Official No. 180.

THE BEAUFORT SCALE OF WIND-FORCE.

REPORT

OF THE

DIRECTOR OF THE METEOROLOGICAL OFFICE

UPON AN

INQUIRY INTO THE RELATION BETWEEN THE ESTIMATES OF WIND-FORCE ACCORDING TO ADMIRAL BEAUFORT'S SCALE AND THE VELOCITIES RECORDED BY ANEMOMETERS BELONGING TO THE OFFICE

WITH A REPORT UPON CERTAIN POINTS IN CONNECTION WITH THE INQUIRY

By

G. C. SIMPSON, M.Sc.,

AND NOTES BY

SIR G. H. DARWIN, K.C.B., F.R.S., W. H. DINES, F.R.S.,

AND

COMMANDER CAMPBELL HEPWORTH, C.B., R.N.R.,

Marine Superintendent.

Published by Authority of the Meteorological Committee.

LONDON:
PRINTED FOR HIS MAJESTY'S STATIONERY OFFICE,
BY DARLING & SON, LTD., 34-40, BACON STREET, E.

And to be purchased, either directly or through any Bookseller, from
WYMAN AND SONS, LTD., FETTER LANE, E.C.,
or OLIVER & BOYD, EDINBURGH;
or E. PONSONBY, 116, GRAFTON STREET, DUBLIN.

1906.

Price One Shilling and Sixpence.

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[*Continued on page 3 of Cover.*

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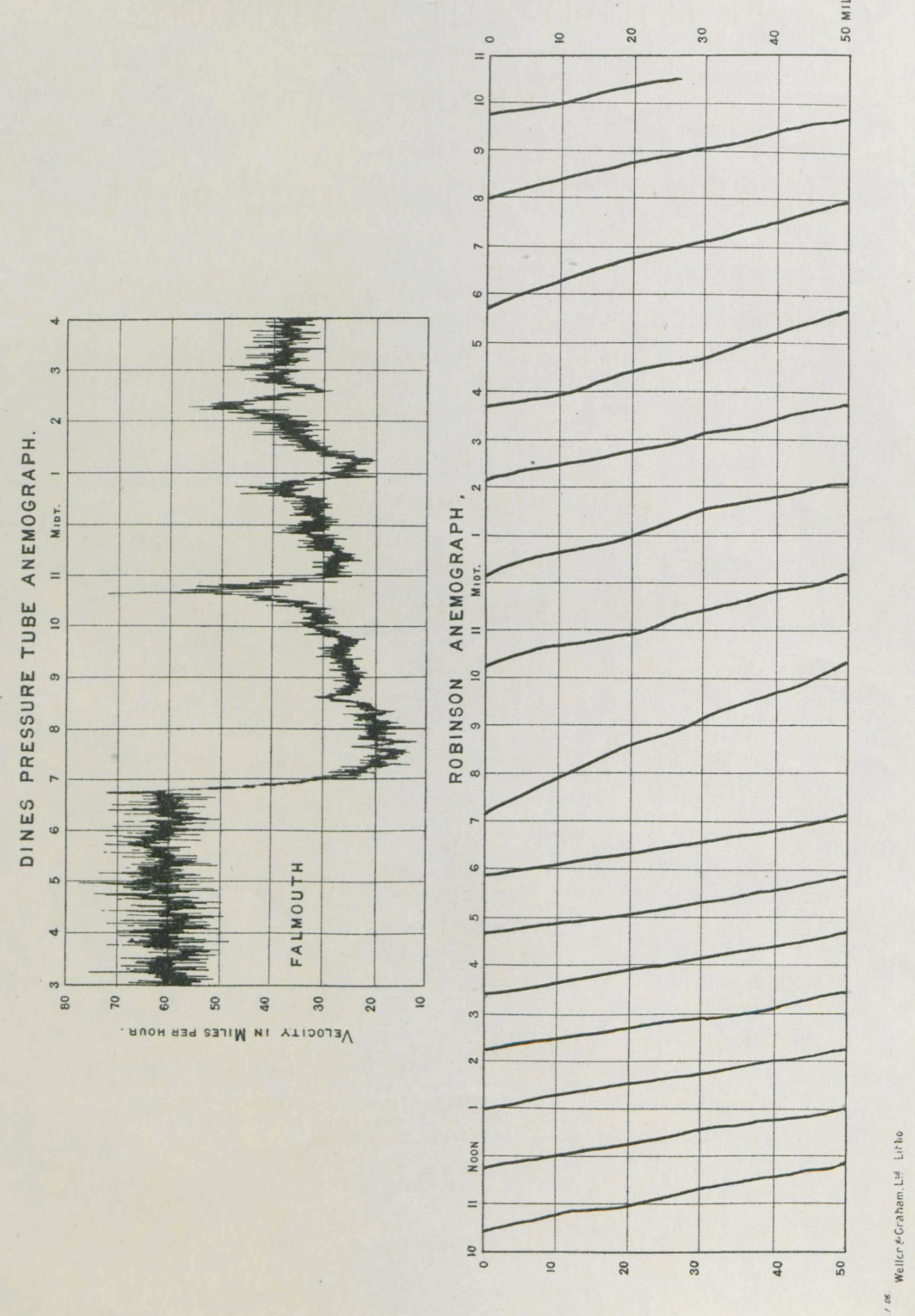
RECORDS OF WIND VELOCITY AT FALMOUTH.
FEBRUARY 25. 1903.



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„ Robinson anemograph.

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Introductory.

For several years past an inquiry has been in progress in the Meteorological Office with the object of laying down a satisfactory table of equivalents between the numbers on the Beaufort scale assigned by experienced observers as a measure of the wind force in the daily observations reported to the Office and the velocities recorded by anemometers at the stations at which the personal estimates of wind force were made.

The subject is much more intricate than might be supposed by those who are not familiar with the details which must be summarised in the result of such an investigation, and it will be appropriate to explain briefly the questions which have to be determined before the numerical calculation of a general scale of equivalents can be approached, and to specify the material available for this purpose.

Determination of hourly wind velocity by anemometers.

Assume first that the velocity of motion of the air is the ultimate measurement to which the numbers of the Beaufort scale shall be referred; the primary question for consideration is how to deal with the instrumental records. Those used in the investigation are of two kinds, obtained from the Robinson cup anemometer and the Dines pressure tube anemometer respectively. The recorded traces of the two instruments are entirely different in character. Specimen traces of each of them on a reduced scale are shown in the frontispiece. The upper diagram shows the trace of the Robinson cup instrument and the lower that of the Dines pressure tube.

The Robinson anemometer.

The traces of the Robinson cup anemometer enable us to tell the total distance which the cups have travelled in any specified interval, and as the velocity of the cups has been shown to be very approximately proportional to the velocity of the wind, we can obtain from the trace the average velocity of the wind in any interval, such as an hour or half an hour. But the trace does not give any satisfactory indication of the separate gusts. The momentum of the revolving cups is considerable, and smooths out the more rapid oscillations, and, besides, the scale of the instrument is so contracted, and the trace, which is made by the movement of the edge of a metal spiral upon metallic paper, is so coarse, that a transient variation of the speed of the cups is indistinguishable in the record. Thus, in using the results of the Robinson anemometer, the average speed during an hour or some other interval of similar magnitude must be adopted as the basis of reference.

The Dines pressure tube anemometer.

The Dines pressure tube, on the other hand, will show variations of wind velocity lasting perhaps for less than a minute, and for winds having an average velocity of about 15 miles per hour and upwards the trace exhibits a succession of oscillations of considerable magnitude. The changes are, indeed, so frequent that it is not generally possible to isolate the portion of the trace corresponding to each gust, though occasionally some of the more prominent gusts are well marked. As a general rule, the trace is such as would be produced by the pen moving comparatively rapidly up and down the paper which travels slowly along. When the instrument is in proper adjustment, the position of the pen on the paper is determined by the speed of the wind at the time, and the paper is graduated to show the velocity in miles per hour. The extreme point reached by the pen in one of the oscillations, shows the maximum velocity in the gust which caused the excursion of the pen, unless the duration of maximum velocity was so short that the mechanism could not move in time.

From the trace of the pressure tube, information of various kinds can be obtained. The most easily identifiable is the speed in one or other of the many gusts or lulls which go to make up the phenomena of wind as they would be experienced by an observer with the exposure of the instrument. The fluctuations of speed are probably sufficiently slow for the turning points of the motion of the pen in the one direction or the other to give an accurate reading of the maximum or minimum velocity. For certain purposes such readings are of great importance, and the light which the appearance of the trace can throw upon what may be called the structure or character of the wind should furnish a subject of special inquiry. But the readings of gusts and lulls do not necessarily give us anything that is comparable with the measures of the Robinson anemometer or the estimate of the Beaufort scale. The further evaluation of the trace of the pressure tube instrument is attended with some uncertainty. A line may be drawn by eye about the central portion of the trace for an interval such as an hour. The wind oscillates in force above and below the selected line, which may accordingly be taken as representing the mean velocity during the interval. Although the estimate of mean velocity made in this way is not rigorous, it is probably sufficient for practical purposes, as the element to be measured is subject to variations of a purely local character, and measurements within a mile per hour may be accepted as satisfactory. Rigorous determinations of mean velocity, as, for example, by attaching a planimeter to the tracing pen, would probably under ordinary circumstances not differ from the eye estimate of mean value by more than that amount. It must be understood in what follows that in the comparison of the Beaufort scale with mean hourly velocity of the wind, the method of using the traces of the pressure tube has been to estimate by eye the position of the line of average velocity for an hour.

Further consideration must be given to the expression of the results of the two instruments in miles per hour. The graduation of the pressure tube record is empirical, and depends upon Mr. Dines's experiments,* from which the appropriate dimensions of the instrument in relation to the recording drum are derived.

Relation of pressure to velocity.

According to other experiments of Mr. Dines, the velocity values can be related to the pressure upon a circular disc one square foot in area by the formula

$$P = \cdot 003V^2 \qquad (1)$$

where P is the pressure of the wind in pounds per square foot and V is the recorded velocity in miles per hour. It may be noted that the fact of the existence of this relation gives a means of comparing one pressure tube instrument with another. Whatever be the shape or dimension of the instrument, the effect of a wind of given velocity is to establish a difference of pressure between the interior and exterior of the float of a certain amount. This difference of pressure is due partly to the impact of the wind on the

* Detailed accounts of these experiments, which were continued over a considerable period, will be found in the Quarterly Journal of the Royal Meteorological Society, Vols. XIV., p. 253; XV., p. 183; XVI., p. 26; and XVIII., p. 165.

opening of the pressure tube and partly to the suction of the air passing the openings in the shaft of the vane. In any case, it is the same for all instruments of the Dines type in a wind of given velocity. If p be the difference of hydrostatic pressure between the interior and the exterior of the float due to a wind of velocity V, then

$$p = kV^2. \qquad (2)$$

If $k = \cdot 00073$ and V is expressed in miles per hour, p is given by the formula in inches of water (*see* p. 49). The shape of the float determines the extent of the vertical motion of the pen for the given difference of pressure between inside and outside. Consequently, computing the pressure from the scale readings by the formula (2) given above, the same pressure value ought to be given by the same recorded velocity. The reading of a given pressure value can be determined by direct experiment upon the recording part of the apparatus disconnected from the wind vane, the pressure difference being produced by a force pump; thus the scale of the instrument can be tested, and the outstanding determination which remains dependent upon Mr. Dines's experiments is the relation expressed by the formula.*

The factor of the Robinson anemometer.

The same experiments, confirmed by additional investigations in Germany and in America, have shown that the factor 3 adopted by Dr. Robinson for his anemometer, partly upon theoretical grounds, for converting the "run of the cups" into the run of the wind, is certainly too high for the anemometer of standard dimensions (9-inch cups with 2-foot arms). Mr. Dines gave 2·1 as the appropriate factor. It is clear that the factor for each instrument must depend upon the state of lubrication, and also upon the accuracy of manufacture of the mechanism. The proper method of procedure is to obtain a factor for each separate instrument by direct experiment or by comparison under appropriate conditions with a standard instrument of the same or some other type whose constant is accurately known. A process of the kind indicated is followed at the Seewarte in Hamburg, where a whirling machine is kept mounted for the purpose. There is no corresponding provision in this country, and, indeed, the possibility of carrying out the accurate graduation of an anemometer by observations in an enclosed space is not fully admitted by all authorities in this country. At the National Physical Laboratory comparisons are conducted by exposing the two anemometers near together on the same building. This process leaves the factor to be used for the standard undetermined in any comparison.

Of the Robinson anemometers in possession of the Meteorological Office, two, namely those at Scilly and at Phœnix Park, are smaller than the standard. The rest are of the standard pattern. Moreover, at Holyhead and at Scilly a pressure tube anemometer is in each case mounted with an exposure that may be considered comparable with that of the Robinson, and frequent comparison has been made in the Observatory Branch of the Meteorological Office by Mr. R. H. Curtis between the readings of the instruments of different types at the two stations mentioned and elsewhere. From the comparison it appears that the factors 2·2 for the standard instrument at Holyhead and 2·8 for the smaller instrument at Scilly give a consistent series of results over the range of wind values which have occurred at the two stations, neglecting very light winds, for which the measurements are in any case somewhat uncertain. These factors are now in use in the Office for the two anemometers, as giving the best available approximation to the actual velocities in miles per hour. It is evident that this method of arriving at a constant for the Robinson anemometer throws the responsibility ultimately upon Mr. Dines's empirical graduation of his pressure tube instrument, and confirmation of the graduation might under certain circumstances be called for; but the results are sufficiently well established for the purpose of the present report. The factor used for the reduction of the readings

* For the formulæ quoted it is assumed that the air is of "standard" density (30 in. 50° F., *see* p. 49). A correction is necessary if the density is above or below standard in consequence of its temperature or pressure, but the correction is not of importance for measurements near the sea level.

of the Robinson anemometer at Shields, Yarmouth, and at Oxford, which are all of standard pattern, is 2·2.*

Other characteristics of the wind in a given interval.

In so far as the indications of the two types of anemometer can be interpreted in terms of the mean velocity of the wind during an interval, either can be employed in an evaluation of the hourly velocity represented by the numbers of the Beaufort scale. No other characteristic of the wind is given by the Robinson instrument, but an inspection of the trace of the pressure tube instrument gives the extreme range of the wind force during an interval, and what may be called the average range—that is to say, the average limits between which the wind oscillates during a given interval. The latter are, perhaps, still less satisfactorily defined by inspection than the mean velocity as indicated above, though the process of estimation is of a somewhat similar character ; and as the information is of considerable importance in indicating the character of the wind which an observer has to estimate on the Beaufort scale, a number of determinations of these limits for Scilly and for Holyhead have been included in the material used in the comparison.

Uncertainties due to the exposure of the instrument.

Any one who has paid attention to the measurement of wind velocity will be cognisant of the fact that close to the surface of the earth, the flow is seriously disturbed by the obstacles which the wind meets. These cause eddies of various kinds, and affect the records of velocity, and sometimes the records of direction also. If the exposure of the cups or of the vane could be carried further away from the interference of trees, buildings, or other obstacles, the record would probably become steadier, and it is believed that, generally speaking, the velocity would become greater.

For this reason there is a tendency among those concerned with wind measurements to consider what may be called an ideal wind, which may be supposed to exist at some undefined distance above the surface of the ground, and to regard the instrumental records as more or less imperfect representations of this ideal unimpeded wind. In consequence of the lightness of its exposed vane, the pressure tube can be mounted so as to be more free from surface interference than the Robinson cups, which are attached to heavy mechanism, and cannot be placed many feet above the roof of the building which supports them. There are no satisfactory means of estimating the effect of the disturbance due to the imperfections of the exposure at the various stations where measurements have been made. It is not impossible that the difference between the factor 2·1 originally given by Mr. Dines and the 2·2 which is obtained by Mr. Curtis's comparison of the cup anemometer with the pressure tube may be attributed to the greater elevation of the exposed part of the pressure tube in the comparisons. But there is not sufficient evidence to show whether the difference is really due to this cause. Supposing that in any situation the instrumental record is affected by the height at which the exposed part is placed, which is probably the case, it is difficult to arrive at any conclusion as to whether an observer who estimates the wind is really referring to the air in his immediate neighbourhood or to the wind which corresponds to the freer exposure of objects which he can see affected by it. For the present no satisfactory means exist for dealing with this uncertainty, and in the absence of any satisfactory

* *See* a note by Mr. Dines, p. 49. It may be noted that the factor 2·2 was adopted for the Robinson anemometer of standard pattern under normal conditions by the Council of the Royal Meteorological Society in 1902 upon the report of the Wind Force Committee of that body, of which Mr. Dines and Mr. Curtis were members, in place of the factor 2·1 which had been adopted previously. In the experiments which Mr. Dines made to determine the relation between the speed of the wind and that of the cups, the "wind wheel" worked under conditions which were not precisely similar to those that exist in actual practice. In the complete anemometer the cups are always geared to a train of wheels for reducing their revolutions, and also to a certain length of shafting, which in the case of some instruments is considerable, for conveying the reduced movement to the recording apparatus. The work which this throws upon the cups may explain the slightly higher factor obtained from a comparison of the actual records of a cup anemometer *in situ* with those of a pressure tube instrument.

inference as to the wind freed from interfering obstacles, the actual record of the instrument must be utilised without reference to the ideal wind.

Beaufort scale estimates.

Having now considered the details of the measurement of the wind velocity, we may turn our attention to the other side of the comparison, viz., the estimates of wind on the Beaufort scale. For these an observer has to assign, from his experience of the state of the wind, a number between 0 (calm) and 12 (a hurricane that no canvas could withstand), in accordance with instructions which help him to define the intermediate points. Admiral Beaufort's original instructions arranged the scale of numbers according to the velocity of a well-conditioned ship of specified rig or the amount of sail she could carry ; but the specification is no longer generally applicable, partly because the rig of sailing ships has been changed and partly because estimates have now to be made on steamers. Moreover, a scale is required that can be used at shore and inland stations as well as afloat.

The gradual disappearance of the means of using Admiral Beaufort's specification has left the determination of the appropriate number for the description of the wind at sea to a tradition, which is apparently sufficiently well understood among sailors for practical purposes, but which has not been expressed in words. The appearance of the sea, the effect on the rigging and other phenomena, may be sufficient to make up a working scale, but it can only be arrived at by personal experience in association with some one who is acquainted with the practice of estimation. At the same time, the necessity for co-ordinating observations on sea with those on land makes it desirable to have the scale specified, if possible, and the improvements in the methods and practice of recording wind velocity point to velocity as the measurement to which existing estimates should be referred.

