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METEOROLOGICAL OFFICE

METEOROLOGICAL OFFICE

PROFESSIONAL NOTES, NO. 44
(*Fourth Number of Volume IV.*)

THE

VELOCITY EQUIVALENTS

OF THE

BEAUFORT SCALE

BY

G. C. SIMPSON, C.B.E., D.Sc., F.R.S.

METEOROLOGICAL OFFICE
R.A.F.
11 MAY 1938
STATION
* MILDENHALL

Published by the Authority of the Meteorological Committee.

LONDON:
PUBLISHED BY HIS MAJESTY'S STATIONERY OFFICE.
To be purchased directly from H.M. STATIONERY OFFICE at the following addresses:
Adastral House, Kingsway, London, W.C. 2; 28, Abingdon Street, London, S.W. 1;
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1926.

Price 9d. Net.

THE VELOCITY EQUIVALENTS OF THE BEAUFORT SCALE

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I.—Historical

In 1838 the British Admiralty adopted a scale of wind force which had been devised in 1806 by Admiral Sir F. Beaufort and instructed all its officers to use this scale in their logs and records. For easy reference the scale is reproduced here :—

0	denotes Calm		
1	... Light Air	just sufficient to give steerage way.	
2	... Light Breeze	with which a well-conditioned man-of-war, under all sail and clean full, would go in smooth water, from—	1 to 2 knots.
3	... Gentle Breeze		3 to 4 knots.
4	... Moderate Breeze		5 to 6 knots.
5	... Fresh Breeze	in which the same ship could just carry close hauled—	Royals &c.
6	... Strong Breeze		Single-reefs and top-gallant sails.
7	... Moderate Gale		Double-reefs, jib, &c.
8	... Fresh Gale		Triple-reefs, courses, &c.
9	... Strong Gale		Close-reefs, and courses.
10	... Whole Gale	with which she could only bear—	Close-reefed main top-sail and reefed fore-sail.
11	... Storm	with which she would be reduced to—	Storm stay-sails.
12	... Hurricane	to which she could show	No canvas.

In the course of time a few slight verbal changes were introduced; but the scale has remained substantially the same as Beaufort drafted it in 1838. Since that date every officer in the British Navy has learnt "to estimate the force of the wind" according to the Beaufort Scale. From the Navy the scale spread to the British Mercantile Marine and, later, to ships of other countries. In 1874 the International Meteorological Committee meeting at Utrecht adopted the Beaufort Scale for international use in weather telegraphy.

In this way the Beaufort Scale has become the chief scale for specifying the force of the wind and is used in all parts of the world, both on sea and land. As originally drawn up the specification of the Beaufort Scale made no reference to the velocity of the wind. With the development of meteorology the need for specifying the Beaufort Scale in terms of wind velocity made itself felt. Many attempts have been made to do this, but it is unnecessary to refer to them all here, it is sufficient to say that they showed very large differences, divergencies of more than 100 per cent between velocity equivalents for the same Beaufort force being frequent(1).

In 1912 Professor Palazzo asked the International Commission for Weather Telegraphy, which met in London during that year, to endeavour to obtain international agreement on the velocity equivalents of the Beaufort Scale, especially for use in weather telegraphy. The Commission appointed a sub-commission consisting of Professor Köppen, Professor Palazzo and Mr. Lempfert to go into the whole matter and to report at their next meeting in Rome in 1913.

It had become clear by that time that most of the old determinations of the velocity equivalents had been superseded by two determinations made by the Deutsche Seewarte (2) and the London Meteorological Office (3) respectively. In each of these determinations the constants of the anemometers had been revised and a correct method developed for comparing the velocity observations with the Beaufort numbers.

