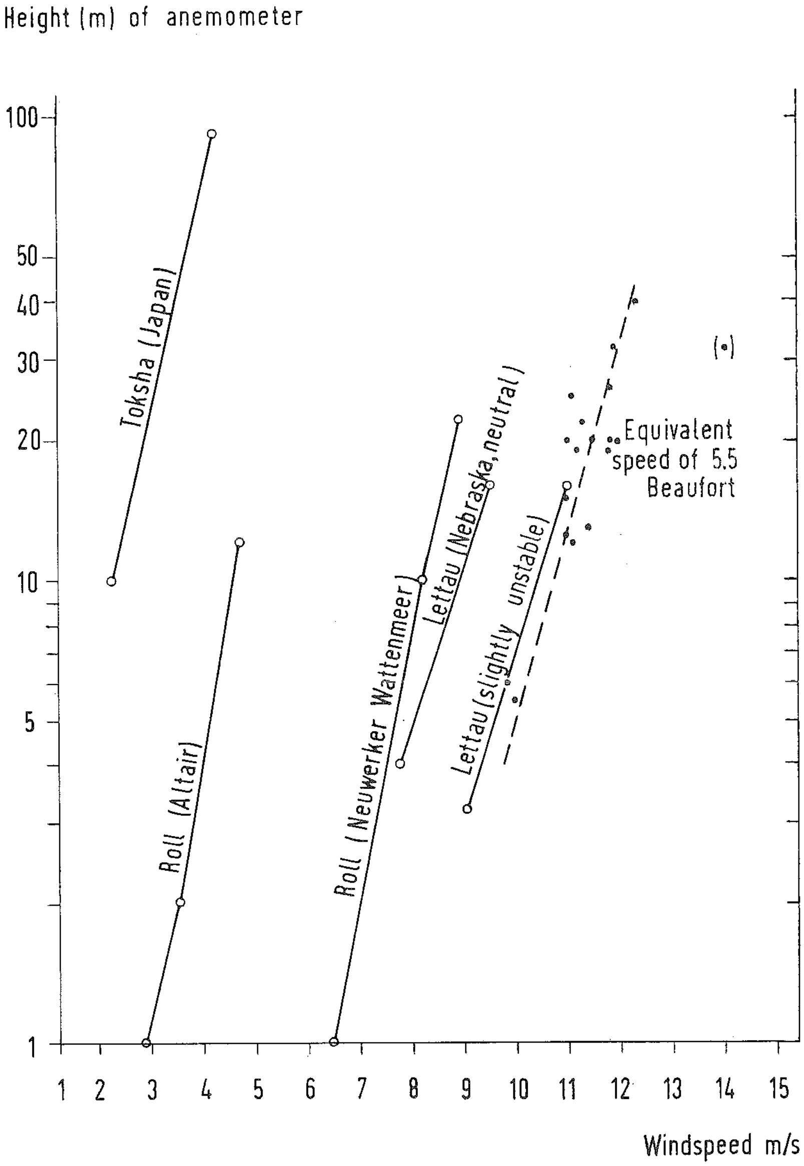

Fig. 5 Variation of equivalent speed to Beaufort scale 'number' 5.5 with height of the anemometer used in the experiment. The variation is compared to several determinations of the vertical profile of the wind speed (e.g. reference 32).

of direct measurements. In computing a regression line the exceptional value of 14.0 m/s from the 'Meteor' observations at the South Atlantic has been neglected; the value from the Netherlands light-vessels referring to an anemometer height of 7 m has also not been used, as later measurements revealed the occurrence of a mean acceleration of the air current at the position of the anemometer cups.

On board the Netherlands whaler 'Willem Barentsz' the wind speed was estimated and measured during the season of 1956/57. The resulting mean equivalent speeds will not be representative for average standard because of the high position of the anemometer, at 40 m above the sea, but as regards this comparison the equivalent speed of the scale's centre point gives useful information.

The influence of the air stability at the land stations Oxford and Halfweg is very difficult to evaluate. For instance, the correction for aerodynamical effects which HAVINGA had applied to the computed equivalents may have been too large, as particularly the early morning observations must often have been made at pronounced stable conditions. The height of the anemometer which would be equivalent to conditions of indifferent stability will probably be less than 25 m.

In spite of the inexactness of the data the regression line seems to give a fair representation of the vertical wind profile as actually measured. The standard deviation of equivalent speeds with respect to the line of regression amounts to 0.7 m/s. It can furthermore be concluded from this that when these 18 sets of measurements are used to establish a certain anemometer height as reference level of the adopted mean series of equivalents, the standard deviation of the mean equivalent of 'force' 5.5 will be $\pm$ 0.15 m/s or, in other terms, the standard deviation of the mean level corresponding to an adopted mean equivalent speed will be $\pm$ 3 m at a height of about 20 m.

1.8 Mean equivalent speeds of the Beaufort scale numbers

Early studies made in the latter half of the 19th century have been reviewed by R. H. CURTIS (1897) who himself determined a series of equivalents on the basis of a detailed comparison of wind observations and anemometer records from a number of English coastal stations. The specific problem at that time appeared to be the establishment of suitable anemometer constants.

Another review was given by W. KÖPPEN (1898) who discussed a number of earlier determinations made from measurements on board ship and combined the results into a series of mean equivalents. His series became known as the 'Seewarte' series. KÖPPEN raised an important question of statistical nature. If the equivalents are computed from the regression of mean measured speeds at given Beaufort numbers, the mean will be dependent to some extent on the frequency distribution of wind speeds measured during the experiment, because the scale intervals comprise a certain range of measured speeds. The other regression of mean Beaufort estimates at given measured speeds will be independent of this distribution. The difference has an important consequence as regards the extrapolation of computed equivalents on to higher wind forces for which usually few observations are available. Since KÖPPEN's study the equivalents have normally been computed according to the latter regression.

In deriving equivalent speeds from a number of British coastal and inland stations G. C. SIMPSON (1906) averaged the individual series 'in treating all the estimates as though they have been made at the same place and by the same observer', with the effect that the Scilly observations which largely outnumbered those from the other stations strongly dominate in the resulting series of equivalents. A mean curve of the form $v = c\,n^{3/2}$ (see page 9) was adapted to the empirical values; the resulting series of equivalents became known as the 'Met. Office' series.

The discrepancies which occurred between the 'Met. Office' and 'Seewarte' series had been very difficult to explain because of the varied nature and sometimes insecure basis of the individual measurements. Undoubtedly further experiments were needed. This conclusion was added by SIMPSON to his recommendation in 1926 of a mean series for international use, which he obtained by averaging his and KÖPPEN's equivalents in a rather special way. From a comparison of the respective equivalents at force 8 he concluded that the mean speeds should correspond to readings of an anemometer at a free exposure of 6 m above the ground. This suggestion has been discussed by KÖPPEN (1926) and more recently by VERPLOEGH (1956). From the discussions of the foregoing paragraphs it may be concluded that the equivalent speed at force 8 cannot be a sufficiently representative measure of the variation of the wind speed with increasing height.

In 1946 the former 'Met. Office' series was adopted for international use. The change was considered necessary as a consequence of a recommendation to raise the standard height, for which the surface wind speed is given in coded reports, from 6 to 10 m (IMC, 1946).

Ten years later the Commission for Maritime Meteorology of WMO adopted a recommendation (ref. 25) for a new series of equivalents which had been derived by VERPLOEGH (1956) from measurements made at Netherlands and German light-vessels and a number of earlier empirical sets referring to observations made in the Atlantic Ocean. The proposal was, however, not accepted by the Executive Committee of WMO. The discussions on this series revealed the need for a greater number of reliable observations in the upper range of the scale; for this purpose new experiments were set up in the years between 1960 and 1963 by a number of maritime countries. The results have been made available to all members of the Commission (ref. 34).

In view of their historical importance the series mentioned in this review are reproduced in table 7.

TABLE 7 *Some earlier series of mean equivalent wind speeds (m/s)*

Beaufort	0	1	2	3	4	5	6	7	8	9	10	11
R. H. Curtis (1897)	0.9	1.8	3.1	4.5	6.3	8.5	11.2	13.9	16.5	19.7	23.7	28.6
W. Köppen (1898)	0	1.7	3.1	4.8	6.7	8.8	10.7	12.9	15.4	18.0	21.0	24.4
G. C. Simpson (1906)	0	0.9	2.7	4.7	7.2	9.8	12.5	15.4	18.8	22.4	26.4	–
'Met Office' series (international (1946))	0	0.8	2.4	4.3	6.7	9.4	12.3	15.5	18.9	22.6	26.4	30.5
International (1926)	0.2	1.1	2.5	4.3	6.3	8.6	11.1	13.8	16.7	19.9	23.3	27.1
G. Verploegh (1956)	0.3	1.5	3.4	5.6	7.8	10.2	12.6	15.1	17.7	20.4	23.3	26.5

A number of old and recent empirical series have been compiled in table 8; their main properties have been discussed on page 27.

TABLE 8 *Equivalent wind speeds in m/s*

	Beaufort number	0	1	2	3	4	5	6	7	8	9	10	11
1874/76	'Gazelle'		–	3.2	4.9	6.8	9.3	11.0	14.1	16.7	19.9	23.4	
1888	Waldo		2.2	3.1	5.4	7.3	10.2	13.3	15.5	17.0	19.2		
1914	Gallé		2.2	3.5	5.5	7.8	10.1	12.2	14.4				
1925/27	'Meteor' - tropics	–	–	3.6	5.6	7.7	9.9	11.9	(13.8)				
	'Meteor' - S. Atl.			(3.0)	6.5	9.0	11.6	14.4	17.3	20.1	22.5		
1936/37	'Schwabenland' - 'Friesland'		2.6	4.3	6.1	7.9	10.0	11.7	(13.5)				
1953	'Meerkatze'		1.8	3.7	5.6	7.8	9.9	12.4	(15.0)				
1963	'Louis Sheid'		2.5	4.0	5.1	7.6	9.7	11.8	14.6	17.7	19.5	(22)	
1963	British O.W.S.		1.7	3.9	5.6	7.9	10.2	12.6	15.1	17.8	21.8	24.6	27.9
1963	Canadian O.W.S.	0.6	1.9	3.8	6.1	8.4	10.5	12.8	15.4				
1963	Burnett (true wind)		2.0	3.4	5.6	7.8	9.7	12.8	15.0				
1963	Burnett (relative wind)		1.0	3.1	5.3	7.8	10.7	13.3	16.2	(19.6)			
1950	German light-vessels		2.9	4.4	6.1	7.8	9.9	12.1	14.1	16.3	17.9	20.1	25.8
1957/58	'Texel' light-vessel		1.2	3.3	5.4	8.1	10.7	13.1	15.5	17.8	19.9	21.7	
1772/73	Halfweg		–	3.8	6.2	8.3	10.3	12.0	14.8				
1906	Holyhead		2.2	4.5	6.7	8.2	10.1	11.8	14.1	17.9	22.8		
1906	Oxford		1.1	3.4	6.0	8.5	10.7	12.1	13.6	15.7			

The foregoing analysis has shown that one should distinguish between wind speed estimates from nearby wind effects (comparatively short averaging time; light-vessels and land stations) and estimates made on board ship where the observer is able to watch effects over a large area (which is equivalent to a greater averaging time). For the latter maritime observations the following set of mean equivalent speeds is derived (table 9).

TABLE 9 *Equivalent speeds for observations on board steamships*

Beaufort number	equivalent speeds in metres per sec. mean	limits	interval between limits	interval lower half	interval upper half	in knots mean	in knots limits
0	0.8	0– 1.3	–	–	0.5	1	0– 2
1	2.0	1.4– 2.7	1.3	0.6	0.7	4	3– 5
2	3.6	2.8– 4.5	1.7	0.8	0.9	7	6– 8
3	5.6	4.6– 6.6	2.0	1.0	1.0	11	9–12
4	7.8	6.7– 8.9	2.2	1.1	1.1	15	13–16
5	10.2	9.0–11.3	2.3	1.2	1.1	19	17–21
6	12.6	11.4–13.8	2.4	1.2	1.2	24	22–26
7	15.1	13.9–16.4	2.5	1.2	1.3	29	27–31
8	17.8	16.5–19.2	2.7	1.3	1.4	35	32–37
9	20.8	19.3–22.4	3.1	1.5	1.6	41	38–43
10	24.2	22.5–26.0	3.5	1.7	1.8	47	44–50
11	28.0	26.1–30.0	3.9	1.9	2.0	54	51–57
12	–	⩾ 30.1	–			–	⩾ 58

The values in the second column have been obtained by averaging the corresponding equivalents of the individual sets; some minor corrections, not affecting the span of the scale were applied in order to arrive at a regular increase of the intervals. The rate of increase of the half-intervals is symmetric with respect to the centre point at 'force' 5.5, as is also shown in figure 6.