Whatever phenomena an observer may use to guide him in forming an estimate, the hourly velocity of the wind is certainly not directly observed by him, nor any characteristic of the wind which can be said *à priori* to be related to the hourly velocity. The observer notices the cresting of the waves, the whistling of the wind, or whatever it may be that he is observing, but he does not necessarily extend his observations over an hour, nor attempt to aim directly at the distance the air would travel in an hour. It becomes a question, indeed, whether the hourly velocity is a suitable element for comparison, or whether the average force of gusts during the period of observation, or the force at the time of observing is not the true physical representation of the determining characteristic.

If there were any means by which different observers' estimates could be practically compared one with another the first stage of an inquiry regarding the proper equivalents for the Beaufort scale would be to verify the practical uniformity of the system of estimation by a comparison of the estimates made in various circumstances as for example on the ships of the Navy, on those of the Mercantile Marine, at Lighthouses, and by other observers at well-exposed shore stations ; but such a course is not practicable. Nor are there sufficient instrumental observations of wind aboard ship to provide a table of equivalents by direct comparison. The only course remaining is to disregard for the time being any differences that there may be between the practice of different observers and to construct a table of equivalents from the estimates of observers experienced in the use of the Beaufort scale, at stations where there are also well-exposed anemometers, and having thus obtained a working scale of equivalents to indicate means by which an observer aboard ship can on the occurrence of favourable circumstances compare his own estimates with certain points in the scale adopted. In view of the unavoidable uncertainties it is not desirable to go into the details of each of the twelve points of the Beaufort scale. It is better to group the numbers and assign limits for the groups, leaving the distinction between the numbers in the groups for subsequent consideration if necessary. Captain Hepworth, Marine Superintendent of the Office, has indicated in a memorandum printed on pp. 53, 54, a practical means of identifying on steam-vessels two points of the scale and has also suggested a method of distinguishing on sailing-ships the winds corresponding to six groups of the twelve numbers of Beaufort's scale.

We have therefore next to consider the actual observations of a competent observer and their examination in relation to the records of an anemometer in his neighbourhood. The comparison is affected by all the uncertainties in the identification of the quantity to be estimated that have been pointed out and the first result of any such examination is to show that even a practised observer assigns the same Beaufort number on different occasions to velocities distributed over a very wide range and the range covered by the estimates of the same figure becomes more extended for the higher figures of the scale. A working result has generally been obtained by taking the mean value of the velocities for all winds estimated as being of a given Beaufort number, or the mean of the Beaufort numbers representing the estimates for a given measured velocity.

Upon the basis of the first of the two processes, Mr. Scott made a comparison in 1874 (Quarterly Journal, Royal Meteorological Society, Vol. 11, p. 109) and a table of equivalents was issued by the authority of the Board of Trade in 1872 (Circular No. 558, M. 4,395/72).

Equivalents by first process.

In 1896, Mr. R. H. Curtis of the Observatory Branch of the Office, who has for a long time taken a great personal interest in anemometry, published in the Quarterly Journal of the Royal Meteorological Society the results of a comparison using the much greater amount of material then available and put forward a table of equivalents.

Equivalents by second process.

In 1898, Professor Köppen (Aus dem Archiv der Deutschen Seewarte, No. 5, 1898) took exception to the scale of equivalents because the values obtained by taking the mean value of all the velocities assigned by estimate as of a given Beaufort number turned out to be different from the scale that would be obtained by taking the mean of the Beaufort numbers corresponding to given velocities. The reasons for this are made clear in Mr. Simpson's paper referred to below.

Statement of the inquiry.

When the Meteorological Council took up the question of issuing a revised working scale in 1901, it was evident that using all the data available the scale of velocity equivalents of the Beaufort numbers and the scale of Beaufort numbers corresponding to given velocities were not reciprocal. Thus the scale of equivalents adopted by Professor Köppen could not be regarded, strictly speaking, as an alternative solution of the problem dealt with by the scale of equivalents prepared by Mr. Curtis, and the Council thought it desirable to have the discussion of the matter presented in some detail. A number of diagrams were prepared from the data compiled by Mr. Curtis showing how the velocities were distributed in the group of estimates of the same number on the Beaufort scale, and *vice versâ*. Sir G. H. Darwin contributed a memorandum on the subject which is printed as an appendix to this Report (p. 43), and which explains concisely how the results of the two methods are related to one another.

Subsequently in order to clear up some outstanding points it was thought desirable to ascertain (1.) whether observers at other meteorological stations and at inland stations used the same scale of equivalents; (2.) whether observers' estimates were seriously different for different wind directions; and (3.) whether the wide range of velocities to which observers assigned the same number was to be accounted for by the selection of the hourly velocity as the measurement to be used for the comparison instead of some other characteristic of the wind.

In order to determine these points an examination of additional data was undertaken. The estimates contributed to the Daily Weather Report from Scilly, Holyhead, Yarmouth, North Shields, and Oxford for the 3 years 1900–1902, were taken out and placed in juxtaposition with the records of the anemometers at the same stations and grouped according to the wind direction. Furthermore, at Scilly and Holyhead the "average range" between which the wind oscillated during the hour and the extreme range within the hour were taken out from the pressure tube records in order that the third point in particular might be dealt with.

The material thus extended included :—

(1.) The data from Scilly, Yarmouth and Holyhead, discussed by Mr. Curtis, and the diagrams representing the distribution of velocities for the several estimates.

(2.) The additional data of the same kind for the years 1900–1902 for the five stations mentioned.

(3.) The special data obtained from the pressure tube readings at Scilly and Holyhead.

The preparation of a report upon the subject was entrusted to Mr. G. C. Simpson, M.Sc., who was acting as honorary assistant to the Secretary of the Council in March, 1905, and continued in a similar relation to the Director until the end of August, 1905. His instructions were (1.) to ascertain from the additional data whether some other characteristic than the mean hourly velocity ought to be chosen to give a satisfactory working scale of equivalents, (2.) to prepare answers to the following questions :—

(*a.*) What is the most probable value of the wind velocity to be inferred from an observer's estimate on the Beaufort scale ?

(*b.*) Can the relation between the Beaufort scale and the hourly velocity, or some other characteristic to be selected, be represented by a single scale of equivalents ?—and if that be not practicable, to prepare :—

(i.) A table of average velocity equivalents for each number of the Beaufort scale computed according to the process adopted by Mr. Curtis.

(ii.) A similar table computed according to the process adopted by Professor Köppen.

In order that he might be able to ascertain precisely the practice of the observers at those stations where the wind was estimated for the purpose of the daily telegraphic reports while it was at the same time automatically recorded by an anemometer, Mr. Simpson was commissioned to visit the stations at Aberdeen, North Shields, Holyhead, Yarmouth, Oxford, and Scilly, and to make personal inquiries.

The results of his report may be briefly summarised here :—

(1.) As regards the measurement to be selected for the comparison, the mean hourly velocity is as suitable as the mean velocity of the wind in the gusts or the lulls, or the extreme velocity in the hour. On the average of a large number of observations, the shape of the curves obtained with the different arguments are similar though the scales are different. The results are not made more homogeneous by adopting one of the other elements in place of the mean hourly velocity, and further as the average velocity of gust and the average extreme velocity are shown to be, roughly speaking, proportional to the mean hourly velocity, the first two can be inferred from the last. Results obtained.

(2.) The estimates vary with the direction differently at different stations. It is not desirable to allow for any general influence of the direction of the wind on the estimate.

(3.) The estimates of force are made entirely independently of the anemometer only at Scilly, Yarmouth and Holyhead, and at those, there is substantial general agreement between the observers as to the scale of equivalents.

(4.) The scale of estimates adopted at Oxford and inland stations, is comparable with those at the coast stations, but it is affected indirectly by the fact that the velocity of the wind has been judged from the rate at which the anemometer cups revolve; thus the conventional scale is not an independent one as that adopted by nautical observers is.

(5.) The equivalent velocities for numbers on the Beaufort scale should be computed by Köppen's method, viz.:—by taking the average of the Beaufort numbers assigned by the observers for the same hourly velocity of wind as recorded by the anemometers. The full line curve of figure 6 represents approximately the proper scale of equivalents. At the same time, having regard to the errors to which the estimates are liable, it is probable that in taking the average velocity corresponding with the Beaufort numbers for a large group of observations by any observer, the equivalent determined by Curtis's method gives a more approximate value than the average of the equivalents assigned for the individual observations (*see* p. 31).

The scale of equivalents which Mr. Simpson has arrived at does not differ materially from that obtained upon Köppen's method by Mr. Curtis from data specially selected by him as likely to give the most trustworthy results.

For use in the Office a curve was prepared which was in practical agreement with either of these. A remarkable feature of the curve is that the velocity corresponding with consecutive Beaufort numbers increases more rapidly than in proportion to the numbers themselves. The wind force upon a square foot varies as the square of the velocity, and, therefore, according to some power of the Beaufort number which is higher than the square.

To carry the matter a stage further, the wind force corresponding with the several Beaufort numbers was computed from the adopted curve of velocity-equivalents by the formula

$$P = \cdot 003V^2,$$

and compared with the curve

$$P = kB^3,$$

to ascertain whether the relation between the force and the Beaufort number could be represented by a cubic curve of that type. With the coefficient $k = \cdot 0105$ the agreement for the first ten Beaufort numbers leaves practically nothing to be desired; the differences between the pressures derived from the observations and the cubic curve are less than one-fifth of a pound on the square foot.

Thus it would appear that there is some close relation between the traditional value of the Beaufort number and the cube root of the wind force, which can be expressed by the relation

$$B = 4\cdot 56\sqrt[3]{P}, \text{ or } P = 0\cdot 0105B^3.$$

There is possibly something about the going or working of a sailing ship beyond what appears in the specification by Admiral Beaufort, which is the hitherto unrecognized basis of this simple relation.

It seems not impossible that the speed of the ship under certain conditions, which was used for the earlier numbers of the Beaufort specification, may be indicated, as it is well known that the practical speed only increases very slowly with increase of wind when the higher values are recorded, and the fact that the horse-power necessary to drive a ship depends upon the cube of the speed is suggestive. Whatever may be the explanation, the existence of this unexpected simple relation supplies a reason for endeavouring, as far as possible, to accommodate the outstanding uncertainties of the Beaufort scale in accordance with the value derived from the relation.

These considerations lead to the formula

$$V = 1\cdot 87B^{\frac{3}{2}} \text{ or } B = \cdot 66V^{\frac{2}{3}},$$

which may evidently be written

$$B = \tfrac{2}{3}V^{\frac{2}{3}},$$

as the most appropriate relation between the velocity of the wind in statute miles per hour, and Admiral Beaufort's numbers for wind force.

The numbers derived from these formulæ have been adopted in the tables which follow.

In order to enable observers at land stations to bring their estimates of wind force into relation with those made on the coast, a specification of the numbers of the Beaufort scale has been drawn up which is based on observations which can be made inland, and is included in Table II.

The numerical results of the inquiry are accordingly represented by the following tables:—

TABLE I.

FACTORS TO BE USED FOR THE DETERMINATION OF ACTUAL VELOCITIES OF THE WIND FROM THE ANEMOGRAPHIC RECORDS OF THE METEOROLOGICAL OFFICE.

Station.	Dimensions.	Factor.
Aberdeen	Standard: 9-inch cups, 2-foot arms	2·2
Armagh		
Deerness		
Falmouth		
Fleetwood		
Glasgow		
Holyhead		
Kew		
Kingstown		
North Shields		
Oxford		
Stonyhurst		
Valencia		
Yarmouth		
Dublin (Phœnix Park)	5-inch cups, 1-foot arms	2·8
Scilly		

For the Robinson anemograph at the Royal Observatory, Greenwich, which differs in certain particulars from the Kew pattern, the formula used for obtaining the velocity (V), in statute miles per hour from the run of the cups (C), by Mr. Dines is $V = 3\cdot 976 + 1\cdot 9815C$, or practically $V = 4 + 2C$ (Greenwich Magnetical and Meteorological Results, 1889, p. lxiii.).

TABLE II.

Specification of the Beaufort Scale with Probable Equivalents of the Numbers of the Scale.

Beaufort Number.	Specification of Beaufort Scale. Admiral Beaufort's General Description of Wind.	Admiral Beaufort's 1805.	Description of Wind.	Mode of Estimating aboard Sailing Vessels.	For Coast Use, based on Observations made at Scilly, Yarmouth and Holyhead.	For Use on Land, based on Observations made at Land Stations.	Mean wind force in lbs. per square foot at standard density. $P = \cdot0105B^3$.	Equivalent hourly velocity for expressing individual estimates in miles per hour, and *vice versâ* ($V = 1\cdot87\sqrt{B^3}$).	Equivalent mean velocity for expressing the average of a large group of estimates in miles per hour, and *vice versâ*.	Probable maximum velocity attained by wind.	Probable mean velocity of wind in gusts.	Probable mean velocity of wind in lulls.	Probable minimum velocity attained by wind.
0	Calm ...	Calm	—	—	Calm ...	Calm; smoke rises vertically.	0	0	3	1·5	·5	0	0
1	Light air ...	Just sufficient to give steerage way.			Fishing smack * just has steerage way.	Direction of wind shown by smoke drift, but not by wind vanes.	·01	2	5	4	3	1	·5
2	Slight breeze...	That in which a well-conditioned man-of-war, with all sail set and "clean full" would go in smooth water from 1 to 2 knots	Light breeze	Sufficient wind for working ship.	Wind fills the sails of smacks, which then move at about 1–2 miles per hour.	Wind felt on face; leaves rustle; ordinary vane moved by wind.	·08	5	8	9·5	7·5	4	3
3	Gentle breeze	3 to 4 knots			Smacks begin to careen, and travel about 3–4 miles per hour.	Leaves and small twigs in constant motion; wind extends light flag.	·28	10	11	15	13	7·5	6
4	Moderate breeze	5 to 6 knots	Moderate breeze.	Forces most advantageous for sailing with leading wind and all sail drawing.	Good working breeze; smacks carry all canvas, with good list. White crest on waves.	Raises dust and loose paper; small branches are moved.	·67	15	15	24	20·5	12·5	10
5	Fresh breeze ...	That to which she could just carry in chase "full and by" Royals, &c. ...			Smacks shorten sail	Small trees in leaf begin to sway; wavelets form on inland waters.	1·31	21	19·5	30	27	16·5	13·5
6	Strong breeze	Single-reefed topsails or top-gallant sails.			Smacks have double reef in main sail. Care required when fishing.	Large branches in motion; whistling heard in telegraph wires; umbrellas used with difficulty.	2·3	27	24·5	38	34	21	17·5
7	Moderate gale	Double-reefed topsails, jib, &c.	Strong wind	Reduction of sail necessary even with leading wind.	Smacks remain in harbour, and those at sea lie to.	Whole trees in motion; inconvenience felt when walking against wind; umbrellas discarded in exposed places.	3·6	35	30	46·5	42	26	21·5
8	Fresh gale ...	Triple-reefed topsails, &c.			All smacks make for harbour, if near.	Breaks twigs off trees; generally impedes progress.	5·4	42	36	56	51	31	26·5
9	Strong gale ...	Close-reefed topsails and courses.	Gale forces...	Considerable reduction of sail necessary even with wind quartering.	—	Slight structural damage occurs (chimney pots and slates removed).	7·7	50	44	66	60	37·5	31·5
10	Whole gale ...	That which she could scarcely bear with close-reefed main topsail and reefed foresail.	Storm forces	Close reefed sail running, or hove to under storm sail.	—	Seldom experienced inland; trees uprooted; considerable structural damage occurs.	10·5	59	53	78	71	44·5	37·5
11	Storm	That which would reduce her to storm stay-sails.			—	Very rarely experienced; accompanied by widespread damage.	14·0	68	—	—	—	—	—
12	Hurricane ...	That which no canvas could withstand.	Hurricane ...	No sail can stand even when running.	—	—	Above 17·0	Above 75	—	—	—	—	—

* The fishing smack in this column may be taken as representing a trawler of average type and trim. For larger or smaller boats and for special circumstances allowance must be made.

The velocity equivalents for the several Beaufort numbers in Table II. indicate the averages of the hourly wind velocities for which the several numbers should be used. The recognition of an appropriate scale of equivalents may lead to greater precision, but it is clear from Mr. Simpson's report and Captain Hepworth's memorandum that in actual practice the velocity equivalents of the several numbers are not sharply differentiated partly because the scale itself is not sufficiently definite, and partly because, the estimates are not sufficiently accordant. To put forward a detailed scale of equivalents as an official statement applicable to present practice would give an appearance of accuracy which is not warranted in existing circumstances, and therefore for official use a less detailed statement of the relation between the Beaufort numbers and the corresponding hourly velocity of the wind is given in the following table :—

TABLE III.

Beaufort Scale.	Corresponding Wind.	Limits of Hourly Velocity.
Numbers.		Miles per Hour.
0	Calm	Under 2
1-3	Light breeze	2 to 12
4-5	Moderate wind	13 to 23
6-7	Strong wind	24 to 37
8-9	Gale	38 to 55
10-11	Storm	56 to 75
12	Hurricane	Above 75

Besides the Beaufort scale, many other scales and tables of equivalents have been proposed by various writers. For these reference may be made to Mr. Curtis's paper. The Beaufort scale is so fully established for marine observations that it would serve no useful purpose to consider any alternative so far as British observations are concerned.

It must be clearly understood that the velocities given as indicating the limits of the divisions of the scale are intended to be *true velocities*. If the table is used in connection with the records of a Robinson anemometer, an appropriate factor must be employed for the reduction of the records. The factor will depend upon the size and type of the instrument. The recording sheets of the anemometers of standard pattern are, as a rule, divided so as to give the reduction by the factor 3, and, as mentioned above, a more appropriate factor is 2·2. Special allowance must be made for this circumstance whenever the readings are employed. To indicate the extent of this allowance, the following table of equivalents has been prepared.

TABLE IV.

Beaufort Scale.	Limits of Actual Hourly Velocity.	Limits of Nominal Velocity. Standard Robinson Factor, 3.
	Miles per Hour.	Miles (nominal) per Hour.
0	0–1	0–2
1-3	2–12	3–17
4-5	13–23	18–32
6–7	24–37	33–50
8–9	38–55	51–75
10-11	56–75	76–102
12	Above 75	—

THE BEAUFORT NUMBER 12.