The following Table and Figure 1 give the results of the two investigations :—

TABLE I—VELOCITY EQUIVALENTS OF THE BEAUFORT SCALE (METRES PER SECOND)

Beaufort number		0	1	2	3	4	5
Seewarte	Equivalent	0	1·7	3·1	4·8	6·7	8·8
	Limits	0–0·8	0·9–2·3	2·4–3·8	3·9–5·7	5·8–7·6	7·7–9·7
Meteorological Office	Equivalent	0	0·8	2·4	4·3	6·7	9·4
	Limits	0–0·2	0·3–1·5	1·6–3·3	3·4–5·4	5·5–7·9	8·0–10·7

Beaufort number		6	7	8	9	10	11
Seewarte	Equivalent	10·7	12·9	15·4	18·0	21·0	(24·4)
	Limits	9·8–11·8	11·9–14·0	14·1–16·6	16·7–19·5	19·6–22·7	(22·8–26·2)
Meteorological Office	Equivalent	12·3	15·5	18·9	22·6	26·4	30·5
	Limits	10·8–13·8	13·9–17·1	17·2–20·7	20·8–24·4	24·5–28·4	28·5–32·5

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It will be seen from the above Table that there are large differences between the two determinations. In the lower part

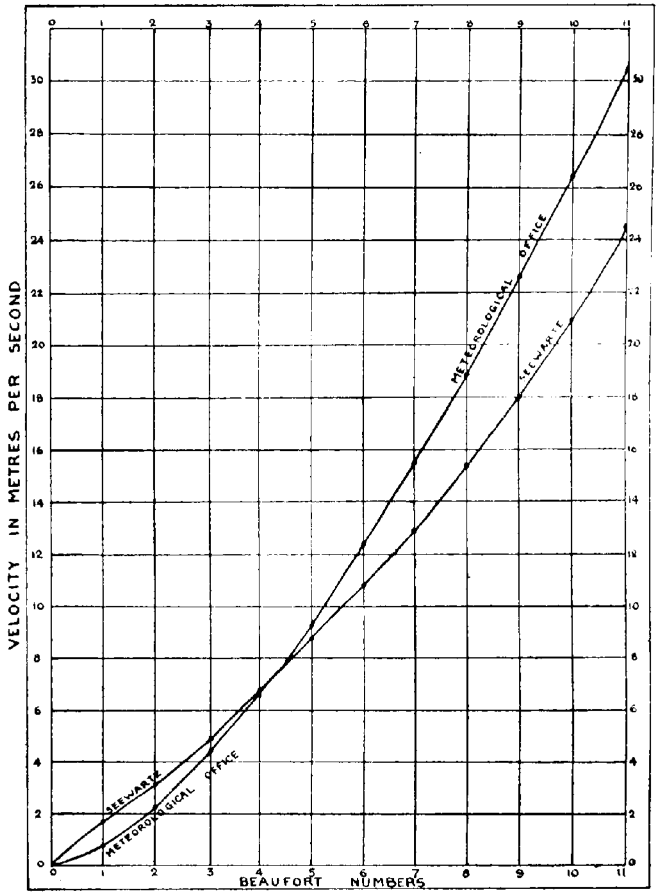

FIG. 1.

of the scale the Seewarte values are higher than the Meteorological Office values, while in the upper part of the scale the reverse is the case. In the lower half the differences are not important, but this is no longer the case in the upper half. From force 8 upwards the Seewarte equivalents are below the Meteorological Office equivalents by a whole Beaufort number; that is the equivalent velocity for force 8 as determined by the Seewarte is below the equivalent velocity determined by the Meteorological Office for force 7, and so on for all the higher numbers. The difference between the two tables becomes more apparent when velocities are considered instead of forces. Thus a wind velocity of 17 m/s. would correspond with force 7 according to the Meteorological Office determination, while according to the Seewarte it would correspond with force 9, a difference which is of the utmost practical importance.