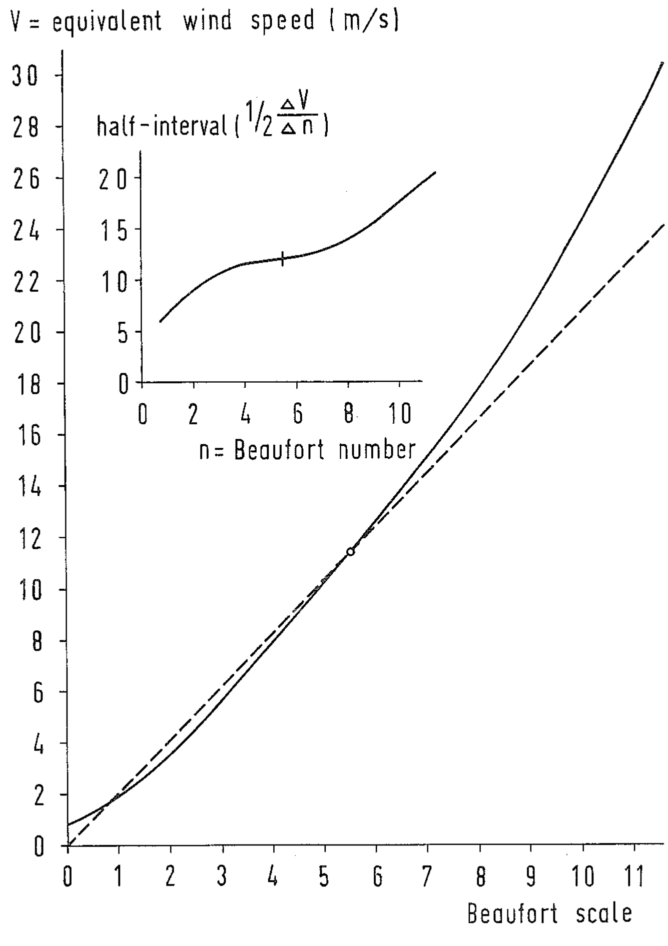

Fig. 6
Speed equivalency curve to the Beaufort Scale, relating to the equivalent speeds of Table 9.

For observations made at land stations and in light-vessels the following scale may apply.

TABLE 10 *Equivalent speeds for observations at land stations and in light-vessels (m/s)*

Beaufort	0	1	2	3	4	5	6	7	8	9	10	11
equivalent speed	0	2.0	4.0	6.0	8.1	10.2	12.3	14.5	16.9	(19.6)	(22.7)	(26.2)
interval	2.0	2.0	2.0	2.1	2.1	2.1	2.2	2.4	2.7	3.1	3.5	

This scale is of less importance in meteorology, as the wind speed is generally measured at these stations. The computed mean values have been adjusted somewhat in order to arrive at regular scale intervals. The approximate linearity of this scale up to force 7 may be accounted for by the fact that the measured wind speed is a better representative for the estimated value. Above force 8 the speed values are extrapolated by means of a similar increase of intervals as is indicated by the former series for maritime observations.

The reference height of wind speeds obtained from observations on board ship may be determined, from the equivalent speed at the centre point of the scale, at 18 *m above the sea surface.*

1.9 The precision of observations now made at sea

Since 1949 the estimated wind speeds have been reported in units of nautical mile per hour (knot). The observer is thus given the opportunity to distinguish between a number of subintervals of a Beaufort interval; this number varies in the international Beaufort Scale from three, at Beaufort force 1, to eight at force 11. From the manner in which the average observer utilises these subintervals a further insight into the precision of estimation may be obtained. Figure 7 gives a frequency distribution of wind speed estimates obtained from an arbitrary sample of a large number of observations (over 71 000) made in the North Atlantic Ocean during winter months.

Apart from a distinct preference for even numbers one may notice a well-defined bias in favour of the speed in the centre of a Beaufort interval. The lag effect is furthermore shown by a distinct drop of the frequencies at the intersection of two Beaufort intervals. The common feature of the distributions within a Beaufort interval appears to be that in a number of cases the report merely indicates the respective Beaufort number, while in other cases an attempt is made to distinguish between the upper and the lower half of the interval. The fraction of the former cases can be computed in the following way.

In the absence of any preference the m_k subintervals of the k-th Beaufort interval, containing n_k observations, would each contain the same number n_k/m_k observations. Suppose a fraction $\alpha_k n_k/m_k$ of each of the other subintervals is reported in the subinterval which represents the Beaufort number as a whole and which contains therefore a peak number n_{kp}. Then

$$n_{kp} = n_k/m_k\,(1 + (m_k - 1)\,\alpha_k) \qquad (9)$$

Denoting the observed number of observations of the j-th subinterval with n'_{kj} $(j = 1 \ldots p \ldots m)$ and taking

$$n_{kp} = n'_{kp} \qquad (10)$$

and
$$(1 - \alpha_k) n_k/m_k = \frac{1}{(m_k - 1)} \sum_{1}^{m_k} n'_{kj}\,(j \neq p) \qquad (11)$$

the fraction α_k may be computed for each Beaufort interval. We find from the sample of data (see table 11):

TABLE 11 *Fraction of non-specified Beaufort estimates*

Beaufort	1	2	3	4	5	6	7	8	9	10	mean
α_k	0.33	0.37	0.35	0.29	0.31	0.38	0.44	0.35	0.40	0.46	0.37

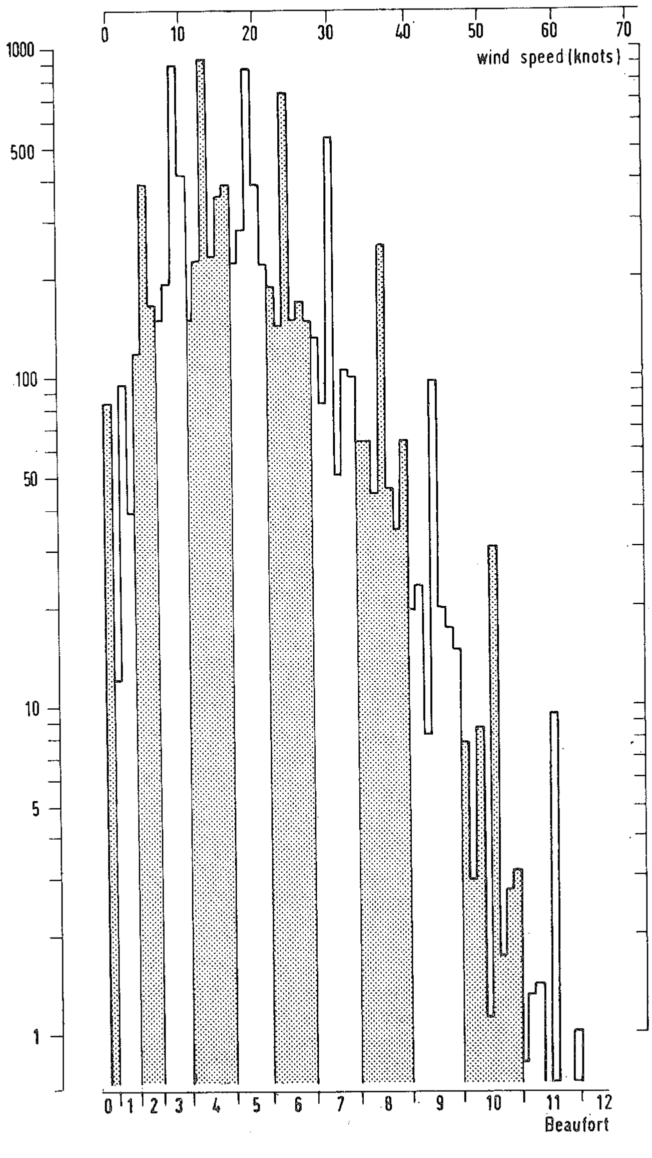

Fig. 7 Frequency distribution (log. scale) of estimated wind speeds, from 71606 Netherlands ship observations in North Atlantic Ocean during winter months (October — April) in the years 1949 — 1962.

It can easily be shown that the fractions are not significantly different, the standard deviations of these values amounting to 0.03 up to force 8 and rising to 0.10 at force 10. The result indicates an equal precision of estimation within a Beaufort interval at all wind forces; it may be considered as an indirect confirmation of the approximate constancy of the standard error of observation with increasing wind force. The analysis indicates that when an observer is given the opportunity to distinguish wind speeds within a Beaufort interval, he usually tends to consider three possibilities: a lower, a middle and a upper subinterval. The middle one will then contain $100/3 \times (1 + 2 \times 0.37) = 58$ per cent of the observations and the other two an equal number of 21 per cent.

When wind speed estimates are reported in knots or in m/s the lag effect, the bias towards even numbers, and the bias towards the centre value of the interval, will largely diminish any gain in precision obtained by subdividing a Beaufort interval. *It would therefore be sufficient for all practical purposes in climatology and synoptic meteorology to have the estimated wind speed reported by means of the mean equivalent speed of a Beaufort number.*

1.10 Concluding remarks

The equivalent wind speeds given in table 9 may be considered representative for observations now made at sea. The form of the equivalency curve can be understood on the basis of the assumption that it is the gustiness of the wind which is primarily observed. As the intensity of gustiness appears to be dependent of the mean wind speed, the observation of the time sequence or the space distribution of gusts leads to a scale of wind 'forces' which is proportional to the mean wind speed.

Because of statistical effects which play a role in the comparison between estimated and measured speeds the curve deviates from linearity, particularly in the lower and upper ranges of the scale. The underlying assumption does not make it necessary to have the form of the equivalency curve explained by means of a psycho-physical relationship; the explanatory assumption already includes a subjective reproducibility of the scale regardless of the nature of wind effects observed.

The general rule which is confirmed by experiment may be worded as follows: observers who are accustomed to their surroundings, i.e. experienced in observing wind effects on environmental objects, will be able to distinguish mean wind speeds to the same degree of precision whatever wind effects are observed.

For most purposes, the overall error of an estimated wind speed which is reported by an arbitrary observer may be indicated by means of a standard deviation of the estimate, with respect to the mean equivalent speed of the corresponding Beaufort number. The overall error is generally made up of three types of errors: (a) the standard error of observation which amounts to half a Beaufort interval; (b) an error due to the fact that the reported unit (m/s or knot) indicates a greater precision than actually is obtained; the Sheppard correction for grouping data in classes should therefore be added; (c) an error due to a possible systematic deviation from the adopted mean equivalency curve in the lower and upper ranges of the scale. This error depends on the conditions of observation, for instance observers standing high above the surrounding sea or on a low deck. An estimate of this type of error is possible from the variation of the exponent k in table 6, it appears to be one order of magnitude smaller than the errors mentioned under (a) and (b).

Enumerating the various errors gives rise to a standard deviation of the overall error $\sigma = 0.58$ I, where I is the Beaufort interval as given in m/s or knots according to table 9.

In the past 70 years the development of thoughts on the reliability of equivalent speeds to the Beaufort wind scale has largely been influenced by results from observations made at some coastal stations, Scilly in particular. The discrepancy of the Scilly series of equivalent speeds with respect to results obtained from measurements in ships and at stations in land was difficult to explain, in view of the large number of observations from Scilly (2630, with 16 observations of Beaufort forces 9 and 10) and the fact that the lighttower watchman at the island of St. Mary's (Scillies) was known to be a very conscientious observer and that the anemometer had an excellent exposure. Recently other series of equivalent speeds became known, also based on a large number of observations, which confirmed earlier results obtained from ship observations; e.g. British O.W.S. (WMO, 1964) with 2781 observations (159 of Beaufort forces 9 to 12 inclusive).