In support of the figure assigned as the equivalent of force 12 (above 75 statute miles per hour) the following table of the highest forces recorded upon the anemometers in connection with the Meteorological Office may be given. It shows no record of wind velocity for an hour exceeding 80 statute miles, and only one, at Fleetwood, between 77 and 80.

TABLE V.

SHOWING THE NUMBER OF GALES OF WIND EXCEEDING 37 STATUTE MILES IN THE HOUR, GROUPED ACCORDING TO THE MAXIMUM HOURLY VELOCITIES RECORDED THEREIN BY ROBINSON ANEMOGRAPHS IN CONNECTION WITH THE METEOROLOGICAL OFFICE.

Station.	Numbers of Gales with Mean Velocities in Statute Miles per Hour between the Limits :												Total No. of Gales.
	37–40.	40–43.	44–47.	48–51.	51–54.	55–58.	59–62.	62–65.	66–69.	70–73.	73–76.	77–80.	
In 15 years, 1890–1904 :													
Deerness	128	78	57	17	12	4	3	—	—	1	—	—	300
Aberdeen	16	3	5	—	—	—	—	—	—	—	—	—	24
Alnwick Castle ...	64	43	28	10	6	5	1	—	—	—	—	—	157
North Shields ...	36	12	8	3	—	1	—	—	—	—	—	—	60
Yarmouth	37	26	11	8	—	1	—	—	—	—	—	—	83
Fleetwood	98	78	59	30	14	12	5	5	3	—	1	1	306
Holyhead	106	55	40	15	10	5	—	1	—	—	—	—	232
Valencia	66	39	12	8	2	1	1	1	—	—	—	—	130
11 years, 1891–1901 :													
Armagh	2	—	—	—	—	—	—	—	—	—	—	—	2
Falmouth Observatory	16	7	1	1	—	—	—	—	—	—	—	—	25
Kew	1	—	—	—	—	—	—	—	—	—	—	—	1
4 years, 1900–1903 :													
Kingstown	48	30	14	6	3	3	2	—	—	—	—	—	106
	37–41.	42–46.	47–50.	51–55.	56–60.	61–64.	65–69.	70–74.					
15 years, 1890–1904 :													
Scilly	206	143	75	41	16	17	2	4	—	—	—	—	504
11 years, 1891–1901 :													
Dublin (Phœnix Park)	6	—	—	—	—	—	—	—	—	—	—	—	6

The Meteorological Office has had pressure tube anemometers in use at Scilly and at Holyhead since the autumn of 1895, and at Pendennis Castle, Falmouth, since the autumn of 1902.

At Scilly, in the ten and a half years during which the anemometer has been at work, the highest rate of wind velocity recorded in a gust was 94 miles per hour. On another occasion 90 miles was reached, and gusts of between 80 miles and 90 miles per hour have been recorded in fifteen other gales.

At Holyhead, during the same period, the highest wind velocity reached in a gust was 87 miles per hour, and in three other gales gusts exceeding 80 miles per hour have been recorded.

At Pendennis Castle, Falmouth, the anemometer has been in use for only three and a half years, but during that interval a rate of 103 miles per hour has been reached once, 93 miles once, and gusts of upwards of 80 miles per hour in connection with six other gales.

According to Mr. Simpson's report, a wind with an average hourly velocity of 80 miles might be expected to oscillate between gusts of 97 miles per hour and lulls of 60 miles per hour, and the extreme velocity might be expected to reach 105 miles per hour. If we allow that such a wind may be reasonably called a hurricane, it would imply that hurricane force in the wind is at the extreme range of experience in the British Isles, although gales of somewhat less severity are not infrequent. This statement probably represents a fair concurrence of opinion, and neither exaggerates nor minimises the velocities experienced in tropical hurricanes to which the name is properly applied. It is, however, possible that the severe gales on our coasts may include gusts of hurricane force. Thus a 70-mile wind, as recorded by an hour's run of the anemometer, might be expected to include gusts of 84 miles with an extreme of 92 miles, and during the occurrence of the strongest gusts hurricane force might be reached.

W. N. SHAW.

Meteorological Office,
February, 1906.

REPORT

BY

GEORGE C. SIMPSON.

December 20th, 1905.

SIR,

I HAVE examined the data collected for the investigation of the relation between the Beaufort scale and wind velocities, and herewith forward a report dealing with the questions you wished me to investigate.

I am, &c.,

GEORGE C. SIMPSON.

The Director,
Meteorological Office.

REPORT.

PART I.

THEORETICAL.

DISCUSSION OF THE METHODS OF COMPARISON USED BY CURTIS AND KÖPPEN.

In 1896 Mr. R. H. Curtis published a paper giving the results of an extensive investigation into the relation existing between Beaufort numbers and the velocity of the wind, based on data obtained from the telegraphic reporting stations at Yarmouth, Scilly, Fleetwood and Holyhead. Introduction.

These data consisted of estimates of the wind's strength made by the observers for the "Daily Weather Report," and the corresponding mean velocities of the wind for the hour about the time of observation obtained from records of the anemometers situated at the respective stations.

In order to compare estimates with recorded velocities, Curtis used the method which up to then had always been adopted in similar discussions, namely, to tabulate the velocities recorded when each of the Beaufort numbers had been estimated, and to take the arithmetic mean of the velocities corresponding to each Beaufort number.

In 1898 Köppen reviewed the different attempts which had been made up to that time to obtain the relation between wind velocities and the Beaufort scale, and raised some very important objections to the method employed by Curtis and other workers. Köppen found that different results were obtained when the same data were used

(1.) To find the mean velocity corresponding to each Beaufort number, and

(2.) To determine the mean Beaufort number assigned by the observers to different velocities.

When Curtis, at Köppen's request, reduced his data by the new method he also found a similar divergence between the results obtained by the two methods, the difference being shown in the following table.

TABLE I.*

Beaufort.		1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.
Equivalent velocity in miles per hour for Scilly	Curtis's method...	3·9	6·7	9·3	13·5	19·8	26·0	31·7	36·9	43·0	51·5	63·1
	Köppen's method	·9	4·5	9·0	14·0	19·8	26·2	33·3	41·7	51·0	61·5	74·5

* "Aus dem Archiv der Deutschen Seewarte," 1898, page 9.

Köppen gives two reasons to account for the divergence between the results obtained by the two methods, but as these reasons are not sufficient to account for it numerically it will be necessary to examine critically the two methods to see if other reasons can be found.

Assumptions used in the investigation.

In order to do this we will postulate that there is a real unique relation existing between the degrees of the Beaufort scale and the velocity of the wind in miles per hour. This relation is such that the Beaufort numbers 1, 2, 3, 4, &c., are represented by the velocities v_1, v_2, v_3, v_4, &c. But as fractions of Beaufort numbers are not employed all velocities between $v_{1\text{-}2}$ and $v_{2\text{-}3}$ (where $v_{1\text{-}2}$ and $v_{2\text{-}3}$ are nearly, but not necessarily exactly, equal to $\frac{v_1+v_2}{2}$ and $\frac{v_2+v_3}{2}$ respectively) will be classified as of Beaufort strength 2. Similarly, Beaufort number 3 includes all velocities between $v_{2\text{-}3}$ and $v_{3\text{-}4}$, &c.

We will also consider that an observer, perfectly familiar with this relation, and able to judge and estimate the wind strength with accuracy, makes a large number of estimates extending over a long period of time; and also that during this period an anemometer having a perfect exposure measures the velocity of the wind in the locality where the estimates are made.

If now we obtain from the anemometer records the mean velocity of the wind in the hour around the time when each estimate was made, we shall provide ourselves with a large number of estimates with their corresponding velocities. Having obtained a sufficient quantity of such pairs we are in a position to discuss them according to Köppen's or Curtis's methods.

Köppen's method of comparison.

In Köppen's method of comparison the pairs are taken and separated into groups, so that all the pairs in each group have the same recorded velocity. Then, by taking the mean of the Beaufort numbers contained in each group, a number (which may be a fraction) is obtained for each velocity; this is Köppen's equivalent Beaufort number for that velocity. Plotting now these results on a curve having Beaufort numbers for abscissa and velocities for ordinates, we get a curve which expresses the relation between Beaufort numbers and velocities as found by this method.

Curtis's method.

In a similar way Curtis's equivalent velocities are obtained by separating the pairs into groups having a common Beaufort number and taking the mean of the velocities in each group. A second curve can then be drawn representing Curtis's relation; this curve will be found to be different from the previous one. (Two such curves, as found from actual observations made at Yarmouth, are shown in Figure 1.)

We will now examine the results obtained by each method, and see if they are likely to be those which one would expect from the real relation postulated.

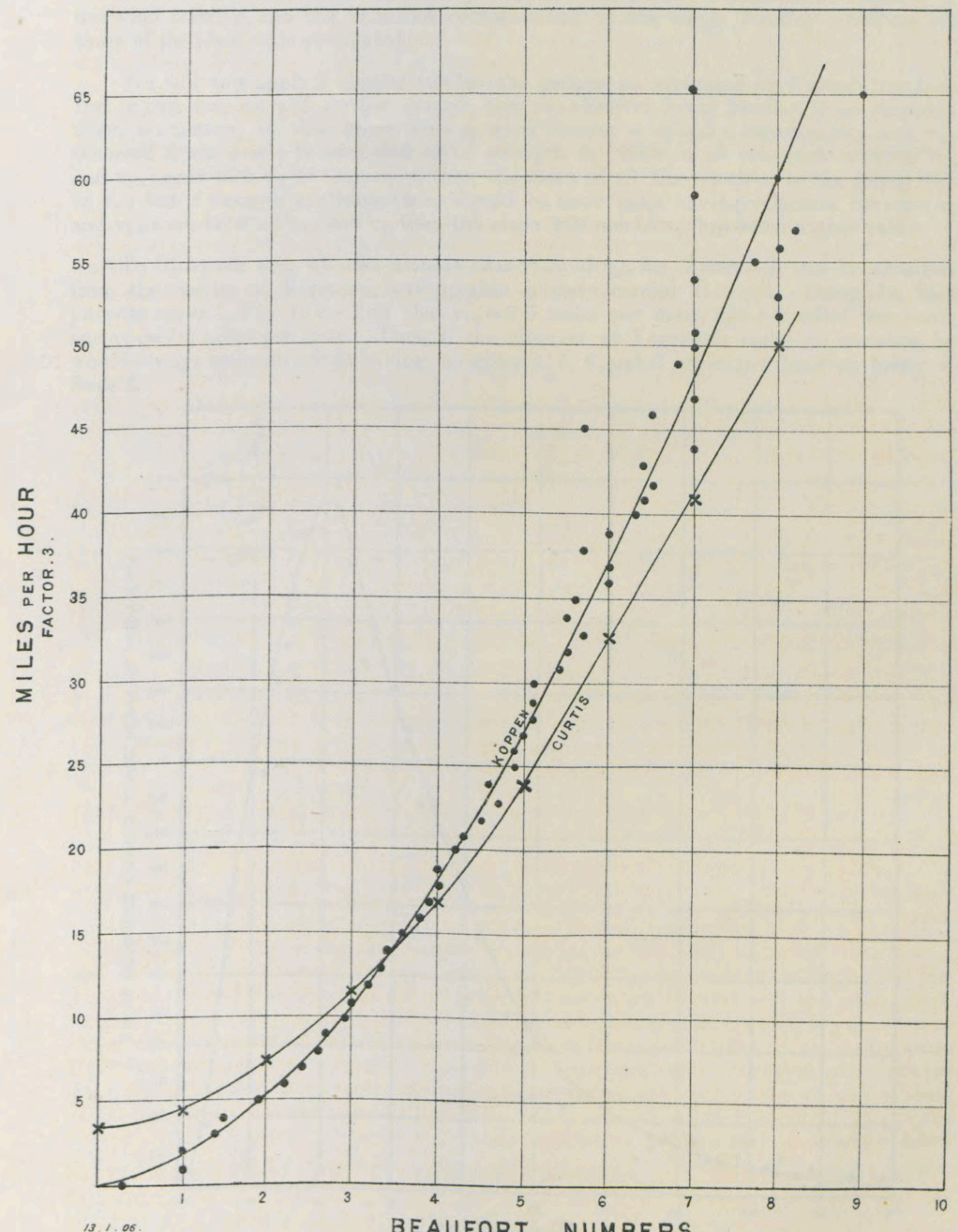
For the sake of simplicity we will discuss Köppen's method first. This will be done most easily by fixing our attention on one of the groups of pairs which corresponds to a definite velocity.

We will take first the group having the velocity v_2. If the observer is experienced and knows his scale thoroughly, he will have estimated all these winds as of Beaufort strength 2; but mistakes will have crept in, some having been estimated as of strength 1 and some as of strength 3. If the observer had no bias, it is safe to assume that the occasions on which he over-estimated the winds having this definite velocity will be equal to those on which he under-estimated it. Thus, if there are a sufficient number of observations in our group, the errors in opposite directions will counterbalance each other, and the mean Beaufort number estimated for all the winds in the group will be 2, which is the equivalent number on the ideal scale.

Let us now consider the group with the velocity $v_{2\text{-}3}$. This velocity is common to the two Beaufort numbers 2 and 3, but the observer having to place it in one or other of these divisions, and having no bias, may be expected to put it as often in 2 as in 3.

Figure 1.

BEAUFORT NUMBERS AND MILES (NOMINAL) PER HOUR.



Weller & Graham. Ltd Litho London.

Other errors will, as before, counterbalance each other, so that the mean of the whole group will be 2·5. Thus, although only whole numbers have been used when estimating, the mean Beaufort value for a definite velocity obtained by this method may be a fraction. Hence the Beaufort numbers obtained by Köppen's method are a continuous function of the wind velocity, and the velocities corresponding to the whole Beaufort numbers are those of the ideal scale postulated.

Examination of Curtis's method.

We will now apply a similar test to the groups as separated by Curtis's method. But in this case we will further assume that the observer made absolutely no mistakes when estimating, so that every time a wind having a velocity between $v_{1\text{-}2}$ and $v_{2\text{-}3}$ occurred it was correctly estimated as of strength 2. Now, if all velocities between $v_{1\text{-}2}$ and $v_{2\text{-}3}$ occur with equal frequency, then the mean of all the velocities in the group will be v_2; but if through any cause there should be more pairs having velocities between v_2 and $v_{2\text{-}3}$ than between $v_{1\text{-}2}$ and v_2, then the mean will not be v_2, but some higher value.

Divergence due to varying frequency of occurrence.

To illustrate this, we will assume that $v_{1\text{-}2}$ and $v_{2\text{-}3}$ for Yarmouth can be obtained from the results of Köppen's investigation already carried through. Using for this purpose curve 1, Fig. 1, we find that $v_{1\text{-}2}=3{\cdot}5$ miles per hour, $v_2=5{\cdot}5$ miles per hour, and $v_{2\text{-}3}=7{\cdot}5$ miles per hour. Thus, if the observer at Yarmouth made no mistakes, he would always estimate winds having velocities 4, 5, 6 and 7 miles per hour as being of force 2.

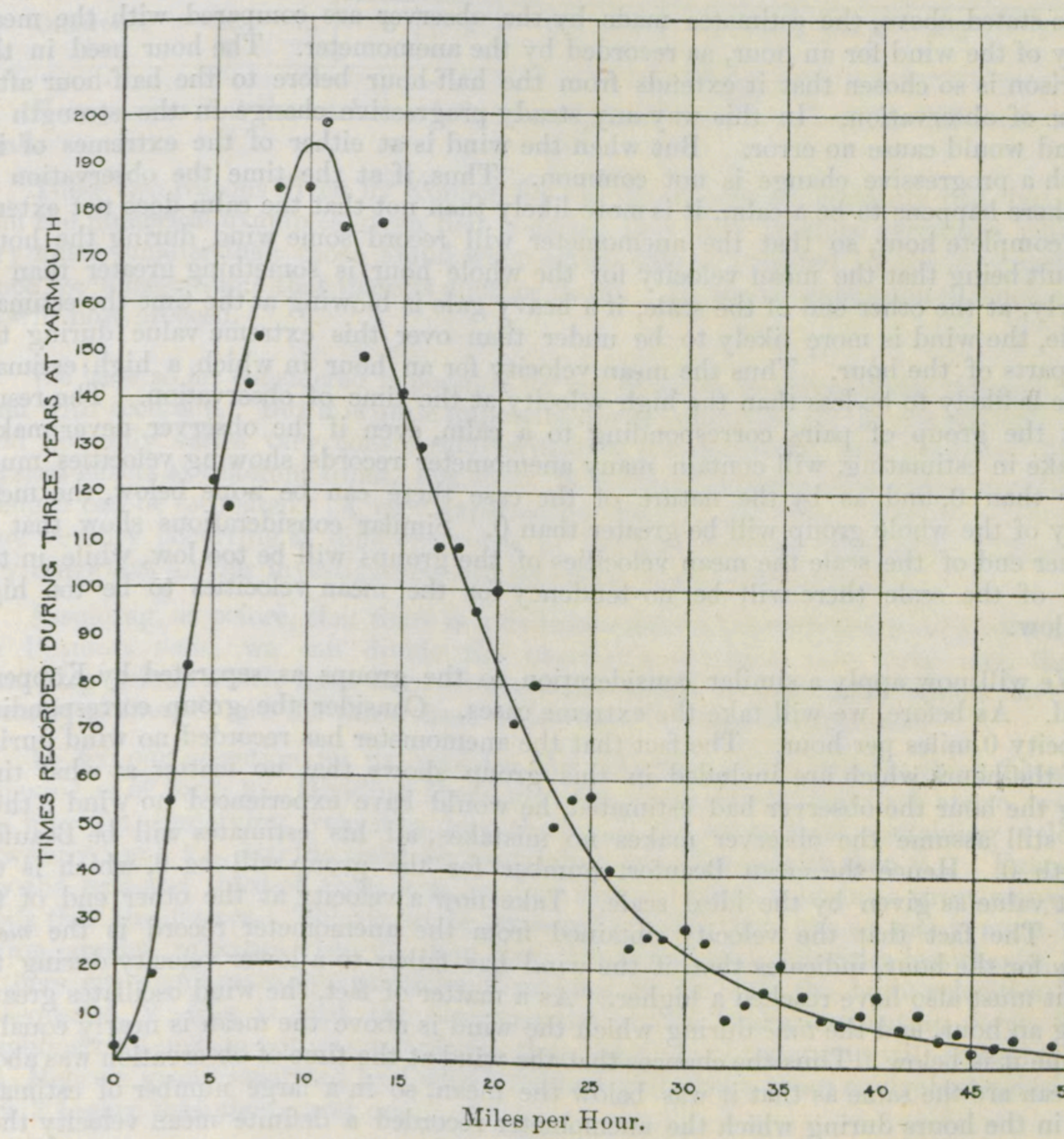


FIG. 2.