These differences were so great that the sub-commission felt itself unable to recommend either of the two determinations for general acceptance. Still, the values of the Seewarte and Meteorological Office were much nearer together than several other scales of equivalents which were in daily use by certain meteorological offices, and Professor Köppen felt that, without deciding which set of values should be finally accepted, it would be possible to fix the limits outside which it would be definitely wrong to go in converting velocities measured by anemometers into Beaufort numbers or *vice-versa.* He, therefore, put before the International Meteorological Committee, at their meeting in Rome in 1913, for official acceptance the following scale which combines the two determinations :—

Beaufort Force	*Velocity* m/s
0	$\frac{1}{2}$
1	$\frac{1}{2}$–2
2	2–4
3	4–6
4	6–8
5	8–11
6	10–14
7	12–17
8	15–20
9	18–24
10	21–28
11	25–33
12	33

Professor Köppen's proposal, however, did not meet with the approval of the International Meteorological Committee, mainly because it did not really solve the difficulty; for it will be noticed that the limits of the velocities for the higher forces overlap. Thus a velocity of 13 m/s might be either force 6 or force 7 and so on with the other forces. There was considerable discussion on the subject, but the Committee considered that the time had not yet arrived for the definitive adoption of numerical values for the velocity equivalents of the Beaufort Scale, and requested the sub-committee to continue its consideration of the subject.

Before anything further could be done the war broke out and no further international action could be taken.

The question was again raised after the war by Signor Marini and at their meeting in London in 1921 the International Meteorological Committee passed the following resolution :—

> "45. That Dr. Simpson be asked to look into the matter of proposing a definite scale of equivalents between the Beaufort numbers and wind velocity in miles per hour and metres per second."

It was clear from the discussion which took place at the meeting of the Committee that the need for an early solution of the problem arose from the use of the Beaufort Scale as the only method for telegraphing the wind velocity in the weather telegrams. Until a definite set of equivalents had been adopted for universal use different meteorological services would continue to report the same anemometer readings as different forces. This was the aspect of the question which I undertook to investigate and the following discussion gives the results of my consideration of the problem.

II.—Estimates and Velocities

It will help in understanding our problem if we consider the two methods of specifying the strength of the wind which have to be reconciled—namely, an estimate on the Beaufort Scale and a velocity measured by an anemometer.

The Beaufort scale defines the strength of the wind by the effect it has on a specified ship under specified conditions of sailing. When a well-conditioned man-of-war can "just carry close hauled, triple reefs, courses, &c." the strength of the wind is force 8 on the Beaufort Scale. There is no ambiguity about this: force 8 is almost as definite a physical quantity as 8 kilograms. If necessary a well conditioned man-of-war can be used to check a Beaufort estimate in the same way as a standard weight can be used to check the weight of a body. But having determined force 8 in this way it does not follow that the wind velocity will be the same in every case, for the velocity necessary to produce the effect on the ship will vary on account of a number of secondary causes, such as the density of the air, the state of the sea, and, possibly, the nature of the wind, whether it is gusty or not.

But long before Beaufort gave his attention to specifying the strength of the wind sailors had evolved a rough scale with descriptive terms which were used by them in their everyday conversation. Sailors describe the strength of the wind by such words as calm, air, breeze, gale, storm and hurricane; and use such adjectives as light, gentle, moderate, fresh and strong to qualify them. A sailor could not define these terms; but he has no difficulty in recognizing the difference between an air and a breeze, a gale and a storm, a storm and a hurricane. The sailor's estimate of the strength of the wind as used in his ordinary conversation is based on its effect on his surroundings: on the waves formed on the surface of the sea, on the amount of broken water, on the sound produced as it blows through the rigging and on the way his ship can stand up to it. These terms are understood by all experienced sailors and are quite independent of any scientific definitions. The success of Beaufort's Scale is largely due to the fact that, as the result of long experience and careful observation, he was able to attach the name which a sailor would use to each of his thirteen scale numbers. He observed that when a sailor said that there was a moderate breeze his "well conditioned man-of-war, with all sail set, and, clean full, would go in smooth water from 5–6 knots;" thus force 4 on his scale was described as a moderate breeze. In the same way all his numerical forces were designated by the appropriate name of the wind which a sailor would use.

The rig of ships has changed, sail has been replaced by steam, but the effect of the wind on the sea has remained, and will always remain, exactly the same. The sailor's description of the strength of the wind being based on effects independent of the rig of his ship has survived all the changes in marine transport and an air, a breeze, a gale and a hurricane mean just the same to a sailor now as they did in Beaufort's time (4).