It is explained in this study, that a conscientious observer, by watching distant wind effects on the sea surface from comparatively great heights (30 to 40 m above the sea) and by waiting a fairly long time before he has made up his mind, increases the 'averaging time' of his observation as compared to the common practice on board ship. The watchman at Scilly, to whom this applies, tended therefore to overestimate small wind speeds and underestimate large speeds. For this reason the equivalent speeds to the 'Scilly wind scale' are smaller in the lower ranges and greater in the higher ranges than corresponding equivalent speeds to the Beaufort Scale with applies to observational practices on board ship.

1.11 Wind direction

The wind direction is estimated from the orientation of crests of wind waves, and from the direction of streaks of foam markedly blown by the wind; the direction is reported in tens of degrees. Before 1949 the 32 compass points were used in reporting the wind direction, the reports were, however, strongly biased in favour of cardinal, quandrantal and intermediate points.

Compass points are still commonly being used in everyday conversation and in official weather bulletins; we may therefore expect that the wind directions which are reported at present are biased in much the same way as they were in earlier times.

In investigating this bias from the frequency distribution of wind directions care should be taken to eliminate any climatological predominance of certain directions. For this reason a sample was taken comprising a large number of observations in the area of the South Indian Ocean, lying south of 35° S. In this region the wind direction is sufficiently variable, and as it includes the 'roaring forties' the observations made

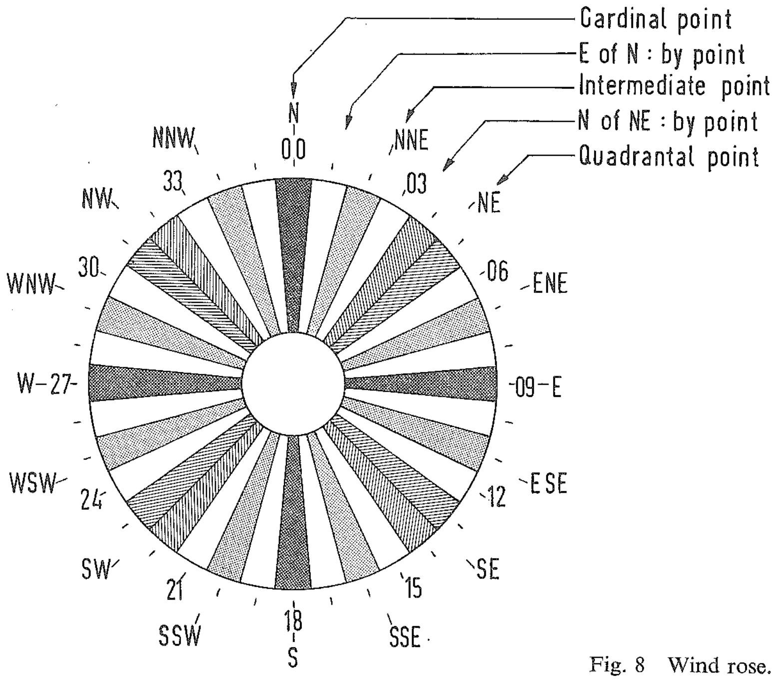

Fig. 8 Wind rose.

in heavy storms will be well represented. Over 70 000 observations were taken from the available climatological data which give the wind direction in 16 compass points, the relatively very few observations at the other points having been equally divided over the adjacent classes.

The observations were listed according to the Beaufort force of the wind; for each group the percentage number of cardinal, quadrantal and intermediate points was computed. The resulting percentages in figure 9 show some interesting features. From Beaufort force 4 the quadrantal points make up exactly one quarter of the total number, there is apparently no preference for either a quadrantal or an intermediate point. However, the latter are biased in favour of cardinal points; the wind force does not seem to have any influence on this effect, except at light winds. In this range the quadrantal points also appear to have attracted some preference. The number of observations at force 12 was too small yet (32 as compared to 506 at force 11) to give reliable information.

The data enable an estimate of the standard error of observation on the basis of the following assumptions. (1) Observational errors have a normal (Gaussian) distribution as a consequence of the empirical circumstance that instantaneous deviations of the mean wind direction are also distributed normally. (2) In cases of doubt the observer will choose at random between quandratal and intermediate points, but when there is a choice between cardinal and intermediate points the former will always be reported. This assumption is made on the basis of the described features of the computed percentages.

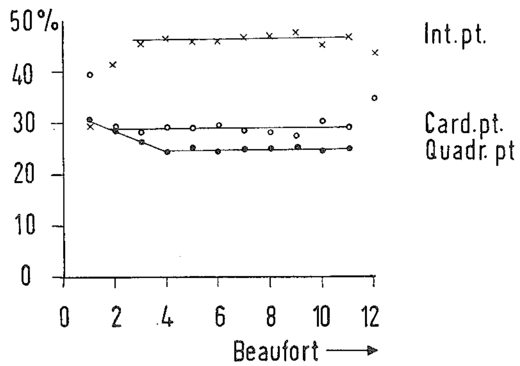

Fig. 9 Relative frequency of reported compass points of wind direction, from 70733 ship observations in the South Indian Ocean.

Thus, it is assumed that the percentage number of observations erroneously not reported in the interval of an intermediate point, represents an area under the curve of the normal distribution of errors (deviations from the centre of the compass point) which falls outside the boundary between a cardinal and an intermediate point. As an average over wind forces 4 through 11 the excess of observations reported in a cardinal point is 3.9% : 25% = 0.156, which corresponds to the computed fraction of 3.9% : 50% = 0.078 of which an intermediate point is short. This value corresponds to a standard deviation of 8° of a normal distribution of which 7.8 per cent falls outside the range of $11\frac{1}{4}$ degrees from the centre. At Beaufort force 2 the shortage of 8.1 per cent at the intermediate points appears to be equally divided over the other two compass points. This value also leads to a standard deviation of 8°.

The suggested constancy of the standard deviation with increasing wind speed is consistent with the results of empirical studies on air turbulence (ref. 31). These indicate that the standard deviation of the wind direction itself is independent of the mean wind speed (it amounts to about 6° over grassland). It should be remembered that as the wind speed increases the signs at the sea surface, which indicate the mean wind direction, become more and more well defined. For instance, the orientation of 'white horses' on the crests of wind waves clearly indicate the mean wind direction from about force 4, while from force 8 the white streaks of foam left behind on the irregularly undulating sea surface facilitate the observation.

The results of this investigation should be restricted to wind conditions at middle and higher latitudes; the direction of constant trade and monsoon winds may be estimated with greater accuracy as is indicated in logbooks by the greater precision of these estimates.

The current practice of reporting wind directions in tens of degrees gives rise to another bias which favours even numbers. In figure 10 an example is given of this effect, which clearly indicates that the 'normal' error is increased in a complicated manner. Because of this new bias it is not possible to interpret reported directions with greater precision than in classes of 20 degrees. A figure which would approximately represent the standard error of these reports may be obtained by adding the Sheppard correction for class intervals to the value of 8°. In this way a standard deviation of 10° is obtained which, however, no longer corresponds to a normal distribution of errors.

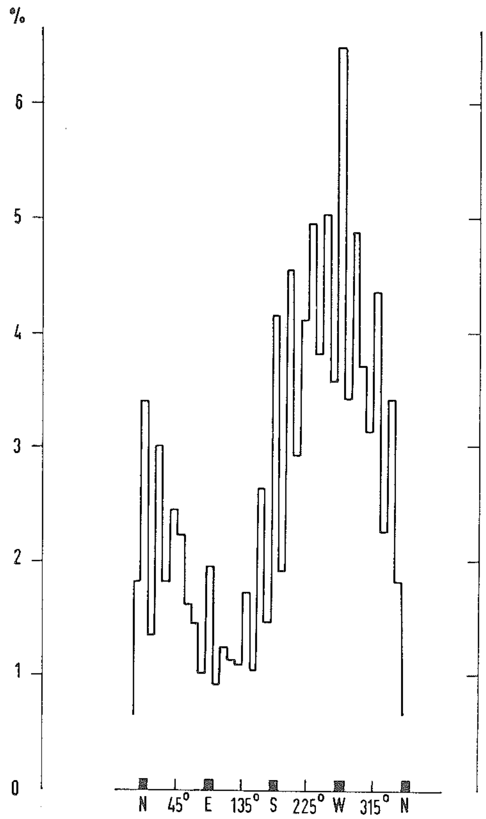

Fig. 10 Relative frequency of observed wind directions, in tens of degrees, at wind forces 3 to 8 inclusive, in the North Atlantic Ocean.

2. THE MEASUREMENT

2.1 A method of comparing the reliability of different measuring techniques

The use of an anemometer on board ship enables the local true wind to be determined with greater precision (although not necessarily with greater reliability) than a visual observation would allow. However, no data are available on the overall reliability of this method when carried out routinely on board merchant vessels. The instrumental errors due to insufficient protection against salting, and those associated with rolling and pitching of the vessel are relatively small for a reliable instrument (M. SANUKI and S. KIMURA, 1953). However, a fixed anemometer often cannot be given a sufficiently free exposure because the site of the wind meter is in part determined by conditions of the vessel's operation and by the accessibility of the instrument. This is the main factor limiting the reliability of the anemometer reading as a measure of the wind speed and direction.

A fixed anemometer is generally installed at a height of about 20, 30 or sometimes 40 m above the sea surface. As the readings are not converted to speeds at a certain standard level and are consequently not corrected for the influence of air stability on the variation of the wind speed with increasing height, they indicate a speed which may deviate, sometimes considerably, from the value which is actually wanted. Furthermore, computational errors in the resulting true wind speeds and directions are inherent to the routine character of the measurement.

The reliability of values of measured winds may quantitatively be investigated by a comparison between measured and estimated values, once a sufficiently reliable mean equivalency and overall error of the latter observations are known. From considerations in the previous chapter it seems worthwhile to develop this idea and apply the results to some experiments that were specially set up for the purpose.

When different methods of measuring the relative wind, or different exposures, are being compared, it is of advantage to directly compare the instrumental readings. When different ships are involved, we need a uniform standard of comparison. In the following discussion it will be shown that, with certain restrictions, we may take as standard the relative wind speed and direction, derived from the estimated true wind with the help of the ship's known speed and course.

We write:

$\bar{r}$ = measured relative wind speed

$\tilde{r}$ = relative wind speed, derived from the observed (estimated) true wind and the ship's known speed and course

$$\begin{aligned} \bar{r} &= \bar{r}_0 + \delta\,\bar{r} \\ \tilde{r} &= \tilde{r}_0 + \delta\,\tilde{r} \end{aligned} \tag{2.1}$$

in which the reference values $\bar{r}_0$ and $\tilde{r}_0$ are defined in such a way that the deviations $\delta\,\bar{r}$ and $\delta\tilde{r}$, due to measuring and observational errors respectively, are zero when averaged: $\overline{\delta\,\bar{r}} = \overline{\delta\tilde{r}} = 0$.