Now, Figure 2 is drawn to show how many times each velocity was recorded at Yarmouth in three years, and from it we find that velocities 4, 5, 6 and 7 miles per hour were recorded 75, 105, 125 and 143 times respectively. That is, the higher velocities are recorded more often than the lower ones. The mean of these velocities is 5·75. Thus we see that, if the observer at Yarmouth knew perfectly well that the velocity of wind for Beaufort number 2 was 5·5 miles per hour, and never made any mistake in estimating, and if his observations were reduced by Curtis's method, the equivalent velocity for this number would appear to be ·25 miles per hour higher.

If we had chosen a group corresponding to a higher Beaufort number, say, force 6, then we should have found the higher velocities in the group less often recorded than the lower ones, so that the mean of the group would be below the correct velocity.

This is one of the two reasons pointed out by Köppen for the difference between the two methods, but it does not account for the whole difference. The example we have worked out is an extreme case, and the difference found was only a quarter of a mile per hour, while the actual difference between the results of the two methods for force 2 at Yarmouth is 2 miles per hour.

Divergence due to using mean hourly velocities.

We will now consider the second cause of divergence pointed out by Köppen.

As stated above, the estimates made by the observer are compared with the mean velocity of the wind for an hour, as recorded by the anemometer. The hour used in the comparison is so chosen that it extends from the half-hour before to the half-hour after the time of observation. In this way any steady progressive change in the strength of the wind would cause no error. But when the wind is at either of the extremes of its strength a progressive change is not common. Thus, if at the time the observation is made there happens to be a calm, it is more likely than not that the calm does not extend over a complete hour, so that the anemometer will record some wind during the hour, the result being that the mean velocity for the whole hour is something greater than 0. Similarly, at the other end of the scale, if a heavy gale is blowing at the time the estimate is made, the wind is more likely to be under than over this extreme value during the other parts of the hour. Thus the mean velocity for an hour in which a high estimate is made is likely to be less than the high velocity at the time of observation. The result is that the group of pairs corresponding to a calm, even if the observer never makes a mistake in estimating, will contain many anemometer records showing velocities much greater than 0, and as by the nature of the case there can be none below, the mean velocity of the whole group will be greater than 0. Similar considerations show that at the other end of the scale the mean velocities of the groups will be too low, while in the middle of the scale there will be no tendency for the mean velocities to be too high or too low.

We will now apply a similar consideration to the groups as separated by Köppen's method. As before, we will take the extreme cases. Consider the group corresponding to velocity 0 miles per hour. The fact that the anemometer has recorded no wind during any of the hours which are included in this group shows that no matter at what time during the hour the observer had estimated, he would have experienced no wind; thus, as we still assume the observer makes no mistakes, all his estimates will be Beaufort strength 0. Hence the mean Beaufort number for the group will be 0, which is the correct value as given by the ideal scale. Take now a velocity at the other end of the scale. The fact that the velocity obtained from the anemometer record is the *mean velocity* for the hour, indicates that, if the wind has fallen to a lower velocity during the hour, it must also have reached a higher. As a matter of fact, the wind oscillates greatly during an hour, and the *time* during which the wind is above the mean is nearly equal to the time it is below. Thus the chances that the wind at the time of observation was above the mean are the same as that it was below the mean, so in a large number of estimates made in the hours during which the anemometer recorded a definite mean velocity there is no tendency for the estimates to be too high or too low. This consideration holds right through the scale, and shows that there is no tendency from this cause for the means obtained by Köppen's method to diverge from the true ones.

It is obvious that if we could measure the wind velocity exactly at the time an estimate is made, this cause of error in Curtis's method would be got rid of. Although it is impossible to obtain the instantaneous velocity of the wind by means of a Robinson anemometer, it is possible to do so from the record of a Dines pressure tube anemometer. Curtis, in order to find the magnitude of the divergence due to this cause, obtained from the Holyhead pressure tube records the mean velocity during ten minutes about the time of estimation, instead of during the hour, and found the following result:

TABLE II.

MEAN VELOCITY.

Beaufort Scale.	0.	1.	2.	3.	4.	5.	6.	7.	8.	9.
Hourly values	2·5	5·1	8·6	12·7	17·1	21·2	24·0	27·6	34·0	38·5
Ten Minute Values	2·2	4·9	8·6	13·0	17·2	21·4	24·4	27·8	33·8	39·1
Difference	·3	·2	·0	−·3	−·1	−·2	−·4	−·2	·2	−·6

Here we see that the variation is in the expected direction, but the difference is only small.

These two reasons given by Köppen for the divergence are certainly real, but we see from the numerical examples given that together they only produce variations which are very much smaller than those found when actual data are treated by the two methods; hence we must assume that there is another cause. To the consideration of such a cause we will now proceed.

Chief cause of divergence.

We have so far considered it possible for the observer to estimate the strength of the wind with accuracy. But it is quite impossible for anyone to do so, for the strength of the wind not only varies very considerably within a few moments, and produces different physical effects at different times, but there is nothing definite in a wind by which its strength can be estimated. A very experienced observer will often estimate winds of the same velocity occurring at different times as being of different strengths. This fact is very important for our investigation, and its effects must be considered.

Assuming, as before, that there is a definite relation between the wind's velocity and the Beaufort scale, we can divide the observer's estimates into three sets, the first containing winds which have been over-estimated, the second those which have been correctly estimated, and the third those which have been under-estimated.

To fix our attention let us consider the velocities of the winds which have been estimated as of force 2. Dividing these into the three sets as described above, we have the first set containing velocities less than $v_{1\text{-}2}$, the second set containing velocities between $v_{1\text{-}2}$ and $v_{2\text{-}3}$, and the third set containing velocities greater than $v_{2\text{-}3}$. Examining now the first and third of these sets, we find that the latter contains a great many more winds than the former. This is to be expected because there are so many more winds having greater velocities than $v_{2\text{-}3}$ than there are winds with velocities less than $v_{1\text{-}2}$, and so there are many more opportunities of making errors with the high velocities. The consequence of this is that the observational errors, when estimating force 2, are unsymmetrical and do not counterbalance, thus the mean of the group will be higher than $v_{1\text{-}2}$. Hence a group separated by Curtis's method will give a mean equivalent velocity for force 2 higher than the correct one.

This reasoning will be, perhaps, more easily followed by means of the following numerical example using the actual data from Yarmouth.

We will assume the correct velocities which correspond to force 2 at Yarmouth may for this purpose, as before, be obtained from Köppen's curve (this assumption will be justified later). The curve gives the required velocities as 4, 5, 6 and 7 miles per hour. The data at our disposal consist of 3,135 estimates with their corresponding velocities. An analysis of these data gives the following table :—

TABLE III.

Velocity.	Times the Velocity occurred.	Times the Velocity was estimated as force 2.
Less than 4 miles per hour	79	26
4, 5, 6 and 7 miles per hour	465	262
Greater than 7 miles per hour	2,591	261

From this table we at once see the great preponderance of errors above the correct velocity ; in fact, these errors are practically numerically equal to the correct estimates. The reason for this is also very apparent, for while the observer had only 465 opportunities to estimate correctly, he had 2,591 occasions on which to under-estimate the velocity. It is impossible for these errors of under-estimation to be counterbalanced by corresponding errors of over-estimation, for if he had over-estimated every single wind with velocity less than 4 miles per hour, which numbered only 79, his under-estimates would still be far from being counterbalanced. The result is that the mean of the group is 7·5 instead of 5·5 miles per hour.

This reasoning is based on the assumption that the correct velocity of the wind for force 2 is understood by the observer at Yarmouth to be 4, 5, 6 and 7 miles per hour. That this is really so can be seen from the following considerations. In Table IV. the same data as used in Table III. have been rearranged to show the number of times each velocity was estimated as either above, below, or of force 2.

TABLE IV.

Number of Times the Velocities 4, 5, 6 and 7 Miles per Hour were estimated as being Above, Below or of Force 2.

Velocity. Miles per Hour.	Times Velocity occurred.	Times Velocity estimated below Force 2.	Times Velocity estimated as of Force 2.	Times Velocity estimated above Force 2.
4	83	39	39	5
5	122	28	83	11
6	117	15	70	32
7	143	11	70	62

Consider first winds having the velocity 4 miles per hour. We see from Table IV. that on the 83 occasions this velocity occurred the observer estimated the winds just as often below force 2 as of that force, and only 5 times did he estimate it as being greater than 2. Thus the observer evidently considered winds having a velocity of 4 miles an hour as being the limit between force 2 and lower forces. Similarly, he estimated winds having the velocity 7 miles per hour nearly as often above force 2 as of that force, so he must have considered such winds as being at the other limit of force 2.

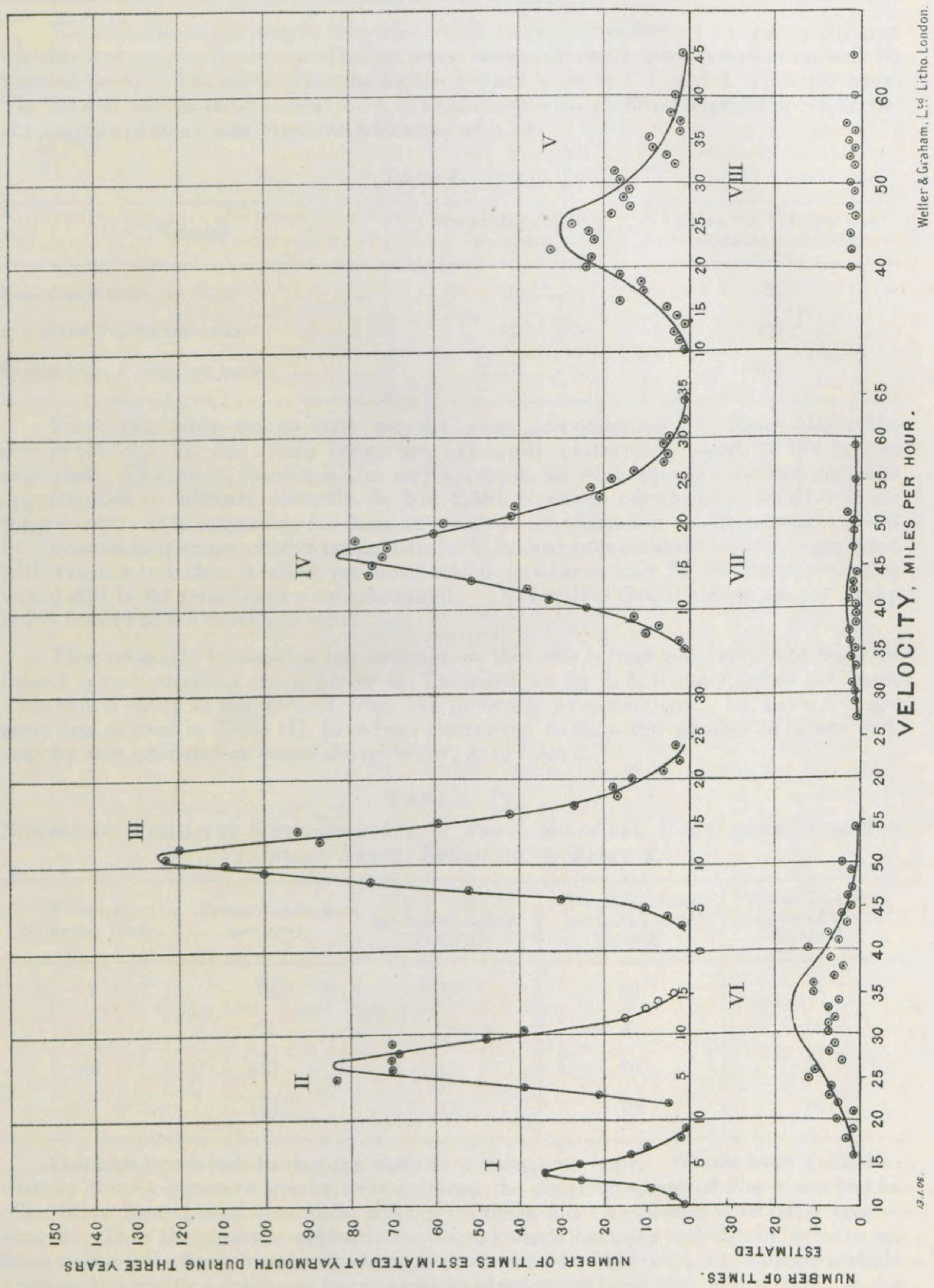


Figure 3.

FREQUENCY OF OCCURRENCE OF DIFFERENT ESTIMATES AT YARMOUTH FOR GIVEN VELOCITIES OF WIND.

With winds of the velocities 5 and 6, the number of times he estimated them as being of force 2 far outbalanced the times he estimated them as being anything else; but what is more, taking winds of these two velocities together, he estimated them as being greater than force 2 exactly as often as he estimated them as being less. Thus the observer considers that winds of the velocities 5 and 6 miles per hour nearly represent force 2. That winds of 5 miles per hour are a little lower and 6 miles per hour a little higher than his ideal of force 2 is shown by the fact that he more often under- than over-estimates the former, while with the latter the reverse is the case.

These considerations show very clearly that we were justified in taking winds having the velocities 4, 5, 6 and 7 miles per hour as those understood by the observer at Yarmouth to correspond to force 2; and they also show that the results of Köppen's method give the equivalent velocities as understood by the observer.

Returning now to the consideration of Curtis's method, we see that for force 2 Curtis's equivalent velocity is higher than the correct value for Yarmouth simply because the observer had 32 times as many opportunities of under-estimating high velocities as he had of over-estimating low velocities, and it is this preponderance of under-estimates which raises the mean velocity above its correct value.

It will be obvious that at the other end of the scale the conditions are reversed. Take force 6, for example; the bulk of the winds which occur at any place are below the typical wind at force 6, and so there will be more errors with winds having too low a velocity than with winds having too high a velocity. Thus the mean velocity of the winds estimated as of force 6 will be lower than it would be without this source of error.

There is one Beaufort number for which the opportunities to over-estimate are nearly equal to those to under-estimate. This force includes the wind having a velocity equal to the mean of all the other winds. For Beaufort numbers below this Curtis's equivalent velocities are too high, and above they are too low. In other words, Curtis's equivalent velocities are all slightly shifted towards the value of the mean velocity of all the winds occurring at the place under consideration.

Summing up now these last considerations, we see that Köppen's method gives the equivalent velocities as understood by the observer, while Curtis's method does not give the same results mainly because the errors of observation are not symmetrical about the correct mean velocity corresponding to each Beaufort number.

OTHER METHODS OF COMPARISON.

There is still another method by which the relation sought might be obtained.

Assuming, as before, that the observer knows the true relation between the Beaufort numbers and the wind velocity, we might expect the true wind corresponding to each Beaufort number to be the one most often estimated as of that number. In other words, if we construct a curve showing the number of times each velocity has been estimated as of a given Beaufort number, the apex of the curve might be expected to indicate the equivalent velocity corresponding to that number. This plan has been followed and curves drawn for each Beaufort number. Relation derived from actual frequency curves.

In Fig. 3 the curves obtained for Yarmouth are shown. These curves are very instructive. They show first how the range over which the estimates of a given number extends, increases considerably as the Beaufort number increases; thus, while estimates of strength 1 only extend over 12 velocities, 0 to 11 miles per hour, the estimates for force 6 extend over 37 velocities, 18 to 54 miles per hour; for forces 7 and 8 the ranges are not so great, but this is no doubt due to the scarcity of these high winds. We also see that while for forces 0 to 5 the apexes are fairly well defined, *i. e.*, the observer can estimate these forces with a fair degree of certainty, that is not so for the higher forces.

In Table V the velocities corresponding to the apexes of these curves are given and compared with the equivalent velocities attained by the other two methods.

TABLE V.

Method.	Beaufort Numbers.							
	1.	2.	3.	4.	5.	6.	7.	8.
Curtis's	4·5	7·5	11·5	17·0	24·0	33·0	41·0	50·0
Frequency	4·0	7·0	11·2	16·5	24·0	33·0	41·0	?
Köppen's	2·0	5·5	11·3	18·5	27·5	37·5	48·5	60·0

Comparing now the results, we see that for low Beaufort numbers, the equivalent velocities obtained by this method are higher than those obtained by Köppen's method, but not quite so high as those obtained by Curtis's method. At force 3 all three methods give practically the same results ; at higher numbers Köppen's equivalent velocities are much the greatest, while those of Curtis's and the new method are nearly the same.

We assume above that this method would give the required relation, because the observer might be expected to estimate the true velocity corresponding to each Beaufort number more frequently than any other velocity, This is only true if he has equal opportunities for estimating each velocity ; if he has not, then the method could not be expected to give the required relation. For instance, if v_2 is the ideal velocity for the Beaufort number 2, it might not be estimated as of force 2 so often as a velocity $v_2 + dv$, for the simple reason that $v_2 + dv$ occurs so much more frequently than v_2. The reverse, of course, holds at the other end of the scale. In fact, all the causes which have already been found to make Curtis's results too high or too low, act in the same way upon this method. If every velocity occurred with the same frequency over the whole scale, then

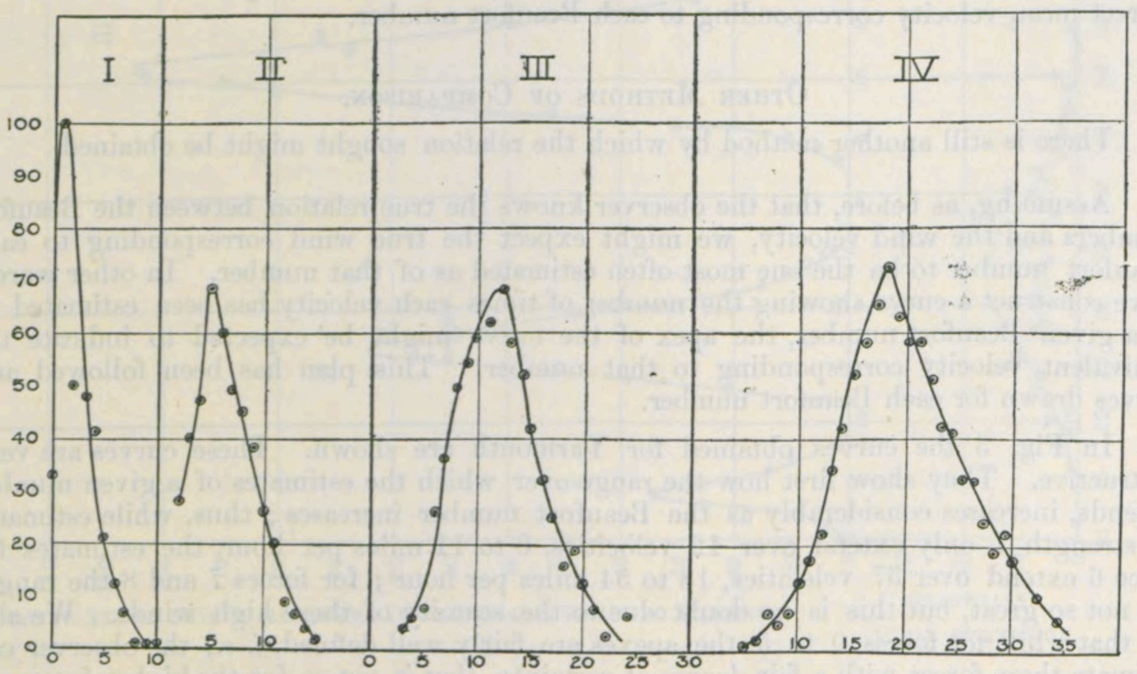


FIG. 4.