Thus the Beaufort Scale of wind force, being anchored to the everyday language of such a conservative class as seamen, has served through a hundred years and is just as useful now, when there is not "a well-conditioned man-of-war" on the sea, as it was when the majority of sailors had sailed and handled such ships.

The Beaufort Scale has no reference to the velocity of the wind, the velocity of the wind during a gale varies from place to place and from time to time, but the gale continues throughout. The velocity of the wind on the deck of a ship is less than the velocity at the top of the mast, but the officer on the sheltered bridge estimates the strength of the wind as a breeze, a gale or a storm in agreement with the look-out in the crow's nest, who is exposed to the full effect of the wind. A seaman does not estimate the strength of the wind by the velocity of the current of air to which he is exposed. A breeze, a gale, a hurricane is a state of the atmosphere and a seaman has only to look at the effect of the wind—on the sea by preference, but he can also estimate from its effect on the land—to use the correct description. This leads us to the conclusion that an experienced seaman when he has learnt to use the Beaufort Scale uses the scale to define a state of the atmosphere. When a sailor estimates the force of the wind at a land station as force 8 he means that, in his opinion if his surroundings were sea instead of land with no change in the wind the effect would be that of a gale. Again, it would make no difference in his estimate whether he was at ground level or on a house top, provided he had an unobstructed view of the effect of the wind over a sufficiently large extent of open country.

If it be granted that the above is a correct description of the significance of an estimate on the Beaufort Scale, it becomes at once obvious that there is an essential difference between a Beaufort estimate and a wind velocity. An estimate describes the effect of the air motion, a velocity can only describe the air motion at a point. When a sailor has described the wind as a gale (force 8) we can measure its velocity and find that on the deck it is 15 m/s, while at the mast head it is 19 m/s, but the sailor will not say that it is blowing force 8 on the deck and force 9 at the masthead. Thus it is possible to measure different velocities with the strength of the wind remaining unchanged. To sum up, while an estimate is largely, if not entirely, independent of the point of observation, a wind velocity can have little significance if the point of observation is not specified.

III.—The Seewarte and Meteorological Office Equivalents

The general consideration which we have just discussed will help us in understanding the apparent discrepancy between the velocity equivalents of the Beaufort Scale as determined by the Seewarte and the Meteorological Office—*see* Table I.

The Seewarte equivalents were derived from the mean of four independent sets of observations which have been grouped by Köppen (2 and 5) as follows :—

TABLE II—SEEWARTE EQUIVALENTS (METRES PER SECOND)

Beaufort Numbers	1	2	3	4	5	6	7	8	9	10
I Ocean -	1·9	3·1	4·8	6·8	8·8	10·2	12·3	14·5	17·3	20·4
II German Coast -	1·8	3·4	4·9	6·5	8·3	10·0	12·0	14·0	?	?
III Norwegian Coast -	1·5	3·2	4·9	6·7	8·7	10·7	12·8	15·1	17·4	19·8
IV English Coast -	1·4	2·7	4·6	6·9	9·2	11·5	14·3	17·8	21·2	25·1
Mean -	1·7	3·1	4·8	6·7	8·8	10·7	12·9	15·4	18·0	21·0

Under "Ocean," Group I, Köppen includes four sets of comparisons made by sailors on board ship. The first was made during 1874-1876, on the sailing ship "Gazelle," to which detailed reference will be made later; the second was made on the "Elizabeth" in 1877, during four heavy storms, two of which were experienced while she was at anchor in Yokohama and two while she was at sea; the third was a short set of observations made in 1882 by Waldo on a North Atlantic liner; and the fourth, a short set made on the steamer "National" during 1889. Köppen gives four times the weight to the first set in obtaining the mean results entered in Table II.

In Group II Köppen includes the observations made by the meteorological observers at five meteorological stations maintained by the Seewarte on the coast of Germany.

Group III contains observations made at five Norwegian lighthouses which were discussed by Professor Mohn.