Since each deviation $\delta \bar{r}_i$ may be considered independent of the deviation $\delta \tilde{r}_i$ of the corresponding observation, because the wind speed is estimated independently of the measurement of the relative wind, the variance of the differences $(\bar{r} - \tilde{r})$ can be written as

$$\sigma^2 (\bar{r} - \tilde{r}) = \sigma^2 (\bar{r}) + \sigma^2 (\tilde{r}) + (\bar{r}_0 - \tilde{r}_0)^2 \tag{2.2}$$

The same analysis can be applied to the simultaneous observations of the direction of the relative wind. When

$\bar{\beta}$ = measured direction of the relative wind
$\tilde{\beta}$ = direction of relative wind, as derived from the observed (estimated) true wind and the ship's known speed and course

and writing in a similar way

$$\bar{\beta} = \bar{\beta}_0 + \delta \bar{\beta} \qquad \tilde{\beta} = \tilde{\beta}_0 + \delta \tilde{\beta} \tag{2.3}$$

we obtain

$$\sigma^2 (\bar{\beta} - \tilde{\beta}) = \sigma^2 (\bar{\beta}) + \sigma^2 (\tilde{\beta}) + (\bar{\beta}_0 - \tilde{\beta}_0)^2 \tag{2.4}$$

Values of $\sigma(\tilde{r})$ and $\sigma(\tilde{\beta})$ can be derived from the geometric construction of the relative wind, shown in figure 11. An error $\delta\tilde{u}$ of the estimated wind speed and an error $\delta\tilde{\alpha}$ of the estimated direction (taken relative to the ship's course) both result in corresponding errors $\delta\tilde{r}$ and $\delta\tilde{\beta}$ of the computed relative wind r. For small errors and $r \neq 0$, one may write (see figure 12):

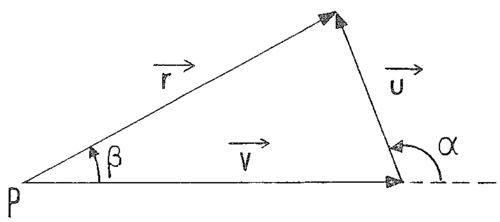

Fig. 11 Wind diagram.

P = origin
v = head wind due to ships' velocity
u = true wind speed
r = speed of relative wind
α = direction of true wind, relative to the ship's course
β = direction of relative wind

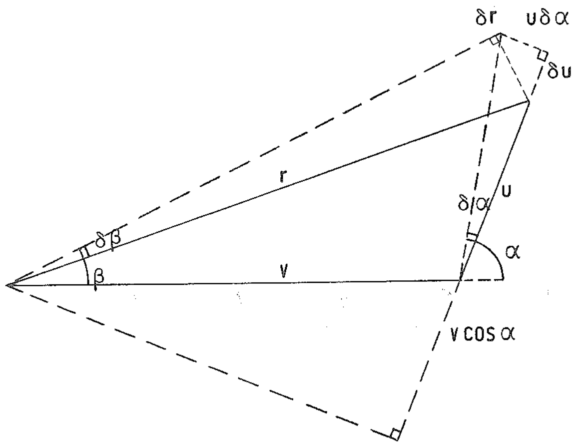

Fig. 12 See text.

$$\delta\tilde{r} = \cos(\alpha - \beta)\,\delta\tilde{u} - u\sin(\alpha - \beta)\delta\tilde{\alpha} \quad (2.5)$$

$$r\delta\tilde{\beta} = \sin(\alpha - \beta)\,\delta\tilde{u} + u\cos(\alpha - \beta)\,\delta\tilde{\alpha}, \quad (2.6)$$

which leads to

$$r\delta\tilde{r} = (v\cos\alpha + u)\,\delta\tilde{u} - v\sin\alpha\, u\delta\tilde{\alpha} \quad (2.7)$$

$$r^2\delta\tilde{\beta} = v\sin\alpha\,\delta\tilde{u} + (v\cos\alpha + u)\,u\delta\tilde{\alpha} \quad (2.8)$$

Introducing the standard errors of observation $\sigma(\tilde{u})$ and $\sigma(\tilde{\alpha})$ and bearing in mind that $\delta\tilde{u}$ and $\delta\tilde{\alpha}$ are not correlated because the speed and the direction of the true wind are estimated independently, the variances $\sigma^2(\tilde{r})$ and $\sigma^2(\tilde{\beta})$ can be expressed into the following relations.

$$r^2\sigma^2(\tilde{r}) = (v\cos\alpha + u)^2.\sigma^2(\tilde{u}) + v^2\sin^2\alpha.u^2\sigma^2(\tilde{\alpha}) \quad (2.9)$$

$$r^4\sigma^2(\tilde{\beta}) = v^2\sin^2\alpha.\sigma^2(\tilde{u}) + (v\cos\alpha + u)^2.u^2\sigma^2(\tilde{\alpha}) \quad (2.10)$$

It should be noted that the comparatively small inaccuracies of the true speed and course of the ship have been neglected in this computation. We may take these into account, according to the geometric construction, as an extra inaccuracy of the estimated true wind.

We now return to the meaning given to the standard deviations $\sigma(\bar{r})$ and $\sigma(\bar{\beta})$. If the standard errors $\sigma(\tilde{u})$ and $\sigma(\tilde{\alpha})$ are known, we may compute the variances $\sigma^2(\tilde{r})$ and $\sigma^2(\tilde{\beta})$ by means of relations (2.9) and (2.10). From a set of comparative wind measurements we may also compute the variances $\sigma^2(\bar{r} - \tilde{r})$ and $\sigma^2(\bar{\beta} - \tilde{\beta})$. Relations (2.2) and (2.4) enable us to compute the quantities $\sigma^2(\bar{r}) + (\bar{r}_0 - \tilde{r}_0)^2$ and $\sigma^2(\bar{\beta}) + (\bar{\beta} - \tilde{\beta}_0)^2$, of which the second terms represent the squared systematic differences between the mean measured relative wind speed and direction and the mean speed and direction obtained indirectly from estimated true winds. If there is no systematic difference, the method enables the computation of the overall errors of measurement $\sigma(\bar{r})$ and $\sigma(\bar{\beta})$. In this way the reliability of measurements made with different instruments at different exposures can be compared. If we would extend the comparison to instrumental readings made on different vessels, at different occasions, the true wind should preferably be estimated at these vessels according to the same average standard.

As we have seen in the previous chapter, for oceangoing vessels such a standard does seem to exist in the range of Beaufort forces 3 up to and including 8. Taking in this range $\sigma(\tilde{u}) = 0.6$ I (I being the corresponding interval of a Beaufort wind force in m/s, see para 1.10) and $\sigma(\tilde{\alpha}) = 10°$ or 0.1745 radians, we arrive at the following set of values for $\sigma^2(\tilde{u})$ and $u^2\sigma^2(\tilde{\alpha})$.

Beaufort	3	4	5	6	7	8	
$\sigma^2(\tilde{u})$	1.42	1.74	1.91	2.07	2.25	2.62	$(m/s)^2$
$\alpha^2\sigma^2(\tilde{u})$	0.92	1.76	2.98	4.60	6.75	8.80	,,

Equivalent speeds and intervals have been taken from table 9, page 31.

2.2 Experimental results

Towards the end of 1960 a programme of special wind measurement was set up by the 'Service Météorologique de la Régie des Voies Aériennes' of Belgium. Mr. J. M. DURY of this Service initiated and developed the programme with the present author who worked out the computations. The cargo-vessel s.s. 'Louis Sheid', under the command of Captain A. DE BILDE, was chosen to take part in the programme. This vessel has just been presented with an award for outstanding meteorological observations.

In the s.s. 'Louis Sheid', which had a normal speed of 14 knots, a wind meter was placed on top of the Samson post on starboard. The wind meter had the form of an aerovane (a small aeroplane), measuring both the speed and the direction of the relative wind, and was manufactured by the Koshin Electric Industry Co, Ltd in Japan. It will be referred to as the Koshin Vane. The mean height of the aerovane above the sea surface was about 25 m, its height above the bridge about 6 m. As the bridge house of the ship extends also 6 m above the main deck, it cannot be said that the exposure of the anemometer was entirely free from the disturbing influence of the upperstructure of the ship. However, the position seemed to offer the best compromise with regard to the management of the instrument and the operation of the ship as a cargo-vessel.

The programme also included the measurement of the relative wind speed with a hand anemometer, to be exposed at a suitable place. This place was usually the flying deck on top of the bridge house. The measurements on board the 'Louis Sheid' may be considered fairly representative of routine wind measurements on board merchant vessels. The fact that the officers were aware of the experiment may not have influenced the representativity much, as the experiment lasted about three years and ship officers changed during that period.

At every observation hour the force and the direction of the true wind was estimated in the usual way, i.e. on the basis of the appearance and the direction of the wind waves. The ship generally steamed along routes across the North Atlantic Ocean, mostly in the vicinity of the southern track for low powered steamers, between the English Channel and the Gulf of Mexico. The observations were made in ocean areas devoid of strong currents which might cause large errors in the observed wind force. The mean equivalent wind speeds which resulted from a comparison with the Koshin Vane measurements are shown in table 8 on page 31; they were computed from a total number of 486 observations. They show that the observers evaluated the force of the wind without a systematic deviation from normal practice, as indicated by the mean equivalents of table 9. It is important to note that these equivalents were not known to the observers who were acquainted with the internationally adopted equivalents which are different. This circumstance is a further prove of the independent character of the estimates with respect to the measured speeds and directions.

In computing the standard deviations the material has been divided in four groups according to the angle of incidence of the true wind; the sectors of 90° each refer respectively to head winds, beam winds (port or starboard) and winds from astern.

The results are:

Koshin Vane	HEAD	PORT	STARBOARD	ASTERN
$\overline{(\bar{r} - \tilde{r})}$	-1.2 m/s	-0.2 m/s	-0.1 m/s	0.2 m/s
$\sigma^2(\bar{r} - \tilde{r})$	3.56 $(m/s)^2$	3.35 $(m/s)^2$	4.08 $(m/s)^2$	3.50 $(m/s)^2$
$\sigma^2(\bar{\beta} - \tilde{\beta})$	62.32 deg.^{2}	124.96 deg.^{2}	91.06 deg.^{2}	1905.82 deg.^{2}
No. of obs.	144	84	110	94
Hand anemometer				
$\overline{(\bar{r} - \tilde{r})}$	-1.1 m/s	-0.5 m/s	-0.5 m/s	0.2 m/s
$\sigma^2(\bar{r} - \tilde{r})$	6.58 $(m/s)^2$	5.03 $(m/s)^2$	5.76 $(m/s)^2$	3.45 $(m/s)^2$
Estimates				
$\sigma^2(\tilde{r})$	2.18 $(m/s)^2$	1.93 $(m/s)^2$	1.88 $(m/s)^2$	1.80 $(m/s)^2$
$\sigma^2(\tilde{\beta})$	31.28 deg.^{2}	74.50 deg.^{2}	69.64 deg.^{2}	1160.07 deg.^{2}
mean speed $\tilde{u}$	9.5 m/s	9.0 m/s	9.0 m/s	8.5 m/s
mean speed $\tilde{r}$	16.0 m/s	11.0 m/s	11.0 m/s	4.0 m/s

The resulting 'comparative standard errors' are:

HEAD	PORT	STARBOARD	ASTERN	HEAD-PORT-STARB.
$\sigma(\tilde{r})$ 1.48 m/s	1.39 m/s	1.38 m/s	1.34 m/s	1.42 m/s
Koshin Vane				
$\sigma(\bar{r})$ 1.18 m/s	1.19 m/s	1.50 m/s	1.30 m/s	1.29 m/s
Hand anemometer				
$\sigma(\bar{r})$ 2.10 m/s	1.76 m/s	1.97 m/s	1.28 m/s	1.98 m/s
$\sigma(\tilde{\beta})$ 5.6°	8.6°	8.3°	34°	7.4°
Koshin Vane				
$\sigma(\bar{\beta})$ 5.6°	7.1°	4.6°	27°	5.8°
			mean speed $\tilde{u}$	9.2 m/s
			mean speed $\tilde{r}$	13.2 m/s

Before discussing these figures another experiment will shortly be mentioned which refers to wind measurements conducted on board the Netherlands cargo-vessel 'Straat van Diemen' (K.J.C.P.L.) during the latter half of 1960 in the Chinese Sea and surrounding waters. In this ship, which had a normal speed of 18 knots, a cup anemometer was installed on top of a Samson post between the foremast and the bridge house, at a height of 26 m above the sea surface. The wind meter had an exposure described by the Shipmaster as unsatisfactory, on the basis of his observation that the behaviour of the rotating cups did not correlate with the sailing capacities of birds in the vicinity of the instrument. The wind direction was not measured on board this vessel. As the wind force was also estimated during the measurements it will be interesting to see what figures result from a similar analysis of measured speeds which, for other reasons, were found unreliable.