Percentage frequency of estimates of the several numbers of the Beaufort scale for given velocities of wind at Yarmouth.

this method would give the true result ; but the uneven distribution of velocities affects it, causing the equivalent velocities to be too high for the low Beaufort numbers and too low for the high numbers.

That it is the uneven distribution of velocities which causes the divergence can be shown in the following way.

Relation derived from relative frequency curves.

We can refer the times of occurrence of each velocity to a common number, say, 100, and see how often each velocity would then have been estimated as of each Beaufort number. If new curves are plotted with the numbers so obtained, they can be considered to be similar to what the actual curves would have been if the velocities had occurred with equal frequency all over the scale. Such curves, calculated from the data for Yarmouth, are shown in Fig. 4. When examining these curves, it must be borne in mind that the reduction to a common number is only permissible when a large number of observations have been taken. In the data for Yarmouth no velocity above 26 miles per hour occurs 30 times, so this method cannot be applied to the higher velocities. But up to 30 miles per hour, as will be seen from the curves, very good results are obtained, and maxima for forces 1, 2, 3 and 4 are sharply marked. These maxima give the following equivalent velocities :—

TABLE VI.

Method.	Beaufort Numbers.			
	1.	2.	3.	4.
Reduced frequency	1	5	11·5	18

By referring to Table V., it will be seen that this is practically the same result as that obtained by Köppen's method.

Thus these two new methods of reduction have led to no further result, for, as with the others, one is influenced by the distribution of frequencies, and the other is independent of it. In what follows, then, we need only consider Curtis's and Köppen's results, bearing in mind that the results obtained by these two methods are practically the same as those obtained by the other two.

APPLICATION OF THE RESULTS OF THE TWO METHODS.

Questions to be answered by investigation.

Having now found the reasons for the difference between the results of the two methods of reduction, we are in a position to discuss the merits and use of each.

This, and other investigations into the relation between the Beaufort scale and wind velocities, have all been undertaken to answer one or other of the following questions :—

1. What is the relation existing between the Beaufort numbers and wind velocity, as understood by those at present using the scale ?
2. What equivalent velocities should be specified in the instructions to new observers ?
3. What is the most probable velocity of a wind estimated as of a given Beaufort number ?
4. What relation should be used when reducing a number of estimates to mean velocities ?
5. What relation should be used when it is required to express a number of measurements of wind velocity by means of the Beaufort scale ?

Answers to questions

1. As to the answer to be given to the first of these questions. there can be no doubt. Köppen's method gives a relation which is quite independent of the fact that the estimates are compared with mean hourly velocities, and also independent of the frequency with which any velocity occurs. As shown in the text above, by analysing given data according to Köppen's method, the relation, as understood by the observer, is clearly indicated. Thus the relations obtained by Koppen's method are those required by the first question.

2. Köppen's equivalents are those which should be specified in the instructions to new observers. That this is so becomes quite clear when we consider what would be the consequence of giving observers instructions based on Curtis's results. Say that A has been observing some time, using the ideal scale postulated above, and B wishes to continue his observations, but, having no instructions, reduces A's data by Curtis's method, and uses the result so found in his future work. Now, it has been shown above that the equivalent velocities for all the Beaufort numbers obtained by Curtis's method are nearer to the mean velocity than those understood by the observer himself when forming his estimates. Thus B starts with a Beaufort scale which is not the same as that used by A, but one in which all the equivalent velocities are slightly shifted towards the mean velocity for all winds occurring at the observing station. If now, after B has been observing for some time, C takes his place, and also derives his idea of the scale from B's results reduced by Curtis's method, he will get a new Beaufort scale with the equivalent velocities still further shifted towards the middle. If such changes continue, and the estimates are correctly made on the basis of the results obtained from the previous observer's data, then, in the end, the final observer will be using a Beaufort scale embracing only one or two velocities about the mean velocity of all the winds at that place.

3. It often happens that it is important to know the velocity of the wind on a certain occasion at a place where no anemometer is erected, but where estimates on the Beaufort scale are taken. But a single estimate cannot be relied on to give the velocity of the wind, for the best observer includes very widely different winds in the same class at different times. In such a case, all we can give is the most probable velocity to be estimated as of the particular force. Here we meet with a difficulty in interpreting the word "probable."

At first sight it would appear as if the most probable wind to be estimated as of a given force would be the one which occurs the most frequently in a large number of actual estimates of that force. If this were correct, then the required velocity could be obtained from the curves of frequencies, as given in Fig. 3. Or, as the maxima of these curves are practically the velocity equivalents as derived by Curtis's method, the most probable velocity to be estimated as of a given force would be Curtis's equivalent for that force.

But there is another way of interpreting the word "probable." We might say that the most probable velocity to be estimated as of a given force is the velocity which is most consistently estimated as of that force whenever it occurs.

It will not be difficult to see from the discussion above that Köppen's equivalents give the required velocity in this case. For in the example we have worked out in detail a wind of velocity 7 miles per hour is *most often* estimated as of force 2, while those of a velocity between 5 and 6 miles an hour is *most consistently* estimated as of that force.

That Köppen's equivalents should be used in this case is also apparent if we realise that these equivalents are those on which the observer, although quite unconsciously, bases his estimate. When the observer estimates a wind as of strength 7, he feels that its force is nearer to that of his ideal wind of force 7, the velocity of which we can find by Köppen's method, than to that of either 6 or 8.

Thus, when we require to find the velocity corresponding to a single estimate, we should use Köppen's equivalent.

4. If a place is not provided with an anemometer, and it is required to find the mean velocity of the wind at that place, an approximate value can be found if estimates have been regularly made there. For example, suppose that in a given period N observations of the wind strength have been taken, consisting of n_0 estimations of Beaufort force 0, n_1 of force 1, n_2 of force 2, &c., so that $n_0 + n_1 + n_2 + \&c. = N$. These estimates can be reduced to velocities if we know the relation between Beaufort numbers and wind velocities. But we must first decide which set of equivalents to use. If we used Köppen's equivalent we should be assuming that velocities occurred over the whole scale with equal frequency, and should neglect the effect of observational errors. Thus for the winds estimated as of strength 2, we should obtain the mean velocity $\frac{n_2 v_2}{n_2}$, which would only be true if the velocities estimated as of strength 2 were symmetrically distributed about v_2. This we have seen above is not the case. For this conversion Curtis's table of equivalent velocities should be used, for these equivalents were obtained from the actual reductions of a similar set of data to that under consideration, and so allow for the results of the asymmetrical distribution of velocities and observational errors.

In order, then, to find the mean velocity of the wind for the given station, we should perform the operation:—

$$\frac{n_0 v_0 + n_1 v_1 + n_2 v_2 + \&c.}{N}$$

where v_0, v_1, v_2, &c., are Curtis's equivalent velocities for the Beaufort numbers 0, 1, 2, &c.; the result is then the mean velocity of the wind at the place under consideration expressed in miles per hour.

5. The answer to the reverse case to that just considered is not so simple. We must first go a little more fully into the question itself. At a certain place a number of anemometer records have been taken, and we wish to find how often each Beaufort number would have been reported by an observer estimating at definite set times. From the records we should first take the mean velocities of the wind during the hours about the set times of observing, and so obtain the series n_0, n_1, n_2, n_3, &c., giving the number of times the velocities 1, 2, 3, 4, &c., miles per hour were registered.

If now we use Köppen's equivalents and from them find that the velocities between v_0 and $v_{0\text{-}1}$, and $v_{0\text{-}1}$ and $v_{1\text{-}2}$, $v_{1\text{-}2}$ and $v_{2\text{-}3}$, &c., were recorded N_0, N_1, N_2, &c., times, we should have a series which would correspond to one made by an observer estimating each wind as it occurred, *if he were able to estimate with perfect accuracy*. It has been shown above that the effect of observation errors are very large, so this series might diverge considerably from one actually made by an observer estimating the winds at the place. There is also another consideration to be taken into account. If an observer had actually made the estimates then, as we have shown in the previous paragraph, by applying Curtis's equivalents to his estimates we could obtain the mean velocity of all the winds observed. If we applied this method to the above series it is obvious the correct mean would not be obtained; but if Curtis's equivalents had been used in forming the series the reverse process of deriving the mean from the Beaufort numbers would give the correct result. Thus we see that in obtaining Beaufort numbers from recorded velocities, Curtis's equivalents give the most satisfactory results.

Summing up our results we find:—

Use of the two sets of equivalents.

1. Köppen's equivalents give the relation between Beaufort numbers and wind velocities as used by observers.
2. Köppen's equivalents must be used when dealing with single observations.
3. Curtis's equivalents must be used when treating observations in the bulk.

PART II.

PRACTICAL.

Results of Methods Applied to Data from Scilly, Yarmouth, Holyhead, North Shields and Oxford.

Effect of wind direction on the estimates.

The data supplied by the Meteorological Office were first examined to find if the observers estimated winds from all directions similarly. It was found that the observations made at Scilly and Oxford were the most independent of the direction of the wind, while those of high winds made at Shields varied very considerably with the wind directions.

Assuming that the anemometer correctly measures the wind velocity at each place, and using the mean of all directions as a basis, then the directions of the wind which appear to be over- or under-estimated are the following:—

TABLE VII.

Observing Station.	Direction of Winds Over-estimated.	Direction of Winds Under-estimated.
Scilly	S. (slightly)	W. and N.W. (slightly).
Yarmouth	S.W.	N.E. and E.
Holyhead	S.W. and S.	N.E.
North Shields	W., N.W., N.	E., S.E., S.
Oxford	N.W., N., N.E. (slightly) ...	S.W., S., S.E. (slightly).

An inspection of the exposures of the anemometers showed that in practically all cases it was rather the exposure of the anemometer, than the estimates which was at fault. It is practically impossible to choose a situation for an anemometer which is equally exposed to winds from all directions; the contour of the land, the presence of trees, buildings, &c., or the support of the anemometer itself—often a tower built for another purpose—are responsible for a more or less serious deflection of the wind. It is often considered that there is a tendency to over-estimate Northerly and under-estimate Southerly winds on account of their temperatures; but if this is so, then at most stations the effect is hidden by that of more or less defective exposure.

General results from the five stations.

Taking, now, all winds together, irrespective of their directions, and reducing them by Curtis's and Köppen's methods, we obtain the following results, to the nearest whole number :—

TABLE VIII.

Curtis's Method.

Equivalent Velocities.	Beaufort Numbers. 0.	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.
Scilly	2	3	6	9	13	20	26	32	39	46	51
Yarmouth	2	3	5	9	12	18	24	30	37	42	—
Holyhead	2	6	11	15	19	21	24	28	34	42	50
North Shields	3	5	8	13	19	24	27	29	43	—	—
Oxford	2	4	7	12	16	19	24	27	29	—	—
Mean	3	5	8	11	15	19	25	29	36	44	51

Figure. 5.

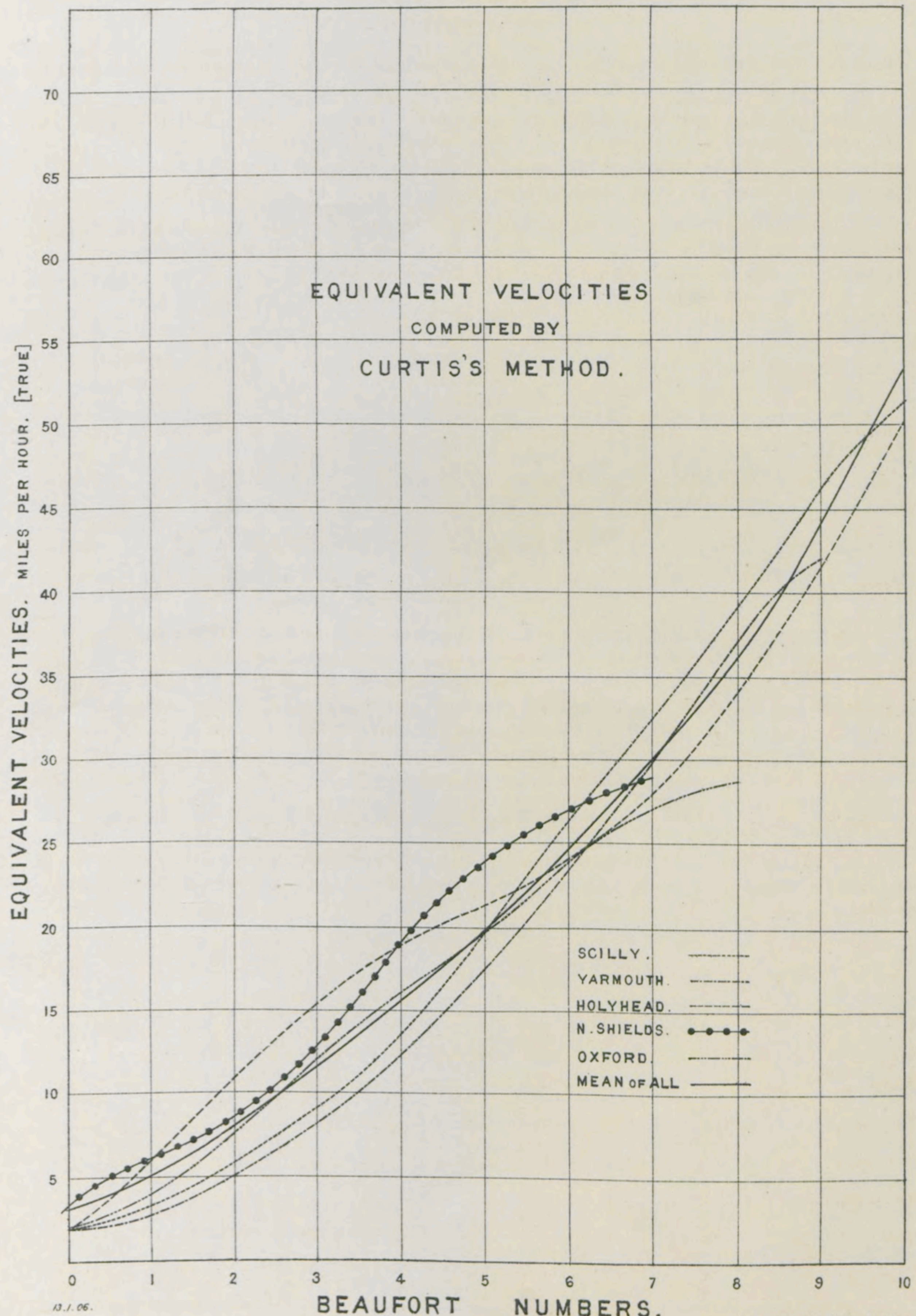


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Figure 6.

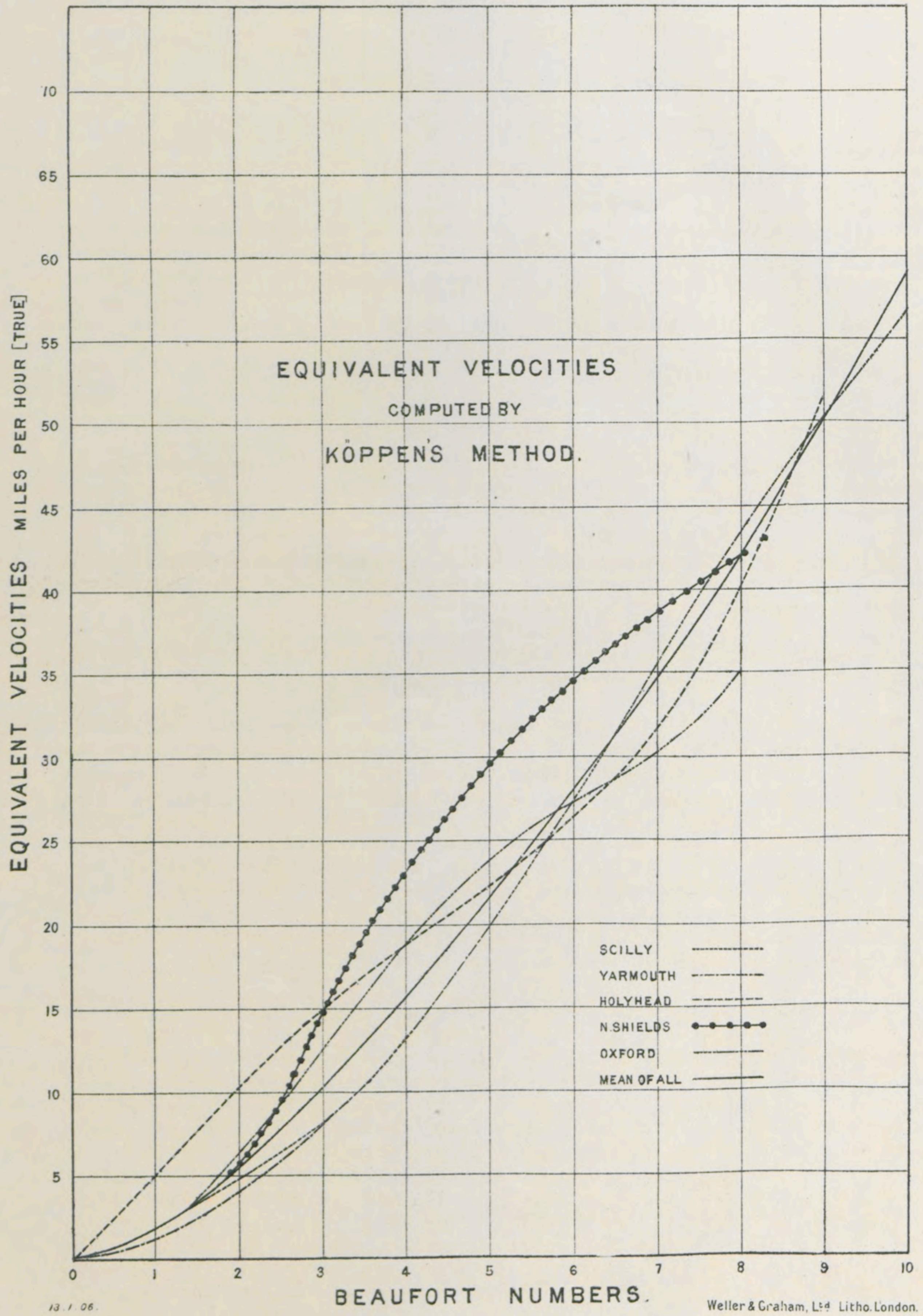


TABLE IX.

Köppen's Method.

Equivalent Velocities.	Beaufort Numbers.										
	0.	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.
Scilly	0	2	5	8	13	20	27	35	43	50	57
Yarmouth	0	1	4	8	13	20	27	35	43	50	—
Holyhead	0	5	10	15	18	22	26	31	40	51	—
North Shields	0	2	6	15	23	30	34	38	42	—	—
Oxford	0	2	7	13	19	24	27	30	35	—	—
Mean	0	2	6	11	16	22	28	35	42	50	58

These values have been plotted in Figs. 5 and 6.

It will at once be noticed that for low Beaufort numbers Curtis's velocities are in every case greater than Köppen's, while from strength 5 onwards Köppen's values become the greater.

Comparison of results from different stations. When comparing the results from the different stations, it will be seen that those for Scilly and Yarmouth are nearly the same; also that the curves for all the other stations lie above these two for light winds, but below for high winds.

Local conditions. An examination of the local conditions under which the observations are made has been of use in explaining these variations.

Yarmouth and Scilly. At Yarmouth and Scilly the observers are men who have been connected with the sea all their lives. Both of them base their estimates of the wind strength upon the condition of the sea and upon the shipping. In order for the observer at Scilly to make his observations for telegraphing to the Meteorological Office, he must leave his house and walk to a thermometer screen situated about a quarter of a mile away in an exposed position, from which a good view of the harbour and sea can be obtained. He has thus a very good opportunity for making a true estimate of the wind. Although the observer at Yarmouth does not have to go far into the open to make his observations, he is engaged all day in an office commanding an uninterrupted view of the sea, and so has an excellent opportunity of forming a true estimate of the strength of the wind from its effect on the sea and shipping.

Holyhead. The conditions at Holyhead are quite different. The observer is situated some distance from the sea, and can only see the protected harbour within the breakwater. Thus with light winds the water is no help to him, and he then bases his estimates upon the effect of the wind upon his near land surroundings. Practically this generally reduces itself to observing the motion of the coastguard's flag, which flies a few yards away from his house. After the wind reaches force 6 the flag is of no more use, for the coastguard takes it in when the wind rises sufficiently high to endanger the yard from which it flies. For winds greater than 6, then, the observer must change his standard, and as now the wind is sufficiently strong for its effects on sea and shipping to be apparent from the observer's house, he uses these as the sign on which to base his estimates. The effect of these facts is very apparent in the curve for Holyhead. For winds estimated as of forces from 0 to 5, the anemometer at Holyhead records much higher velocities than at most of the other stations, the reason being that the observer is estimating the wind on the land near his house, which is more or less sheltered, while the anemometer is measuring the wind in a well-exposed position nearer the sea. At force 6 a point of inflection occurs on the curve, and afterwards the curve for Holyhead runs remarkably near to those for Scilly and Yarmouth, all these observers now basing their estimates on the effect of the wind upon the sea and shipping.

North Shields.

Turning to Shields, we have again different conditions of observing. The observer is employed at the post office, while the thermometer screen is situated in a square surrounded by houses about five minutes' walk away. On one side of the square is the house on which the Robinson cup anemometer is placed. When walking from the office to his screen, the observer passes through narrow streets, and forms an estimate of the wind from its effect upon the dust, smoke and people, and when he arrives at the square looks at the cups to see if they are revolving as he would expect from his estimate. By the time he returns to the office to send his message he has formed his estimate. In this case the observer in the narrow streets is sheltered very much from the wind, while the anemometer, which is much higher than any of the surrounding houses, feels its full effect. Thus we should expect the curve for Shields to lie above that for exposed places like Yarmouth and Scilly, and this is found to be so.

Oxford.

The results from Oxford are not altogether satisfactory for an investigation of this nature. The anemometer is well exposed on the top of the Radcliffe Observatory, and the observers base their estimates entirely upon the velocity of revolution of the cups.* When asked to describe the effects of the different forces upon trees, smoke and people, they were not able to do so, the wind never having been estimated by such signs. This method of estimation has been in use at the Observatory for over twenty years, and so it is difficult to say how the relation between apparent velocity of the cups and the Beaufort scale first originated; but the fairly close agreement between the estimates and the velocity of the wind for the Beaufort numbers given in Scott's "Meteorology" suggests the one being derived from the other. Also this agreement was referred to by one of the observers in conversation, showing that this scale had been used in the past to check the estimates.

Mean results.

Besides the curves for each station, mean curves are given in Figs. 5 and 6. These means are calculated as though all the estimates had been made at the same place and by the same observer, that is, the individual observations from all five stations are put together and the whole treated as the results from one place. The mean values given in this manner, when plotted, form very regular curves, from which the following Table has been compiled, which may be taken as fairly well representing the real relation between the Beaufort scale and velocity, as understood in Great Britain.

TABLE X.

Equivalent Velocities for Great Britain obtained by	Beaufort Numbers.										
	0.	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.
Curtis's method ...	3·0	5·0	8·0	11·0	15·0	19·5	24·5	30·0	36·0	44·0	53
Köppen's method ...	0·0	2·0	6·0	10·5	16·0	22·0	28·0	34·5	42·0	50·0	59

It might be held that the curves for Yarmouth and Scilly should have been combined, and the results for these two places taken as the relation. As there is a

* Although this method of estimating the wind strength is not satisfactory for the purposes of this investigation, yet it appears to be excellent for the purpose for which the estimates are made; *i.e.*, to report to the Meteorological Office the apparent strength of the wind.

tendency for inland observers to under-estimate the winds on account of their more or less sheltered positions, this ought to be taken into account. On the other hand, as the higher winds are seldom experienced inland, the relation for high winds should be mainly obtained from the results of such places as Yarmouth and Scilly. A glance at Figs. 5 and 6 shows that the mean curves meet these requirements, for they are higher than those for Scilly and Yarmouth for the lower Beaufort numbers, but become practically the same at forces higher than 5.

SPECIFICATION OF THE BEAUFORT SCALE.

Physical signs of the wind strength.

In order to obtain some idea of the physical effects of the different wind strengths, each observer has been asked to describe as nearly as possible the signs by which he forms his estimates. As stated above this could not be done at Oxford, as it is impossible to describe the velocity of anemometer cups. The observer at Holyhead gave the effects on a flag, but in order to get results comparable with those of Yarmouth and Scilly, he was asked to describe the behaviour of fishing boats according to the different wind strengths. The results are given in the following Table:—

TABLE XI.

B.	Scilly.	Yarmouth.	Holyhead.	North Shields.	Holyhead (Flag).
0	Calm	Calm	Calm	Calm	Calm.
1	Fishing smack goes about 1 mile per hour. Has just got steerage way.	Slight motion of clouds. Slight breeze.	Fishing smack has steerage way.	Light air, smoke just travelling and anemometer cups *just* going round. Practically no effect on leaves.	Will not carry flag out. Smoke shows direction of wind.
2	Smack goes between 2 and 3 miles per hour. Sails just full.	First perceptible wind. Steady motion of the air. Will move a fishing smack, but not against the tide.	Smack goes about 1 or $1\frac{1}{2}$ knots through water. Cannot go against tide.	Slight breeze can be felt on face. Smoke travelling slowly. Anemometer going very slowly.	Flag partly out.
3	Smack goes between 3 and 4 miles per hour. Just starting to careen. Wind in some directions raises ripples.	Boat just begins to careen.	Smack goes about 4 knots, and can carry all sail.	Gentle breeze. Leaves in motion. Anemometer cups going steadily round.	Flag about three-quarters out.
4	All sails well full, and goes through water quickly, with a good list.	Workable breeze. Can carry all canvas, even with light vessels. White horses with E. breeze.	Boats have list, and still carry all canvas, but must take care.	Moderate breeze. Leaves and twigs of trees in fairly strong motion. Raises loose paper and dust. Quick motion of cups.	Flag out straight, but droops.
5	Must shorten sail. Boat begins to throw water, so that men must put on oilskins. Most boats stop fishing.	Fresh breeze. Begin to shorten sail with light smack, or take care to stand by to shorten sail.	Take in gaff top-sail.	Fresh breeze. Dust and paper flying and trees shaking. Umbrella easily managed, but hat must be held at street corners. Anemometer cups going very fast.	Fresh breeze. Very similar to No. 4, but flag out straighter and droops less often.
6	Must have double reefs in, and fishing boats do not leave harbour to fish.	If going with wind can carry canvas, but must shorten sail in tacking.	Reef mainsail and shift jibs.	Strong breeze. Trees shaking and wires whistling. One has difficulty with umbrella. Anemometer little use in estimating, as cups go so fast that they are practically invisible.	Strong breeze. Flag out straight much longer than it droops.
7	Moderate gale. No fishing boats leave harbour.	Smacks would remain in harbour, and those at sea would lie to.	Boats do not go out.	Moderate gale. Whole trees moving.	Moderate gale. Flag is generally taken in by coast-guard.
8	Gale	Gale. All smacks make for harbour, if near.	Gale	Gale	Gale.

Specification.

Admiral Beaufort's specification of the winds for each step of his scale being no longer of practical use, the following specifications have been drawn up based on the data of Table XI.

The use of this Table would bring future estimates into uniformity with those being made at present in the British Isles :—

TABLE XII.

Beaufort Numbers.	General Description.	Specification for Estimating on Sea.	Specification for Estimating on Land.
0	Calm	Calm	Calm ; smoke rises vertically.
1	Light air... ...	Fishing smack just has steerage way.	Direction of wind shown by smoke drift, but not by wind vanes.
2	Light breeze ...	Wind fills the sails of smacks which then move at about 2 miles per hour.	Wind felt on face ; leaves rustle ; ordinary vane moved by wind.
3	Gentle breeze ...	Smacks begin to careen and travel about 4 miles per hour.	Leaves and small twigs in constant motion ; wind extends small flag.
4	Moderate breeze	Good workable breeze ; smacks carry all canvas with good list. White crests on waves.	Raises dust and loose paper ; small branches are moved.
5	Fresh breeze ...	Smacks shorten sail	Small trees in leaf begin to sway ; wavelets form on inland waters.
6	Strong breeze ...	Smacks have double reef in main sail. Care requisite when fishing.	Large branches in motion ; whistling heard in telegraph wires ; umbrellas used with difficulty.
7	Moderate gale ...	Smacks remain in harbour and those at sea lie to.	Whole trees in motion ; inconvenience felt when walking against wind ; umbrellas discarded in exposed places.
8	Fresh gale ...	All smacks make for harbour.	Breaks twigs off trees. Generally impedes progress.
9	Strong gale ...	Steam navigation becomes difficult.	Slight structural damage occurs. (Chimney pots and slates removed.)
10	Whole gale	Navigation attended with danger.	Seldom experienced on land ; trees uprooted ; considerable structural damage occurs.
11	Storm	Steamers only managed with difficulty.	Very rarely experienced ; accompanied by wide-spread damage.
12	Hurricane ...	Hurricane.	

Comparison of Cup and Pressure Tube Anemometers.

At Scilly and Holyhead besides the cup anemometer already considered, there are also pressure tube anemometers. In order to compare the results of the two kinds of instruments, wind velocities have been obtained from the pressure tube anemometers and these reduced by Curtis's method. The following Table shows the comparison.

TABLE XIII.

Scilly.

—	0.	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.
Cups	2	3	6	9	13	20	26	32	39	46	51
Pressure tube	–	2	6	9	14	20	27	32	38	45	52

Holyhead.

—	0.	1.	2	3.	4.	5.	6.	7.	8.	9.	10.
Cups	2	6	11	15	19	21	24	28	34	42	50
Pressure tube	–	6	12	17	21	23	26	29	35	44	50

The factor of the cup anemometer at Scilly (5-inch cups on 12-inch arm) has been taken as 2·8, and that at Holyhead (Kew Standard Pattern) as 2·2. The pressure tube velocities are taken directly from the scale printed on the papers supplied with the instrument. For Scilly the two anemometers give practically identical results, much nearer than one might expect from two instruments differing so essentially in principle. The agreement is not quite so good at Holyhead, the pressure tube giving slightly the higher results. The reason for this is not apparent, as the instruments at Holyhead are exceedingly well-kept. The difference is nearly a constant of 2 miles per hour, and so is more likely to be a zero error, than an error in the factor (2·2) used for reducing the Robinson anemometer. But the agreement between these two instruments is near enough for all practical purposes, and the difference does not at all affect the results of this investigation.

Physical Characteristics of Wind used in Estimating.

Base of estimates.

It is well-known that a wind is not a regular motion of air, but is made up of a series of lulls and gusts. The question has been raised as to what an observer estimates ; whether he estimates the strength of the wind from the gusts, the lulls, or the mean velocity.

Wind characteristics obtained from pressure tube records.

All reductions of the Beaufort Scale have been effected by assuming the latter. The results so obtained would not be true if the estimates were based on the gusts or the lulls. If the mean velocity of the wind in the gusts or in the lulls could be compared with the Beaufort Scale it is possible that quite different results would be obtained ; and results which might indicate that the estimates were based on one or other of them, rather than on the mean velocity. The pressure tube anemometer gives a record which lends itself to making this investigation. From the reproduction of an actual trace shown in the frontispiece it will be seen that each gust of the wind is represented by a sudden rise and fall of the curve, the reverse representing a lull. If now a few of the highest points recorded on the curve during an hour are taken, these may be considered to represent the velocity of the wind in the gusts, and from them the mean velocity of the gusts could be obtained. The expression " mean velocity of the gusts " is a very loose term, and cannot be accurately defined ; but experience has shown that with a little practice it is possible to obtain a high degree of consistency in measuring such a quantity. In a similar way the mean velocity of lulls can be obtained. From the curves one can also obtain the absolute highest and lowest velocities occurring in an hour. Thus from the pressure tube anemometer curves it is possible to obtain four measurements other than that of the mean velocity, viz :—

1. The mean of the gusts.
2. The mean of the lulls.
3. The absolute highest velocity attained during one hour. (Absolute max.)
4. The absolute lowest velocity during the hour. (Absolute min.)

The pressure tube traces from Scilly and Holyhead have been treated in this way, and the results compared with the corresponding estimates.

Our first object is to find if an observer bases his estimate of the wind strength on the mean velocity of the wind, on its velocity in the lulls, on its velocity in the gusts, or on either of its maximum or minimum velocities. If any one of these is the real basis of his estimate, then we should expect that more consistent results would be obtained when his estimates were compared with that factor than when compared with any other. With this idea curves of frequency similar to those shown in Fig. III were drawn for each of these four new factors, but in all particulars they proved similar to those drawn for the mean velocity, and appeared to give neither more nor less consistent results.

Relation between Beaufort number and seven characteristics of the wind.

Then the data for each factor were treated by Curtis's method, the results being given in Tables XIV. and XV., and plotted on Figures 7 and 8. It will at once be seen that the five curves are similar and so give no clue to which factor the observer used when estimating.

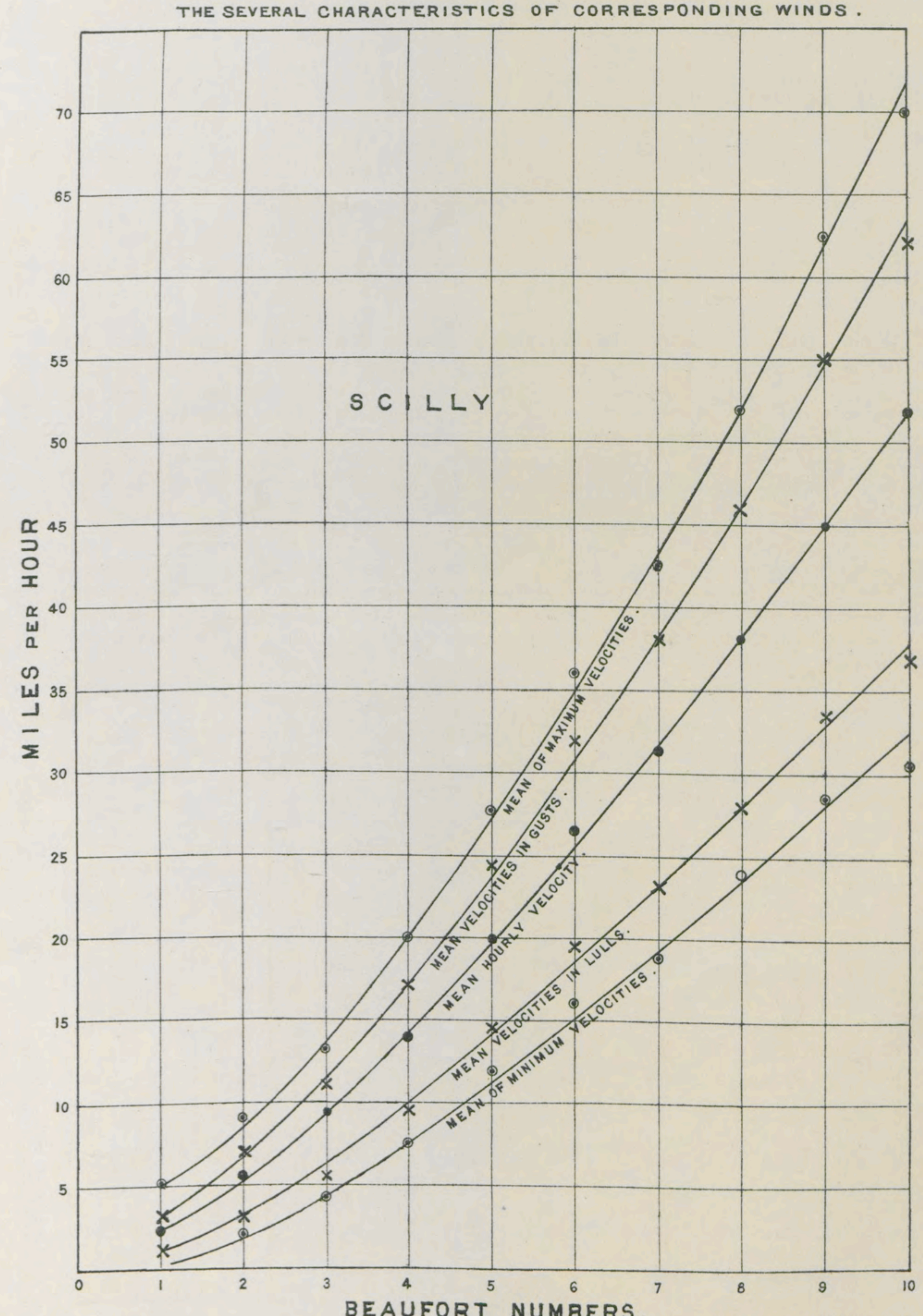
TABLE XIV.