Restricting the material to observations of head, port and starboard winds, as above, the 141 observations gave the following results:

$\overline{(\bar{r}-\tilde{r})}$	: −0.2 m/s	$\sigma(\tilde{r})$:	1.32 m/s
$\sigma^2(\bar{r}-\tilde{r})$:	4.29 (m/s)^2	$\sigma(\bar{r})$:	1.60 m/s
$\sigma^2(\tilde{r})$	: 1.74 ,,	mean speed $\tilde{u}$:	8.5 m/s
		mean speed $\tilde{r}$:	13.2 m/s

We may compare the latter results with those obtained from the 'Louis Sheid'. We may safely assume that instrumental errors are negligible for all three instruments; the differences of $\sigma(\bar{r})$ are largely to be attributed to differences of exposure. As might be expected, the hand anemometer gives the least reliable readings. It is interesting to see that in the case of following winds the direction of the relative wind becomes rather indeterminate, both by measurement and computation. The fact that the Koshin Vane was installed on starboard may explain the larger deviations of the measured wind direction from port and of the measured speeds from starboard. More observations are, however, needed to investigate these directional differences in closer detail.

2.3 On the reliability of the true wind obtained from measurement

For meteorological purposes it should be sufficient to report the true wind speed in units of one metre per second, which roughly equals 2 knots and which corresponds to about half a Beaufort scale interval. In view of the accuracy obtained by measurement a greater precision seems fallacious, as shown next.

On board the 'Louis Sheid' the computed true wind speeds were mostly rounded off to whole m/s, sometimes the speed was given in half m/s. The analysis by the present author included a recomputation of true wind speeds, already computed on board ship; quite naturally, in some instances a slightly different result was obtained. As computational errors can never be avoided in routine work, it will be very instructive to see the order of magnitude of the errors which appear from this investigation into observations made by, nevertheless, enthusiastic and reliable observers.

The differences of true wind speeds, as computed from the Koshin Vane readings on board and by the author are distributed as follows:

difference (m/s)	−5	−4	−3	−2	−1	0	1	2	3	4	5	6
no. of obs.	*1*	*1*	*11*	*9*	*61*	*315*	*72*	*11*	*6*	*1*	—	*1*

The (symmetric) distribution is not normal; although there is a preponderance of very small differences due to a different way of rounding off, the larger differences of 3 m/s occur rather frequently.

An indication of the effect of exposure can be found from a comparison between the true wind speeds computed from the hand anemometer readings and those of the Koshin Vane, taking the relative wind direction as read from the Koshin Vane.

The resulting differences of hand anemometer minus Koshin Vane are:

difference (m/s)	−7	−6	−5	−4	−3	−2	−1	0	1	2	3	4	5	6	7
no. of obs.	*1*	—	*3*	*4*	*19*	*38*	*95*	*205*	*65*	*35*	*14*	*6*	*1*	*1*	*2*

This almost symmetric distribution is also not normal, the larger differences occurring too frequently. In about 10 per cent of the cases the difference amounts to more than 2 m/s (roughly one Beaufort interval). The data give an indication of the magnitude of differences one may expect to find between wind speed reports of two steaming vessels which both carry an anemometer, SOLELY on the basis of measuring errors.

It may be inferred from these comparative studies, which include only a few of several sources of error, that the overall error of measurement should at least be taken at 1 m/s in the range up to wind force 10 to which the 'Louis Sheid' observations refer. In this range the overall error of wind speed estimation has the mean value of 1.3 m/s.

As regards the true wind direction, the observations enable its computation from the Koshin Vane readings and also from speeds read by hand anemometer combined with relative wind directions as read from the Koshin Vane. A comparison of the results of these two different methods is quite interesting, as it gives an indication of the influence of the accuracy of the wind speed measurement on the accuracy of the resulting true wind direction.

The distribution of differences is found to be:

difference	0°	5°	10°	15°	20°	25°	30°	35°	40°	90°
no. with pos. sign	*248*	*66*	*33*	*21*	*9*	*2*	—	*1*	*3*	*1*
no. with neg. sign		*46*	*31*	*12*	*6*	*4*	*5*	*4*	*1*	

The standard deviation of the distribution is 10°. The same comparison was made using the true wind directions obtained from the Koshin Vane readings and computed on board. The introduction of routine errors has the effect that the distribution of differences now ranges from −90° to +90°, the standard deviation amounts to 14°. The larger differences are of course found in cases of winds coming in from astern; in these cases the indirect measurement of the true wind direction is least reliable. *Since the visual direct observation may be regarded reliable for meteorological purposes and comparatively accurate (standard error* 10°), *the larger computational errors might be avoided in wind measurement if the observer checks his computed wind direction by means of direct visual observation. This check should belong to the regular procedure of wind measurement on board moving vessels.*

2.4 Conclusions

A practical question in meteorology is whether it is warranted to try and introduce a general rule for the observation of wind on board ship, viz. that wind should be measured instead of estimated visually. The answer is self evident in the rare case of winds of hurricane strength, because of the limit of estimation in this range. At normal wind conditions and in storms, the 'Louis Sheid' observations illustrate that the accidental errors of wind measurement have the same order of magnitude as those of wind estimates. The measuring errors depend, however, on the relative wind direction. If one receives a wind report from a steaming vessel on which an anemometer is installed, one should be aware of the fact, that the report will be less reliable in the case of a following wind.

As in shown in para 2.2, the reliability of the measuring site on board ship may be tested in a comparative way on the basis of wind estimates.

The comparison of measured and estimated winds can of course never reveal the existence of systematic errors in one of the two methods. Some sort of standard should be included in the discussion. First of all the standard will include the mean equivalency curve, like the one, for instance, that was derived in chapter 1 from a large number of empirical studies. Secondly, because the equivalence can only be empirically derived, one should know the factors which cause a deviation from the mean equivalency curve, and the sign and possible magnitudes of the deviation itself. These were discussed in chapter 1.

3. ON THE ANALYSIS OF SURFACE WINDS

3.1 The surface gradient wind

The method used in the Netherlands for routine analysis of wind fields is based on the elaborate study of the relation between wind and pressure in the friction layer of the atmosphere, made in 1915 by T. HESSELBERG and H. V. SVERDRUP. From a simplified equation of motion which describes the balance of the gradient force, the Coriolis force and the friction force acting on a non-accelerated unit of mass of air, it was shown that the friction angle β (see figure 13) is a constant with respect to the speed and direction of the surface wind, for given conditions of the vertical mass exchange. On the basis of an assumed proportionality between the friction force and the surface wind speed, the friction angle can be related to two other friction quantities which are commonly used in practice: the friction coefficient c, defined by relation (3.2) and the angle α between isobar and surface wind direction.

$$\text{tg}\, \beta = \text{cotg}\, \alpha - c.\, \text{cosec}\, \alpha \quad (3.1)$$

$$v = c/f.\, G \quad (3.2)$$

where v = surface wind speed, G = gradient force and f = Coriolis parameter.

HESSELBERG and SVERDRUP give values for β for a number of land stations. The frictions angles vary from 35° to 49°. The authors observed that the differences should not need to indicate real differences of conditions pertained to friction. The measuring circumstances (type and exposure of anemometer, local practices of estimating the wind speed) may probably play an important role.

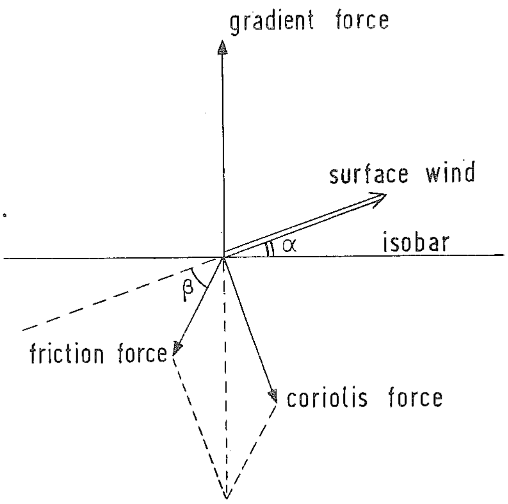

Fig. 13

Forces on a non-accelerated volume of air.

The present author derived mean values of c and α for given ranges of air — sea temperature difference (the usual parameter for the stability of the lower air layers above the sea surface) from about 4000 ship observations in the North Atlantic Ocean.

The resulting friction angle β appeared to have a constant value of 42° (unpublished report). The data were used by H. C. BIJVOET (1957), together with older data computed by W. BLEEKER, in his study on the determination of the surface wind from weather charts, which led to the construction of a new overlay to be used in routine work.

It may be noted here that empirical data of the friction coefficients are usually derived with the help of estimated wind speeds. In these particular studies suitable equivalents to the Beaufort Scale were taken.

In constructing his overlay BIJVOET discussed in detail the influence of non-stationary effects, in particular the isallobaric effect. He showed with some examples that a neglect of the effect may give rise to errors of c exceeding 10 per cent in the vicinity of fast moving fronts and troughs and near rapidly deepening pressure centres. In applying a correction one should, however, analyse the issallobaric field in close detail, for, as BIJVOET was able to show, even greater errors are introduced when the distances over which $\Delta p/\Delta t$[1] is determined are taken too large, i.e. larger than about one degree latitude. For this reason it does not seem possible to apply a suitable correction when determining the gradient wind over ocean areas from the available ship reports. On the other hand, practice has shown that the reported surface winds in the vicinity of deepening pressure systems often deviate consistently from the computed surface gradient wind by more than 5 knots. Especially in view of wave forecasting such systematic errors should be avoided in analysing wind fields. A possible solution for routine work might be to construct models of excessive cases and apply the resulting correction whenever a similar case turns up.

Although BIJVOET's overlay was originally constructed for an easy determination of the surface gradient wind at one latitude (55°) only, but for four specific values of air — sea temperature difference, the present author found that its principle may also be applied in the construction of a suitable overlay for an entire ocean area, extending over a large range of latitudes. The coefficients appearing in the gradient wind equation — the friction coefficient, the air density and the Coriolis parameter — attain values which coincide in such a way as to permit a formal conversion of the correction due to changing air stability, into a correction of latitude. The error thus introduced does not exceed 4 per cent. For a proof the reader is referred to BIJVOET's original study from which it may easily be deduced.

The new overlay which was constructed by the present author is reproduced on page 50; the upper diagram shows how to determine the wind speed at stable or unstable conditions. The thick curve indicates the correction to be applied to the real latitude when the local air-sea temperature difference deviates from zero. For instance, when at latitude 50 N $T_a - T_s = -2$ °C, one should take the wind diagram constructed for latitude 45 N. The set of diagrams enable a quick and detailed determination of the surface gradient wind over large ocean areas (see figure 15).

[1] $\Delta p/\Delta t$ commonly the three-hourly change of local air pressure.