SCILLY.

Beaufort Number.	A. Mean of Absolute Max.	B. Mean of Gusts.	C. Mean.	D. Mean of Lulls.	E. Mean of Absolute Min.	B–D. Average Range.	A–E. Extreme Range.
1	5·0	3·0	2·0	1·0	1·0	2·0	4·0
2	9·0	7·0	5·5	3·0	2·0	4·0	7·0
3	13·0	11·0	8·5	5·5	4·0	5·5	9·0
4	20·0	17·0	14·0	9·5	7·5	7·5	12·5
5	27·5	24·5	20·0	14·5	12·0	10·0	15·5
6	36·0	32·0	26·5	19·5	16·0	12·5	20·0
7	42·5	38·0	31·5	23·0	19·0	15·0	23·5
8	52·0	46·0	38·0	28·0	24·0	18·0	28·0
9	62·5	55·0	45·0	33·5	28·5	21·5	34·0
10	70·0	62·0	52·0	37·0	30·5	25·0	39·5

Figure 7.

AVERAGE RELATION BETWEEN THE BEAUFORT NUMBERS AND THE SEVERAL CHARACTERISTICS OF CORRESPONDING WINDS.



13.1.06.

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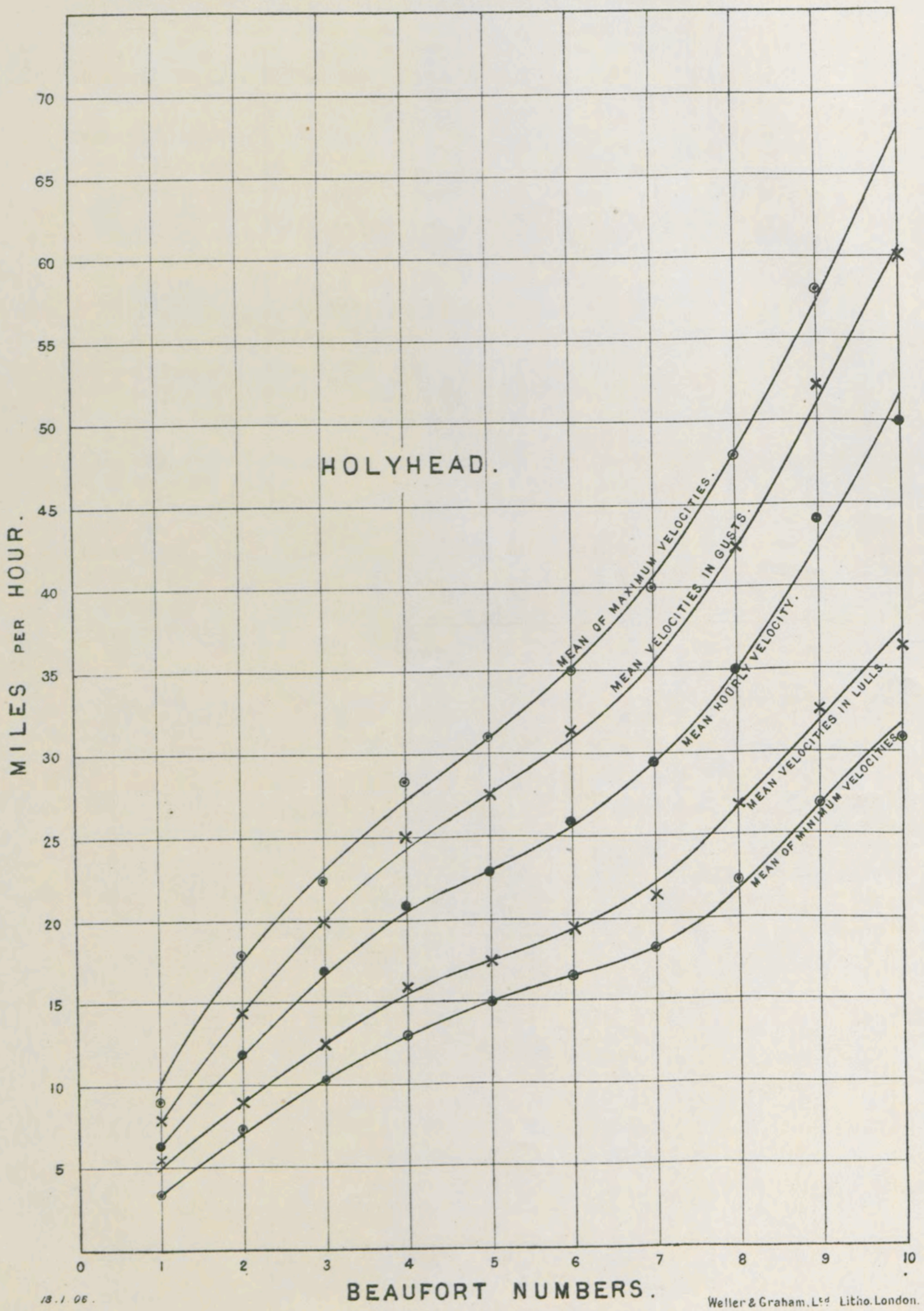
Figure 8.

Average relation between the Beaufort numbers and the several characteristics of the corresponding wind.



18.1.06.

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TABLE XV.

Holyhead.

Beaufort Number.	A. Mean of Absolute Max.	B. Mean of Gusts.	C. Mean.	D. Mean of Lulls.	E. Mean of Absolute Min.	B–D. Average Range.	A–E. Extreme Range.
1	9·0	8·0	6·5	5·5	3·5	2·5	3·5
2	18·0	14·5	12·0	9·0	7·5	5·5	10·5
3	22·5	20·0	17·0	12·5	10·5	7·5	12·0
4	28·5	25·0	21·0	16·0	13·0	9·0	15·5
5	31·0	27·5	23·0	17·5	15·0	10·0	16·0
6	35·0	31·5	26·0	19·5	16·5	12·0	18·5
7	40·0	35·0	29·5	21·5	18·0	13·5	22·0
8	48·0	42·5	35·0	27·0	22·5	15·5	25·5
9	58·0	52·0	44·0	32·5	27·0	19·5	31·0
10	61·5	60·0	50·0	36·5	31·0	23·5	30·5

The difference between the mean of the gusts and the mean of the lulls gives a quantity which may be called the "average range" of the wind's velocity. Similarly, the mean extreme range can be found from the difference between the mean absolute *General character of wind.*

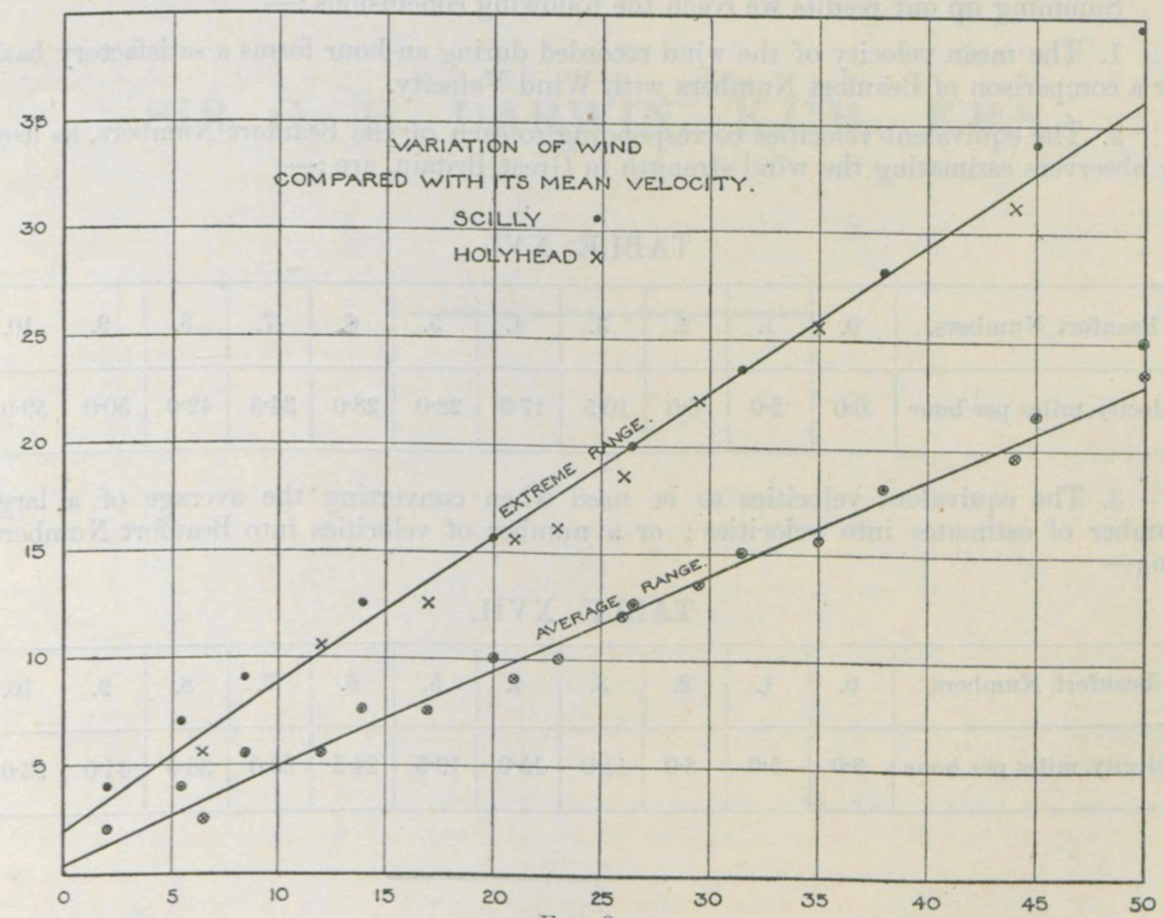

Fig. 9.

maximum and the mean absolute minimum. These values are given in columns B–D and A–E of Tables XIV. and XV. When the numbers in columns A, B, D, E, B–D, and A–E are plotted against those in column C, Fig. 9, it is found that each column produces a straight line, on which the points lie with great regularity; the inclination of this line is the same for the data of the two Tables, so that, when combined, the Tables produce the same result.

From these curves we obtain the following relation. If v is the mean velocity of the wind for the hour, then for that hour :—

1. Probable extreme maximum velocity $= 1{\cdot}5 + 1{\cdot}3v$.
2. Probable mean velocity of wind in the gust $= {\cdot}5 + 1{\cdot}2v$.
3. Probable mean velocity of wind in lulls $= -{\cdot}5 + {\cdot}76v$.
4. Probable extreme minimum velocity $= -1{\cdot}0 + {\cdot}65v$.
5. Probable extreme range of velocity $= 2{\cdot}0 + {\cdot}68v$.
6. Probable average range of velocity $= {\cdot}5 + {\cdot}45v$.

This is a most striking result, and means that the *gustiness* of the wind is linearly proportional to the velocity of the wind, both when the mean of the gusts and lulls, and the absolute extremes are taken into account. A still more striking feature is that the values for Scilly and Holyhead are practically the same, showing that in spite of the difference of the exposure of the two anemometers, the "character of the wind" is the same at the two places.

From this we draw the conclusion that it is quite immaterial as to whether the observer estimates the wind strength from the gusts, lulls, or mean velocity, for these are so related that the results can be converted from one to the other by means of the equation given above.

Conclusions. Summing up our results we reach the following conclusions :—

1. The mean velocity of the wind recorded during an hour forms a satisfactory basis for a comparison of Beaufort Numbers with Wind Velocity.

2. The equivalent velocities corresponding to each of the Beaufort Numbers, as used by observers estimating the wind strength in Great Britain, are :—

TABLE XVI.

Beaufort Numbers.	0.	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.
Velocity, miles per hour	0·0	2·0	6·0	10·5	17·0	22·0	28·0	34·5	42·0	50·0	59·0

3. The equivalent velocities to be used when converting the average of a large number of estimates into velocities; or a number of velocities into Beaufort Numbers, are :—

TABLE XVII.

Beaufort Numbers.	0.	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.
Velocity, miles per hour	3·0	5·0	8·0	11·0	15·0	19·5	24·5	30·0	36·0	44·0	53·0

BEAUFORT'S SCALE OF WINDS.

BY

SIR G. H. DARWIN, K.C.B., F.R.S.

BEAUFORT'S SCALE OF WINDS.

The comparison of readings of the anemometer with estimates of the wind according to Beaufort's scale leads to two distinct problems, namely :—

First. To determine the velocity of the wind in miles per hour corresponding to any given number in Beaufort's scale.

Secondly. If we have a large number of estimates of the wind according to the scale at any place of observation, what is the equivalent in miles per hour of the mean of the winds entered under any given scale estimate ?

It might be supposed, at first sight, that these two questions are identical, and I believe that some meteorologists have erroneously adopted the answer to the first problem as being that of the second. In order to mark the distinction between the two problems, I should prefer to state the second problem thus :—

If we have a large number of estimates of the wind according to the scale, what is the correct scale value corresponding to the mean of the winds entered under any given scale estimate ? When the correct scale value has been found, the answer to the first question will afford the result in miles per hour.

In order to obtain the solutions of these problems it is convenient to regard Beaufort's scale as continuous. It will be easy subsequently to pass to the consideration of the actual discontinuous scale. I will further suppose that the estimates in the scale are, on the average, absolutely consistent with themselves, so that any given estimate is only subject to chance errors of observation. The larger part of these errors of observation probably depends on the fact that the observer only takes a sample of the wind as estimated over an interval of a few minutes, while the anemometer may be taken to afford the mean velocity as estimated over an hour. I thus assume that any given velocity in miles per hour admits of precise statement in Beaufort's scale. In other words, our first problem has an exact solution.

Now suppose that there are a large number of observations of the wind taken in duplicate by anemometer and by estimate at the same place and time. Imagine a diagram of these observations constructed with a horizontal line for abscissæ representing wind velocity as given by an anemometer, zero velocity being on the left, and the higher velocities successively towards the right. Take a vertical line as ordinate, and let it be graduated according to Beaufort's scale, zero being at the bottom where the vertical line meets the horizontal one, and the higher values of the scale arranged equidistantly above zero. Then any given pair of observations of the series may be represented by a dot placed at the proper distance horizontally, according to the observed wind velocity, and at the proper height vertically according to the estimated value in the scale. When all the pairs of observations are entered, the diagram will consist of a patch of shading darker towards the middle and lighter towards the edges.

Now consider a vertical strip of the diagram corresponding to any number of miles per hour, and the next higher number of miles ; for example, a strip bounded by the ordinates drawn at 20 and 21 miles per hour. It is clear that if winds of all velocities within the strip are equally prevalent, the centre of inertia of all the dots lying in this strip, or, in other words, the centre of inertia of the shading of the strip, will be found at the point in Beaufort's scale corresponding to a velocity half-way between the two velocities which bound the strips: in the numerical example at 20½ miles per hour. The centres of inertia of all the successive vertical strips may be joined by a curve which gives the Beaufort's scale for each velocity and affords the solution of the first problem. I will call this the curve of Beaufort's scale.

Next consider a narrow horizontal strip of the diagram. The dots which lie in this strip represent all the various winds which the observer has estimated at the same value in the Beaufort scale; and the dots towards the left end of the strip represent the over-estimates of low velocities, while those towards the right end represent the under-estimates of high velocities. Since these over-estimates cannot in general equal the under-estimates in number, the centre of inertia of the dots on the strip does not in general correspond with the correct mean of the wind velocities corresponding to this group of observations. But it is easy to find that mean, as I shall now explain.

The true Beaufort scale reading corresponding to any velocity is the point on the curve of Beaufort's scale corresponding to the abscissa for that velocity. It follows, therefore, that if we transport each of the dots in the narrow horizontal strip under consideration vertically downwards or upwards, and deposit it on the curve, the vertical distance through which each dot is transported gives the correction which ought to be applied to the observer's estimate before conversion into miles per hour is undertaken, and the ordinates of the points on the curve represent what may be considered as corrected estimates by the observer. Now, the centre of inertia of the transported dots gives the true (or average) Beaufort scale reading, and the true corresponding average wind velocity for the group of winds represented by the dots on the strip. It is clear that, except in the particular case when the over-estimates balance the under-estimates, this centre of gravity will in general lie outside the strip from which the dots were transported.

This procedure by transportal is clearly a correct way of evaluating the estimates in miles per hour, but if the curve of Beaufort's scale is not very much curved, and if the dots are not very widely spaced out, I think that a result which would be practically adequate might be obtained without actually effecting the transportals. On this hypothesis the centre of the inertia of the transported dots will lie on the curve of Beaufort's scale. The transportal of the dots vertically upwards or downwards cannot alter the abscissa of the centre of inertia, although it will alter the ordinate. Hence we may determine that abscissa from the untransported dots, and may next draw an ordinate through the centre of inertia of the untransported dots; the point where that ordinate meets the curve of Beaufort's scale will be approximately the centre of inertia of the transported dots. It determines by its position the corrected Beaufort scale corresponding to the given group of winds which were all estimated as the same; it also gives the corresponding wind velocity in miles per hour.