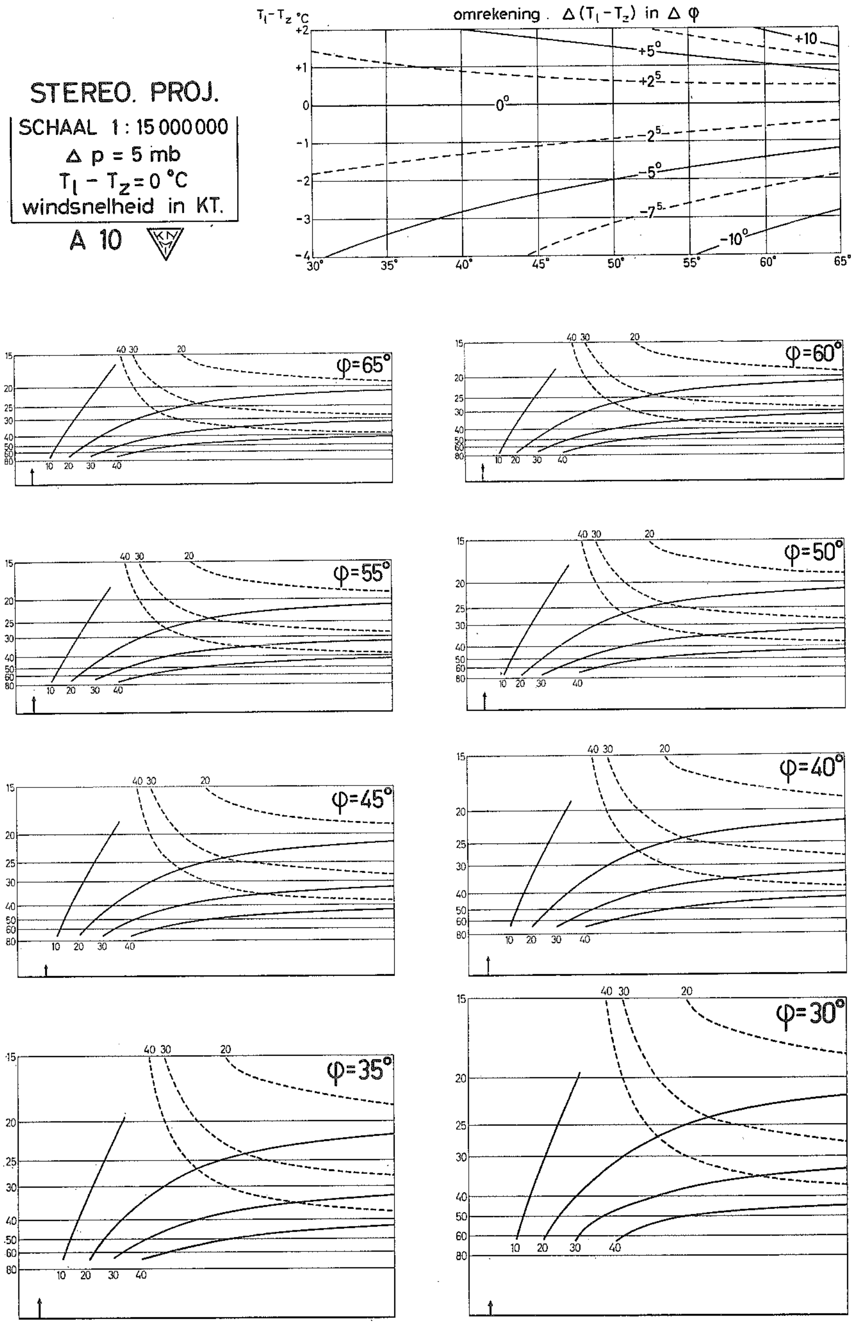

Fig. 14 Scale for surface gradient wind in knots.

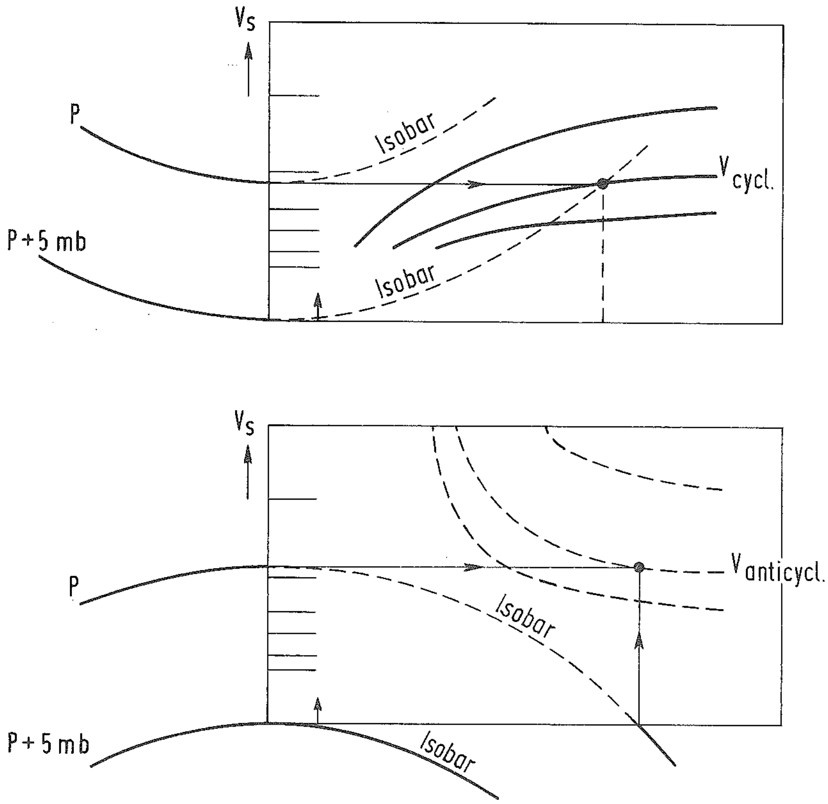

Fig. 15 Use of overlay for determination of surface wind speed over sea from pressure gradient. The scale V_s refers to geostrophic conditions (straight isobars).

3.2 On the comparison of observed winds and surface gradient winds

The surface gradient wind usually represents a mean figure over an area of roughly one degree latitude in diameter. Local wind reports may deviate from this value because of local differences of the wind speed and direction. This feature has not always sufficiently been recognized. The ill-fame of wind speeds obtained by estimation probably stems from the rather common practice, in routine analyses, of assuming too easily that observers' errors are the cause of the often large differences.

In order to get an insight into the order of magnitude of local wind differences a tabulation was made of pairs of observations from ships sailing within 60 n.miles of each other on the North Atlantic Ocean. Care was taken to include only cases of 'synoptically homogeneous' conditions, i.e. as far as the macro-analysis allowed, the overall wind conditions should be equal at the two vessels. Since all observations, except a very few, referred to estimated winds, only observations made in full daylight, at 1200 GMT, were used. Surface gradient winds were also computed over the areas concerned from weather charts.

The first question we want to investigate is, if a ship is reporting a certain wind speed, which speed may we expect to be reported from another ship in the immediate vicinity as described above. To find an answer on this question the two ship reports to be compared were noted as A and B, ship A always being to the north or to the west of ship B in the small area. Since the pairs of observations were taken all over the ocean, the selection is an arbitrary one with respect to the pressure gradient and thus also with respect to the sign and magnitude of the wind speed difference between A and B. Indeed, as may be seen from the data given in table 12, identical distributions of reported wind speeds at A and at B were obtained. In this table the wind speeds which were reported in knots were reconverted into numbers of the Beaufort Scale, in which scale the wind force was originally observed.

TABLE 12 *Contingency table of wind forces, observed simultaneously at 12.00 GMT on board ships sailing within 60 n.miles from each other. North Atl. Ocean, carefully selected cases of 'homogeneous' weather in the area; winter.*

ship B	ship A											
Beaufort	0	1	2	3	4	5	6	7	8	9	10	sum
0	2	–	6	2	1							11
1	1	6	11	5	5	1						29
2	–	3	20	27	12	8						70
3	4	6	32	86	57	26	2					213
4		3	4	62	94	49	11	4				227
5		3	6	26	70	133	74	22	8			342
6			1	3	18	69	57	30	9			187
7				2	4	18	33	50	23	3		133
8						1	10	18	24	7	4	64
9							1	10	6	6	1	24
10								2	2	2	1	7
sum	7	21	80	213	261	305	188	136	72	18	6	1307

The marginal frequency distributions have the following characteristics:

— mean wind force at A and at B : 4.80 Beaufort

— standard deviation at A and at B : 1.80 Beaufort.

The contingency table appears to be symmetrical with respect to the 45°-line through the origin; in other words A and B can be interchanged. We have:

— correlation coefficient : $r = +0.76$

— standard deviation s(A) of A with respect to the regression in line $\bar{A}$ against B, which is equal to the standard deviation s(B) of B with respect to the other regression line of $\bar{B}$ against A : 1.17 Beaufort.

Thus, a wind report from a second ship, sailing within 60 n.miles from the first reporting vessel in a 'synoptically homogeneous' area, may deviate from the first report according to a distribution which has a standard deviation of 1.17 Beaufort, as an average over all wind forces 1 to 10. The deviations are also caused by observational errors. In Chapter 1 the latter error was estimated at 0.58 Beaufort. Subtraction of the corresponding variances gives an estimate of the variance of real wind force differences in the area. The resulting standard deviation appears to be 1.03 Beaufort or 2.2 m/s.

The observed wind speeds at A and B were each compared to the corresponding surface gradient wind W, after conversion of the estimated wind forces into knots by means of the equivalents given in table 9, page 31. The differences of A to W and B to W were investigated at those ranges of the gradient wind, which correspond to successive Beaufort intervals. As it is not necessary to distinguish between A and B, the ship reports will be referred to as (A, B) in the next table.

TABLE 13. *Comparison of observed speeds and computed gradient wind speeds*

	Range of W (according to Beaufort intervals)	(1–2)	3	4	5	6	(7–10)	all speeds
(a)	$\overline{(A,B-W)}$ (knots)	0.09	0.72	1.16	-0.98	1.17	0.72	
(b)	$\overline{(A,B-W)^2}$ $(knots)^2$	15.37	20.65	22.83	18.38	29.49	34.40	24.80
(c)	standard deviation derived from $(b)^{1/2}$	3.9	4.6	4.8	4.3	5.5	5.9	5.0

The mean differences *do not* deviate significantly from zero. It should be reminded that the variance $\overline{(A,B - W)^2}$ refers to differences between the gradient wind W and the individual observed wind speeds in the small areas over which the particular value of W was measured. Since the gradient wind speed constitutes in fact an average speed over the area concerned, we should compare W to the *average* of the observed wind speeds, if we want to arrive at an estimate of the mean 'standard error' of W. This estimate can be obtained by subtracting from the variance $\overline{(A,B - W)^2}$ the variance of differences between local ship reports. Table 13 indicates $\overline{(A,B - W)^2} =$ 24.80 knots = 1.38 Beaufort. From table 12 $s^2(A) = s^2(B)$ was found to be 1.36 Beaufort. Thus, the differences between local ship reports appear to account wholly for the observed difference (A,B — W).

The results of this comparison are partly trivial. Firstly, they arise from a selection of cases in which the pressure gradient could rather accurately be determined in the vicinity of the ships. A similar selection was made in the earlier studies from which the friction coefficient *c* had empirically been established. The result $\overline{(A,B - W)} = 0$ has therefore no other meaning but a confirmation of these earlier results.

The comparison of standard deviations indicates that the surface gradient wind had not been determined independently of the reported wind speeds in the area. It is very difficult to determine the pressure gradient with sufficient accuracy without having at least a rough idea of the local wind speed. This is because even a comparatively dense network of ship reports permits local adjustments of the isobaric spacing which may very easily result in gradient wind speed variations of about 5 knots. If the weather charts were analyzed without a knowledge of reported wind speeds, the interpolation errors would have dominated. As it was not intended to investigate errors of this kind, it could not be avoided to consider the general order of magnitude of wind speeds reported in the surrounding areas. Consequently, all that may be inferred from the data given here is merely that the meteorologists who performed the analysis had acquired from experience a rather good knowledge of the possible differences between reported speeds and those computed from the pressure gradient.

As regards wind direction, the analysis may give more information, as the direction of the isobars could be determined accurately enough without using reported wind directions. The data were grouped according to the same ranges of W. The angle α was taken at 15° for unstable conditions, at 20° for stable conditions and at an intermediate value for neutral stability and at wind forces above Beaufort 8. These values resulted from an earlier study by VERPLOEGH (internal report, see BIJVOET (1957).

TABLE 14 *Comparison of observed directions and computed gradient wind direction*

	Range of speeds W (Bf)	1–2	3	4	5	6	7–10	≤ 3	≥ 4
	Wind direction								
(a)	mean (A–B)	2.7°	–0.6°	–1.1°	–0.9°	–1.4°	0.9°	0.2°	–0.4°
(b)	mean (A,B–W)	–0.5°	1.8°	3.3°	1.1°	–0.8°	0.2°	1.3°	0.9°
(c)	variance $(A–B)^2$	880	672	516	432	400	300	720	423
(d)	variance $(A,B–W)^2$	853	542	343	355	317	272	615	323
(e)	no. of cases	49	159	249	326	263	259	208	1097
(f)	overall error of observation (see page 39)							10°	10°
(g)	estimate of st. dev. of local differences, derived from $((c) - 2.(f)^2)^{1/2}$							23°	15°
(h)	estimate of st. dev. of W, derived from $((d) - (f)^2 - {}^1/_4(g)^2)^{1/2}$							20°	13°

The analysis shows that, while the mean values which had been taken for the angle α represent the average conditions sufficiently well, for specific cases deviations may occur which have the same order of magnitude as the local differences of the wind direction within the chosen area.

3.3 Surface wind charts

The discussion of the previous paragraphs was mainly focussed on the significance of actual wind observations with respect to analysing surface wind patterns over the ocean. It is endeavoured to have the analysis (diagnosis of wind patterns) primarily based on wind observations from ships, while the isobaric pattern is used to interpolate over ocean areas where ship reports are lacking. The interpolation is guided by the principle that the analysis should give consistent wind patterns on subsequent charts. The possibility of bringing out significant details should be investigated in each case on the basis of an error discussion of the observations, in connection with the reliability of the analysis of the isobaric pattern over the area concerned.

A knowledge of the structure of characteristic wind patterns (models) in the various pressure systems is a help for the drawing of forecast wind charts from prognostic weather charts.

In this connection the thorough study of A. I. SORKINA (1958) on 'the Preparation of Surface Wind Charts over Seas and Oceans' should be mentioned. While SORKINA focussed her attention on the relation between the isobaric gradient and the surface wind speed and direction, the present study on the significance of maritime wind observations may be considered as a supplementary investigation.

Charts 1 to 4 give examples of some characteristic surface wind patterns which may be found in developing and mature depressions over the Atlantic Ocean.

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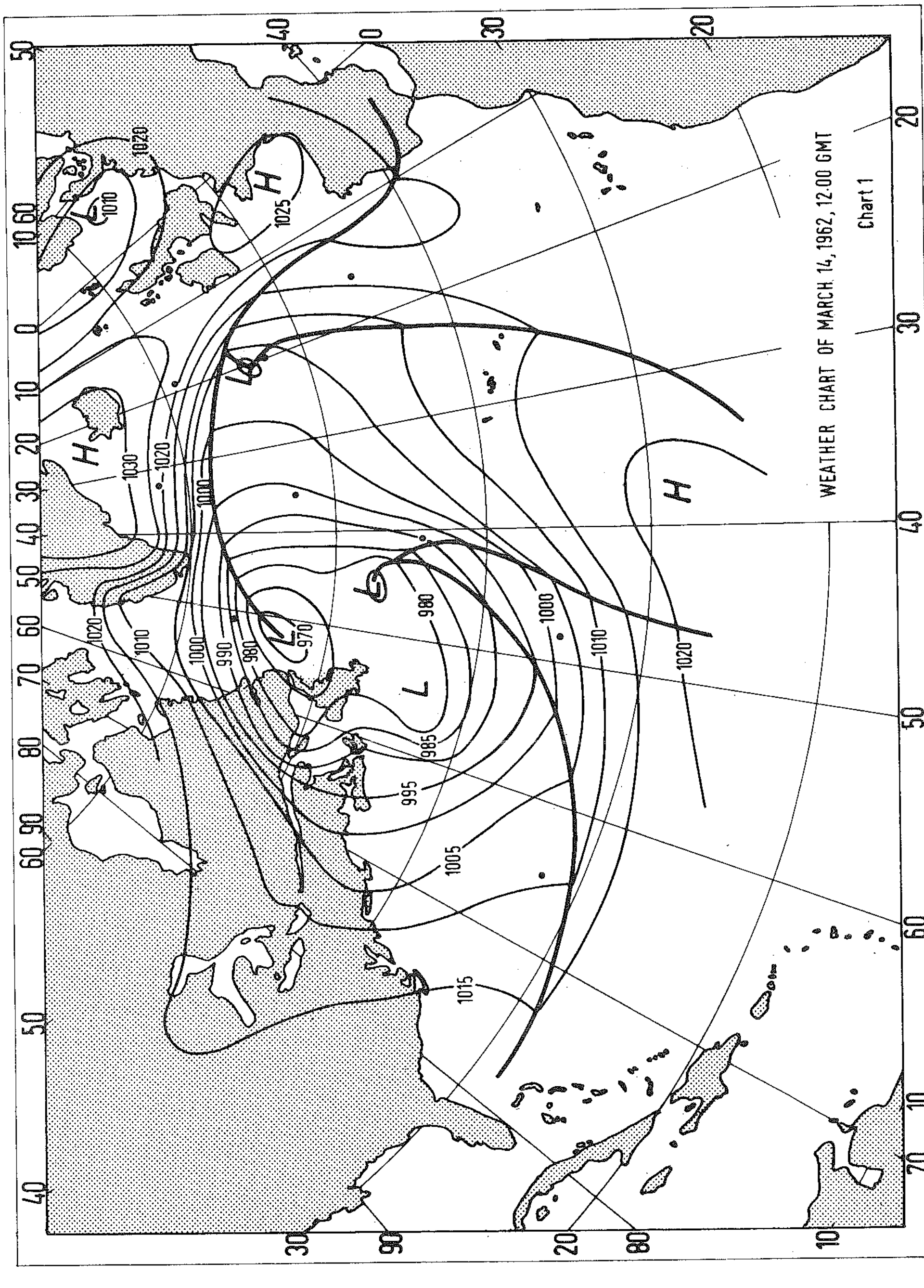
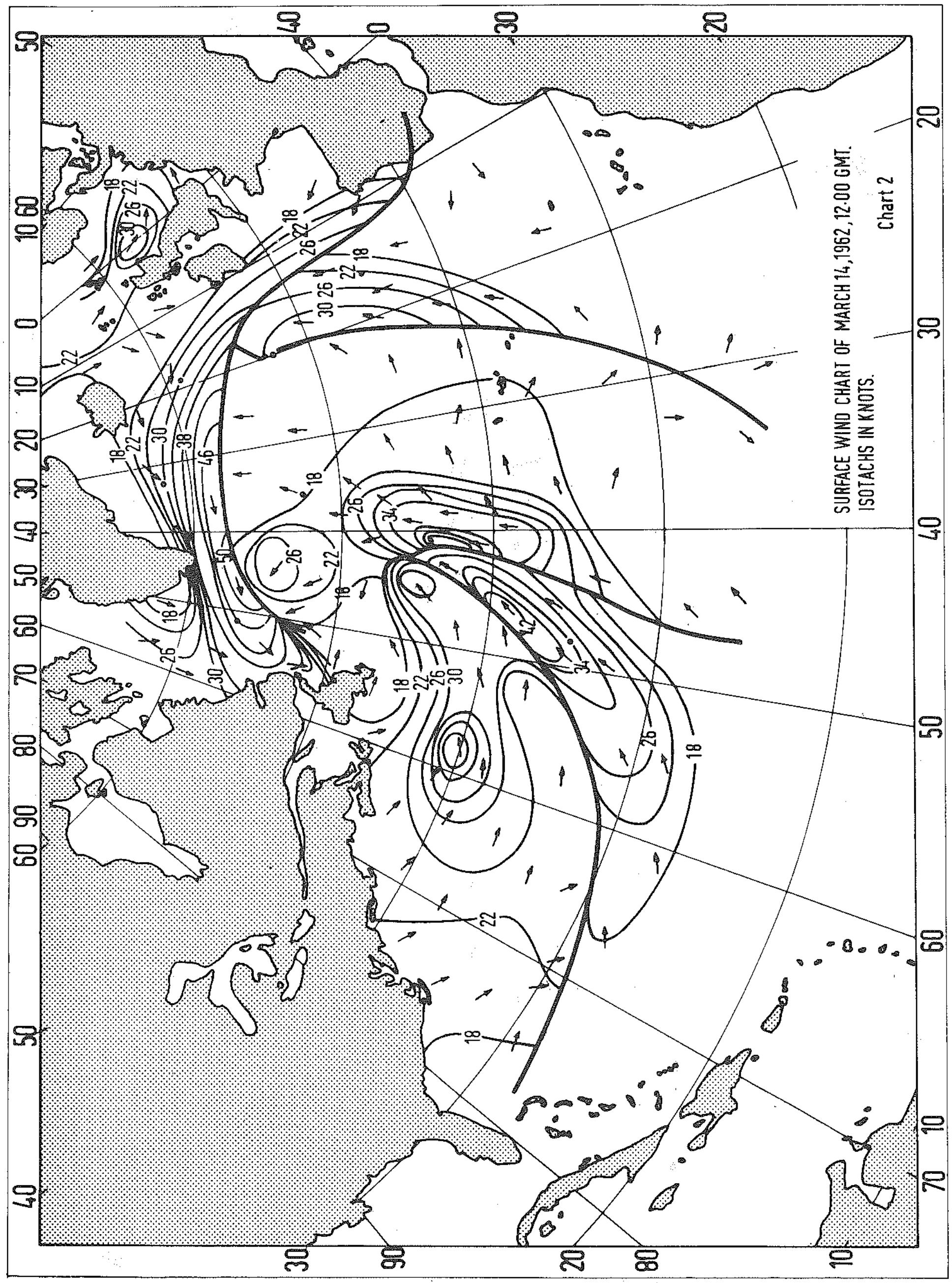
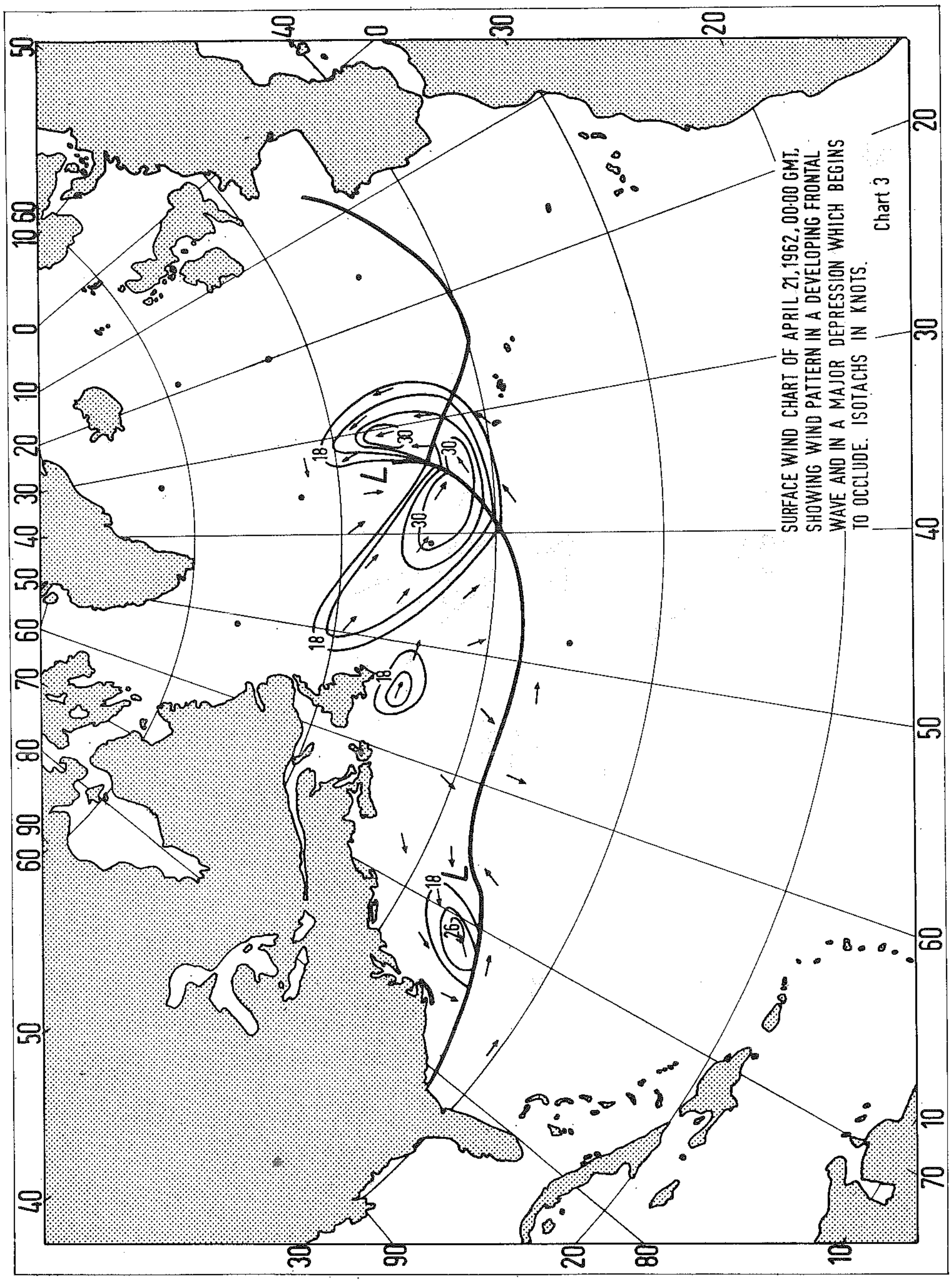