The only difference between the more rigorous treatment by transportal and the approximate treatment just described, is that in the latter we accept as the ordinate of the required centre of inertia that ordinate of the curve of Beaufort's scale which corresponds with the abscissa of the centre of inertia; that is to say, we *assume* that the centre of inertia lies on the curve. But the accuracy of this hypothesis should be tested by determining the ordinate of the true centre of inertia of the transported dots. This would only involve a small amount of arithmetic. I suspect that with rough observations of the kind under consideration the curvature of the curve of Beaufort's scale would play so small a part that the centre of inertia of the transported dots would to all intents lie on the curve of Beaufort's scale. If this last prevision should be verified,* the whole result may be very succinctly embodied in two curves. The first of these is the curve of Beaufort's scale so frequently referred to; the second is the curve passing through the centres of inertia of all the horizontal strips. The vertical distance between these two curves represents the correction to the estimates on Beaufort's scale, which should be applied before the conversion to wind velocities is carried out. The estimates thus corrected may at once be converted into miles per hour by means of the curve of Beaufort's scale. The solution of the second problem is thus found either by the more rigorous method of transportal or by this approximate method.

I have hitherto supposed Beaufort's scale to be continuous instead of discontinuous, as is actually the case. If the curve of error for any wind velocity—that is to say, for the dots lying in any vertical strip—is symmetrical, the discontinuity in the scale will exercise no appreciable effect on the result, for it will not affect the determination of the curve of Beaufort's scale, and it will only affect to a slight extent that correction to the solution of our second problem which depends on the curvature of the curve.

In this case, then, the discontinuity of the scale can exercise no appreciable effect. But if the curve of error is asymmetrical some correction to our results would theoretically be needed. It would not be very difficult to determine this, but with observations of this rough character of estimates of wind force I do not think it is worth while to consider the point.

G. H. DARWIN.

March, 1903.

* The curves of the Beaufort scale (*see* my report) are so slightly curved that this prevision may be accepted.—G. C. S.

THE FACTOR

OF

THE KEW PATTERN ROBINSON ANEMOMETER.

BY

W. H. DINES. F.R.S.

THE FACTOR OF THE KEW PATTERN ROBINSON ANEMOMETER.

BY

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A considerable series of observations, made in different places, and tabulated and worked up by different observers, have shown that if the velocity of the centres of the cups of the Kew pattern Robinson Anemometer be multiplied by 2·2, the number so obtained will agree very closely with the velocity of the wind recorded by the pressure tube anemometer, and that the relation will hold for all velocities that occur in practice. Presumably it is this fact which has led to the adoption of the factor 2·2, and it is therefore of importance to ascertain what ground there is for assuming the tube anemometer to give a correct value.

The method of graduation was one that admitted of great accuracy; the particulars will be found in the Quarterly Journal of the Royal Meteorological Society, Vol. XVI., p. 208, 1890. The chief part of the effect depends on the pressure exerted by the wind in the open mouth of the tube, and since the experimental observation of this pressure agreed exactly with that obtained by using the formula for the rate of efflux of a fluid through a hole under a given pressure, it seems fairly certain that the value may be taken as rigorously correct. The effect of the suction is more uncertain, but I see no reason to doubt that it was correctly ascertained, although no mathematical formula can be quoted to support it.

The relation according to which the tube anemometers should be calibrated is $h = \cdot 00073v^2$, where h is the pressure in inches of water, and v is the velocity in miles per hour (pressure 30·00 inches; temperature 50° F.), h being the difference of pressure in inches of water between the two connecting tubes. Admitting that this relation is correct, and I have no doubt that it is sufficiently so for all practical purposes, it is still somewhat uncertain to what extent the tube anemometer approximates to the true velocity of the wind. The tube anemometer is essentially a pressure instrument, and the mean velocity of the wind if deduced from the mean pressure will certainly be too high. It will be well to take a definite case to make the reason of this clear. Suppose that the velocity for half an hour is 18 miles per hour, and then for the next half hour 36 miles per hour. For the first half hour the pressure is 1 lb. per square foot (very nearly), for the second 4 lbs. per square foot. The mean pressure is for the hour $2\frac{1}{2}$ lbs. and this corresponds to a velocity of 28·4 instead of 27·0 miles per hour, a difference of about 5 per cent.

If the pen of the anemometer could be depended upon to follow exactly the velocity variations that occur at the vane, no error from this source could occur, but with the more rapid variations there is certainly some lag, and, if so, the pen will follow a rise in the wind velocity more rapidly than a fall, since the force on the moving parts during the rise is greater than during the fall. (*See* Quarterly Journal of the Royal Meteorological Society, Vol. XVII., p. 180, 1892.)

It follows, therefore, that the recorded mean velocity is too high, but it is very doubtful if the error can amount to 1 per cent. It is hardly likely, even if the mean velocity were deduced from the mean pressure, that in practice the excess could be $1\frac{1}{2}$ per cent., for the velocity of the wind is only now and then at any distance from its mean for the time being. For a wind that is not appreciably altering in strength for one hour, the most frequent velocities for the hour are those lying near to the mean, and the total duration of the lulls and extreme gusts is small. It is only the very rapid changes of velocity which the pen is not quick enough to follow that can influence the mean recorded by the anemometer, and hence, I think, that if the relation $h = \cdot 00073v^2$ be correct, the anemometer record is correct to 1 per cent.

Since a considerable number of pressure tube anemometers are now in use in many parts of the world, it seems to me desirable that a fresh experimental determination of its constants should be made, for the undoubted discrepancy remains that the Kew pattern Robinson anemometer, when tested independently, and when tested by comparison with other velocity anemometers, gave a lower factor than 2·20.

It is a matter of congratulation that now the error, if there be one, is only a question of 2 or 3 per cent., instead of, as it was for so many years, one of 25 to 30 per cent.

ON

COMPUTING WIND FORCE AT SEA.

BY

CAMPBELL HEPWORTH, C.B.,

COMMANDER R.N.R., MARINE SUPERINTENDENT.

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During the past fifty years steam has so largely superseded sail as the means of propelling seagoing vessels, and so many changes have taken place in the build, rig, and tonnage of sailing vessels and in the conditions under which they are sailed, that the Beaufort scale for registering the force of the wind has become unintelligible to the majority of seamen in active service.

It appears desirable, therefore, that some method of determining the force of the wind, and thereby of referring it to some recognised numerical notation, should be established for the information of observers on board of steamers; and that the Beaufort scale should be so modified as to make its equivalents referable to the conditions of modern seamanship as exercised on board of any square-rigged sailing vessel, and, for the most part, on any vessel propelled by sails.

There are imperfections in the Beaufort scale which should be avoided when revising it. Forces 1 to 4 refer the observer to the rate at which a warship of Admiral Beaufort's time could sail in smooth water, clean full; a quantity, by the way, varying in a merchant ship according to her build and trim even in those days, and presumably, in a warship also. Forces 5 to 9 refer to another standard; the sail the same class of ship could carry in chase "full and by." The standard by which force 10 is to be judged seems incomplete since no mention is made as to whether the typical ship is running or fore reaching.

In the modified scale submitted, although the unit of reference does not remain exactly the same for all wind velocities, the criteria in all cases are clearly specified and are applicable to vessels of, practically, any size and rig.

The observer on a steamship, by comparing the speed at which the vessel is travelling in a calm with the wind force he experiences when standing in an exposed position on board of her obtains a standard to aid him in the construction, mentally, of a scale of equivalents on the same lines as that of the Beaufort notation. Another fixed value for his scale may be obtained by the comparison of the same wind force, experienced in an exposed position when the vessel is running at the same speed dead before the wind with that of the actual force of the wind as experienced when the vessel is stopped. For instance the wind experienced by an observer in an exposed position on board a steamer steaming in a calm, say, 15 knots or 17·26 statute miles per hour is a moderate breeze. When the same amount of wind is felt by an observer in an exposed position on board the vessel when running 15 knots dead before the wind, a moderate gale is blowing

The observer must, of course, have not only the experience of the force of the wind when running before it, but also when stopped, before he can in this way obtain his standard of moderate gale force. Such opportunities are not, however, infrequent in their occurrence.

It seems extremely doubtful whether the force of the wind can be correctly estimated by its effect upon the sea. Winds blowing from a polar quarter raise more sea than do winds blowing from an equatorial quarter. Sea disturbance is frequently the effect of wind blowing at great distances from the observer. Without an increase of wind an increase in sea disturbance may be caused by a sudden change in its direction. Sea disturbance is reduced by the fall of rain or hail, and is increased by the opposition of tide or current to the wind's direction.

Proposed Specification for Use at Sea.

Beaufort Scale.	Description of Wind.	Mode of Estimating aboard Sailing Ships.	Mean Velocity.
1–3	Light breeze ...	Sufficient wind for working ship	7
4–5	Moderate breeze	Force most advantageous for sailing with leading wind and all sail drawing.	17
6–7	Strong breeze ...	Reduction of sail necessary even with leading wind.	30
8–9	Gale force ...	Considerable reduction of sail necessary even with wind quartering.	45
10–11	Storm force ...	Close-reefed sail running, or hove to under storm sail.	65
12	Hurricane ...	No sail can stand even when running	From 75 upwards.

LIST OF PUBLICATIONS

Issued by the Meteorological Office.

2. Occasional Publications and Reports—*cont.*

Sunshine :—

Sunshine Records of the United Kingdom for 1881. (Official, No. 56, 1883). 4*s*.

Ten Years' Sunshine in the British Isles, 1881–90. (Official, No. 98, 1891.) 2*s*.

Temperature :—

Temperature Tables for the British Islands. 10*s*. 6*d*. Supplement:—Difference Tables for each Five Years for the Extrapolation of Mean Values. (Official, No. 154, 1902.) 3*s*.

3. Instructions in the use of Instruments, &c.

Barometer Manual. (Official, No. 8, 1871.) [Out of print.]

Barometer Manual for the Use of Seamen. With an Appendix on the Thermometer, Hygrometer, and Hydrometer. Fourth Edition, extensively revised, 1902. (Official, No. 61.) 3*d*.

Fishery Barometer Manual. New Edition, 1887. (Official, No. 3.) 6*d*.

Instructions for Meteorological Telegraphy. New Edition, in preparation. (Official, No. 2.) Prepared for the use of Observers exclusively.

Instructions in the use of Meteorological Instruments. Reprinted 1892. (Official, No. 24.) [Out of print.]

Hints to Meteorological Observers in Tropical Africa, with Instructions for taking observations, and Notes on Methods of recording Lake Levels. (Official, No. 162, 1902.) 9*d*.

Forecasting :—

Aids to the Study and Forecast of Weather.—By W. Clement Ley, M.A. (Official, No. 40, 1880.) 1*s*.

Principles of Forecasting by means of Weather Charts.—By the Hon. Ralph Abercromby, F.R.Met.Soc. Second Edition, Revised, 1885. (Official, No. 60.) [Out of print.]

4. Marine Meteorology.

Charts.—

Arabian Sea :—

Daily Weather Charts for the period of six weeks ending June 25, 1885, to illustrate the tracks of two cyclones in the Arabian Sea. (Official No. 80, 1891.) 10*s*.

Atlantic :—

Charts of Meteorological Data for the Nine 10° Squares of the Atlantic, which lie between 20° N. and 10° S., and extend from 10° to 40° W., with accompanying Remarks, ending with the Best Routes across the Equator. (Official, No. 27, 1876.) 24*s*.

Monthly Current Charts for the Atlantic Ocean. From Information collated and prepared in the Meteorological Office. Published by the Admiralty. (Official, No. 132, 1897.) 7*s*.

4. Marine Meteorology—*continued.*

Charts—*continued.*

Atlantic (North) :—

Charts of Meteorological Data for Square 3 Lat. 0°–10° N., Long. 20°–30° W., and Remarks to accompany the Monthly Charts, which show the Best Routes across the Equator for each Month, &c. (Official, No. 20, 1874.) 20*s*.

Charts illustrating the weather of the North Atlantic Ocean in the Winter of 1898–99. (Official, No. 142, 1901.) 6*s*. 6*d*.

Currents and Surface Temperature of the North Atlantic Ocean, from the Equator to Latitude 40° N., for each Month of the Year. With a General Current Chart. (Official, No. 12, 1872.) 2*s*. 6*d*.

Discussion of the Meteorology of that Part of the Atlantic lying North of 30° N., for the Eleven Days ending 8th February, 1870. With Charts. (Official, No. 13, 1872.) 5*s*.

Meteorology of the North Atlantic during August, 1873, with 31 Synoptic Charts. (Official, No. 32, 1878.) With Book of Charts. 15*s*.

Synchronous Weather Charts of the North Atlantic and the adjacent Continents, 1st August, 1882, to 3rd September, 1883. Parts I. to IV. (33 sheets each) (Official, No. 71, 1886.) 17*s*. each Part.

Atlantic (South) :—

Charts showing the Surface Temperature of the South Atlantic Ocean in each month of the year. (Official, No. 4, 1869.) 2*s*. 6*d*.

Wind Charts for the Coastal Regions of South America. From Information collated and prepared in the Meteorological Office. Published by the Admiralty. (Official, No. 159, 1902.) 7*s*.

Monthly Wind Charts of the South Atlantic. Published by the Admiralty. (Official, No. 168, 1903.) 6*d*. each

The relation between Pressure, Temperature, and Air Circulation over the South Atlantic Ocean. (Official, No. 177, 1905.) 9*d*.

Atlantic, Indian, and Pacific Oceans :—

Charts showing the Surface Temperature of the Atlantic, Indian, and Pacific Oceans. (Official, No. 59, 1884.) 21*s*.

Charts showing the Mean Barometric Pressure over the Atlantic, Indian, and Pacific Oceans. (Official, No. 76, 1887.) 10*s*. 6*d*. Supplementary Chart, 6*d*.

Atlantic (North) and Mediterranean :—

Monthly Pilot Charts, commencing April, 1901. (Official, No. 149.) 6*d*. each; subscription for one year, 5*s*. (exclusive of postage).

Indian Ocean :—

Monthly Current Charts for the Indian Ocean. From Information collated and prepared in the Meteorological Office. Published by the Admiralty. (Official. No. 124, 1896.) 7*s*.

Monthly Pilot Charts of the Indian Ocean. (Official No. 181.) In the press.

Indian Ocean (North) :—

Meteorological Charts of the portion of the Indian Ocean adjacent to Cape Guardafui and Ras Hafún. (Official, No. 92, 1891.) 6*s*.

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LIST OF PUBLICATIONS

Issued by the Meteorological Office.

4. Marine Meteorology—*continued.*

CHARTS—*continued.*

Indian Ocean (South) :—

Cyclone Tracks in the South Indian Ocean. From information compiled by Dr. Meldrum, C.M.G., F.R.S. (Official, No. 90, 1891.) 7*s.*

Meteorological Charts for the Ocean District adjacent to the Cape of Good Hope, with accompanying Remarks. (Official, No. 43, 1882.) Charts, 25*s.* Remarks, 7*s.*

Pacific Ocean :—

Quarterly Current Charts for the Pacific Ocean. From Information collated and prepared in the Meteorological Office. Published by the Admiralty. (Official, No. 134, 1897.) 5*s.*

Wind Charts for the Coastal Regions of South America. From Information collated and prepared in the Meteorological Office. Published by the Admiralty. (Official, No. 159, 1902.) 7*s.*

Red Sea :—

Meteorological Charts of the Red Sea. (Official, No. 106, 1895.) 21*s.*

Southern Ocean :—

Meteorological Charts of the Southern Ocean between the Cape of Good Hope and New Zealand. (Official, No. 123, 1899.) 12*s.*

OTHER PUBLICATIONS ON MARINE METEOROLOGY :—

Contributions to our Knowledge of the Meteorology of the Antarctic Regions. (Official, No. 18, 1873.) 2*s.*

Contributions to our Knowledge of the Meteorology of the Arctic Regions. (Official, No. 34, 1885.) Vol. I. : Part I., 2*s.* ; II., 10*s.* ; III. and V., 6*s.* each ; IV., 5*s.*

Contributions to our Knowledge of the Meteorology of Cape Horn and the West Coast of South America. (Official, No. 11, 1871.) 2*s.* 6*d.*

4. Marine Meteorology—*continued.*

OTHER PUBLICATIONS ON MARINE METEOROLOGY—*cont.*

Notes on the Form of Cyclones in the Southern Indian Ocean.—By C. Meldrum, M.A., F.R.S. (Non-Official, No. 7, 1873.) [Out of print.]

On the Physical Geography of the part of the Atlantic which lies between 20° N. and 10° S., and extends from 10° to 40° W. A Paper read before the British Association at Bristol, in August, 1875.—By Captain H. Toynbee, F.R.A.S. (Non-Official, No. 10, 1876.) [Out of print.]

On the Winds, &c. of the North Atlantic along the Tracks of Steamers from the Channel to New York. Translated from a Paper issued by the Deutsche Seewarte, Hamburg. (Non-Official, No. 5, 1872.) 6*d.*

Report to the Committee of the Meteorological Office on the Meteorology of the North Atlantic.—By Captain H. Toynbee, F.R.A.S. (Non-Official, No. 2, 1869.) 1*s.*

Report on the Gales experienced in the Ocean District adjacent to the Cape of Good Hope, between Lat. 30° and 50° S., and Long. 10° and 40° E.—By Captain H. Toynbee, F.R.A.S. (Official, No. 44, 1882.) 7*s.* 6*d.*

Routes for Steamers from Aden to the Straits of Sunda and back. Translated from a Paper issued by the R. Meteor. Inst. of the Netherlands. (Non-Official, No. 4, 1872.) [Out of print.]

5. Miscellaneous Publications.

Harmonic Analysis of Hourly Observations of Air Temperature and of Pressure at British Observatories. (Official, No. 93, 1891.) 12*s.*

Report of an Inquiry into the Connexion between Strong Winds and Barometrical Differences.—By Robert H. Scott. (Non-Official, No. 1, 1868.) 6*d.*

Report on the Storm of October 13–14, 1881.—By Robert H. Scott, F.R.S. (Official, No. 46, 1882.) 1*s.* 6*d.*

Report to the Committee of the Meteorological Office on the Use of Isobaric Curves.—By Captain H. Toynbee, F.R.A.S. (Non-Official, No. 3, 1869.) [Out of Print.]

Trajectories of Air in Travelling Storms. (Official, No. 174, 1905.) Part I. 7*s.* 6*d.*