WEATHER CHART OF MARCH 14, 1962, 12.00 GMT
Chart 1

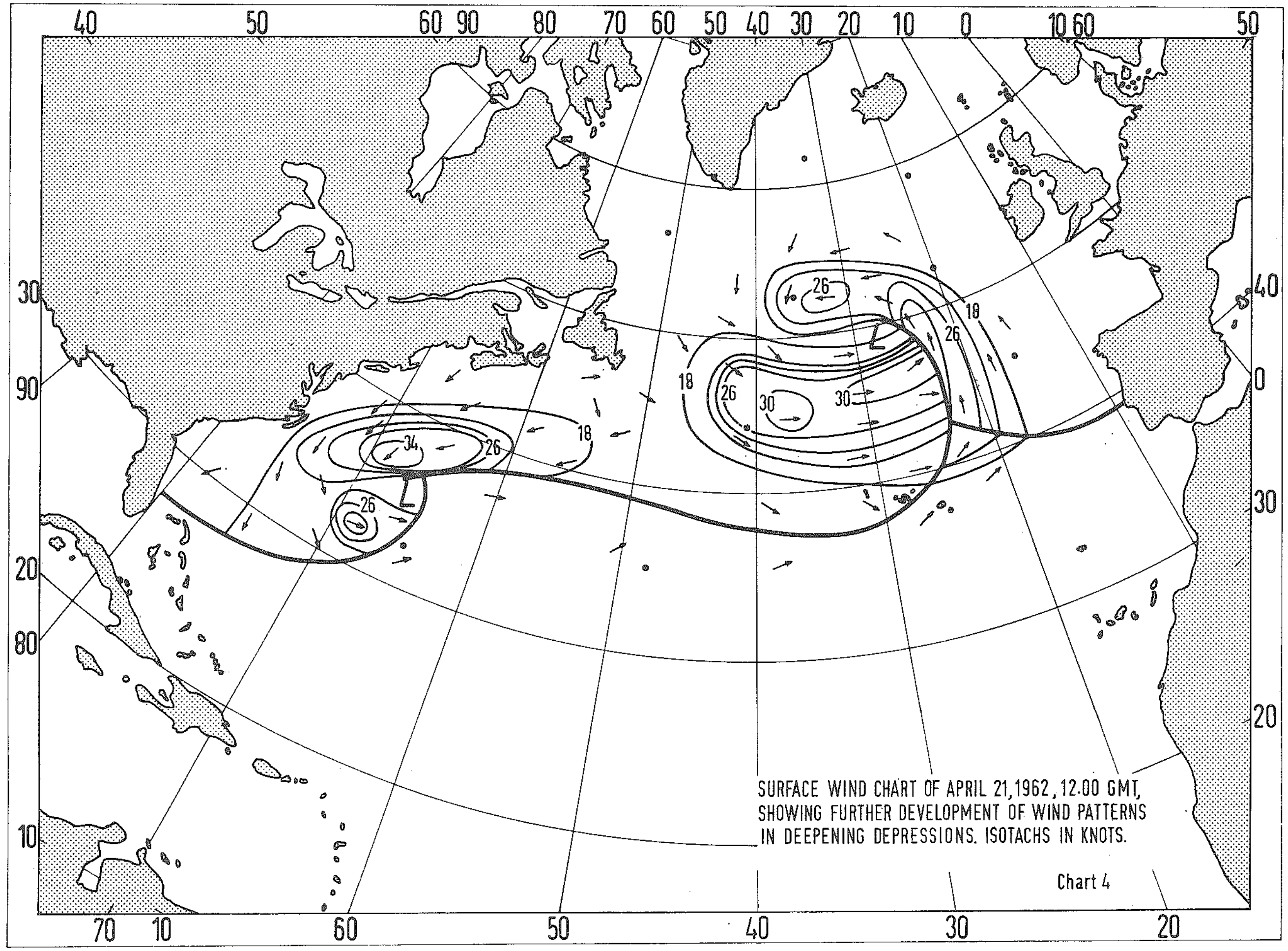


SURFACE WIND CHART OF MARCH 14, 1962, 12.00 GMT.
ISOTACHS IN KNOTS.
Chart 2



SURFACE WIND CHART OF APRIL 21, 1962, 00:00 GMT, SHOWING WIND PATTERN IN A DEVELOPING FRONTAL WAVE AND IN A MAJOR DEPRESSION WHICH BEGINS TO OCCLUDE. ISOTACHS IN KNOTS.

Chart 3



SURFACE WIND CHART OF APRIL 21, 1962, 12.00 GMT, SHOWING FURTHER DEVELOPMENT OF WIND PATTERNS IN DEEPENING DEPRESSIONS. ISOTACHS IN KNOTS.

Chart 4

SUMMARY

Most studies on the analysis of surface winds deal with the relation between pressure field and surface wind. In the present study the reliability of wind observations from ships is analysed in detail. Since even at the present time over 80% of the ship reports refer to visual wind observation, the Beaufort Scale has become one of the main topics in this study.

Up till now the Beaufort Scale was investigated analytically from the form of the curve of equivalent wind speeds against the scale intervals. In the present study a theory is developed which aims at predicting the construction of the Beaufort Scale as given by its equivalent wind speeds. It is postulated, on the basis of experience, that what is primarily observed is the distribution of gusts in space (from visual effects at the sea surface) or the gust frequency in time (from effects on flags, tree branches, etc.). Such observations lead to an evaluation of a wind force which is directly proportional to the wind speed. The postulate was verified on the basis of two wind scales which were developed independently: a scale developed by JAN NOPPEN in 1735 in Holland from observations on land, and the well-known Beaufort Scale developed in 1805 from ship observations. An empirical rule evolved from this investigation: whatever wind effects are observed the same wind scale will evolve. The rule corresponds to the postulate.Possible errors of observation, relating to the kind of wind effects observed, the spacing of the scale intervals and the non-linearity of the scale of equivalent speeds are discussed. The magnitude of the overall error of observation is found to be $\alpha = 0.6\,I$, where I = scale interval in m/s. Mean equivalent wind speeds are given which seem to apply to the average shipborne observer. The overall error in observed wind directions in 8° when they are estimated according to compass points and 10° when reported in tens of degrees, due to a bias towards even values in the latter case.

The reliability of wind measurements made routinely on board ship is discussed. A method is indicated by which the reliability of the measured relative wind on different ships can be compared with the help of estimated winds as a common reference. The reliability of the anemometer's exposure can thus be tested. A comparatively good exposure gives a mean overall error of measurement of the true wind of 1 m/s as compared to 1.3 m/s for wind speed estimates.

The extent to which a single wind observation may represent the average wind speed over a sea area of 60 miles in diameter is also discussed. Since the surface gradient wind speed constitutes such an average, a knowledge of the magnitude of the spread of 'spot values' with respect to an areal mean is important with a view to analysing detailed surface wind patterns over the sea. The standard deviation of a wind observation with respect to the mean wind, computed either as an average of two observations (taken within 60 miles from each other) or from the pressure gradient, amounts in both cases to 2.5 m/s.

Charts 1 — 4 give some characteristic examples of surface wind patterns in developing and in occluding depressions over the ocean.

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APPENDIX

Beaufort number	Descriptive term	Specifications for observations at sea (W.M.O.)
0	Calm	Sea like a mirror.
1	Light air	Ripples with the appearance of scales are formed, but without foam crests.
2	Light breeze	Small wavelets, still short but more pronounced; crests have a glassy appearance and do not break.
3	Gentle breeze	Large wavelets; crests begin to break; foam of glassy appearance; perhaps scattered white horses.
4	Moderate breeze	Small waves, becoming longer; fairly frequent white horses.
5	Fresh breeze	Moderate waves, taking a more pronounced long form; many white horses are formed (chance of some spray).
6	Strong breeze	Large waves begin to form; the white foam crests are more extensive everywhere (probably some spray).
7	Near gale	Sea haeps up and white foam from breaking waves begins to be blown in streaks along the direction of the wind.
8	Gale	Moderately high waves of greater length; edges of crests begin to break into the spindrift; the foam is blown in well-marked streaks along the direction of the wind.

THE BEAUFORT SCALE

Effects of apparent wind on shipboard (according to H. W. MacPhail)	Specifications for observations on land (W.M.O.)
Smoke rises straight up.	Calm; smoke rises vertically.
Barely perceptible smoke drift.	Direction of wind shown by smoke drift but not by wind vanes.
Wind barely felt on face. (A tendency to overestimate wind needs to be avoided when the temperature is below 32°F.) Smoke rises at 80°.	Wind felt on face; leaves rustle; ordinary vanes moved by wind.
Wind felt on face (same note as above). Smoke rises at 70°. Taut halliards shake slightly. Pennant extends and flaps.	Leaves and small twigs in constant motion; wind extends light flag.
Slight pressure of wind felt on face. Smoke rises at 50°. Slack halliards curve and sway but do not assume fixed bent position. Taut halliards do not bend but whip slightly. No noticeable sound in rigging. Flapping of pennant more marked at fly end. Heavy flag flaps limply but does not extend.	Raises dust and loose paper; small branches are moved.
Wind felt on face as if close to ordinary electric fan; stings face in temperature below 33°F. Smoke rises at 30°. Slack halliards whip while bending continuously to leeward. Taut halliards maintain slightly bent position. Low whistle in rigging. Heavy flag does not extend but flaps along entire length.	Small trees in leaf begin to sway, crested wavelets form on inland waters.
Wind stings face in temperatures below 35°F. Slight effort to maintain balance against wind. Smoke rises at 15°. Both slack and taut halliards whip slightly in bent position. A low moaning, rather than a whistle, is heard in the rigging. Heavy flag begins to extend and flaps more vigorously.	Large branches in motion; whistling heard in telegraph wires; umbrellas used with difficulty.
Wind stings face in temperatures below 38°F. Necessary to lean slightly into wind to maintain balance. Loose oilskins begin to inflate and pull against the strength of one's arms. Smoke rises at 5° to 10°. There is still a slight whip in the halliards. Whistling and medium moaning heard in the rigging. Heavy flag extends full length and flaps at fly only. Loose canvas protectors around bridge whip slightly against supports.	Whole trees in motion; inconvenience felt when walking against the wind.
The head is pushed back by the force of the wind if allowed to relax. Oilskins inflate and pull strongly. Halliards rigidly bent. Loud whistle in rigging. Heavy flag flies straight out and whips from the hoist. Loose canvas 'dodgers' or protectors held tight against supports.	Breaks twigs off trees; generally impedes progress.

Beaufort number	Descriptive term	Speciffcations for observations at sea (W.M.O.)
9	Strong gale	High waves; dense streaks of foam along the direction of the wind; crests of waves begin to topple, tumble and roll over; spray may affect visibility.
10	Storm	Very high waves with long overhanging crests; the resulting foam, in great patches, is blown in dense white streaks along the direction of the wind; on the whole, the surface of the sea takes a white appearance; the tumbling of the sea becomes heavy and shock-like; visibility affected.
11	Violent storm	Exceptionally high waves (small and medium-sized ships might be for a time lost to view behind the waves); the sea is completely covered with long white patches of f oam lying along the direction of the wind; everywhere the edges of the wave crests are blown into froth; visibility affected.
12	Hurricane	The air is filled with foam and spray; sea completely white with driving spray; visibility very seriously affected.

fects of apparent wind on shipboard ccording to H. W. MacPhail)	Specifications for observations on land (W.M.O.)
	Slight structural damage occurs (chimney-pots and slates removed).
	Seldom experienced inland; trees uprooted; considerable structural damage occurs.
	Very rarely experienced; accompanied by widespread damage.

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