In Group IV are combined a number of old determinations made at English coast stations and discussed by Curtis, Chatterton and Scott. The original data were corrected by Köppen in the light of later research.

The Meteorological Office equivalents were derived by comparing estimates and anemometer records at five meteorological observatories in different parts of England (3). The individual series gave the following results :—

TABLE III.—METEOROLOGICAL OFFICE EQUIVALENTS

Beaufort Numbers	1	2	3	4	5	6	7	8	9	10
					Metres per second.					
Scilly	1·0	2·1	3·7	6·0	8·9	12·3	15·6	19·2	22·6	25·5
Yarmouth	0·6	1·6	3·6	5·8	8·9	12·3	15·6	19·0	22·3	—
Holyhead - -	2·2	4·5	6·7	8·2	10·1	11·8	14·1	17·9	22·8	—
North Shields -	1·0	2·9	6·7	10·3	13·4	15·4	17·2	19·0	—	—
Oxford - -	1·1	3·4	6·0	8·5	10·7	12·1	13·6	15·7	—	—
Mean- - -	·9	2·7	6·5	7·2	9·8	12·5	15·4	18·8	22·4	26·4
Adopted values -	·8	2·4	4·3	6·7	9·4	12·3	15·5	18·9	22·6	26·4

In each case the observations used were those contributed to the *Daily Weather Report* for the three years 1900–1902 and numbered 3,000, approximately in each case. The values entered in the line " mean " are not the arithmetical means of the results for each station, but they were calculated separately by treating all the estimates as though they had been made at the same place and by the same observer; in other words, the individual observations from all five stations were put together and the whole treated as the results from one place. As the higher velocities were observed much more frequently at Scilly, Yarmouth and Holyhead than at the other stations, this method of treating the observation results in the equivalents of the higher forces being mainly dependent on the estimates made at these three stations.*

In the line, " adopted values," are the equivalent velocities adopted by the Meteorological Office based on the formula $v = 0{\cdot}836B^{\frac{3}{2}}$, in which v = velocity in m/s and B the Beaufort numbers.

A possible reason for the discrepancy between the Seewarte and Meteorological Office equivalents would be a difference in the estimates made by the observers. In fact, it has been stated that the Seewarte equivalents are affected by the fact that high winds are seldom experienced on the German coast and, therefore, the observers tend to overestimate the few high winds which do occur. This, however, could not be said of the

* The values given in Table III. were converted from miles per hour into metres per second from the original sheets before they were " rounded." The numbers of observations used were not stated in the original paper, but are given as Appendix I. to this paper.

observers who made the observations described in Table II. as "Ocean" and "Norwegian Coast," Groups I and III. It will be noted that the Seewarte equivalents for Groups I and III. are very similar, and the means of the two groups for Forces 7, 8 and 9 are 12·5, 14·8 and 17·3 m/s, respectively. These values are all lower than the final values adopted by the Seewarte. On the other hand the observers at Scilly, Yarmouth and Holyhead also agree very well with one another and the mean equivalents for Forces 7, 8 and 9 obtained by the Meteorological Office from their observations are 15·1, 18·7 and 22·6 m/s.

Now all these observations were taken by experienced seamen, yet the equivalents differ by more than a whole Beaufort number. I find it extremely difficult to believe that two sets of experienced seamen would consistently differ in their estimates of the higher Beaufort forces by a whole number. If this argument is carried to its logical conclusion we should be faced with the fact that while German and Norwegian sailors agree with one another in their estimates, British sailors differ from them both by a whole Beaufort number.

When one considers the close intercourse between sailors of all nations and the frequency with which foreign sailors are employed on British ships it is impossible to believe that there can be this national difference. If the Seewarte observations had all been taken by landsmen, at land observatories, while the Meteorological Office observations had been made by sailors at well exposed coast stations, the difference in the equivalents might have been explained in this way. But, as a matter of fact, the Seewarte Group I was obtained by sailors at sea and their Group III by seamen who, to quote Professor Mohn (6), "were experienced in estimating the wind by the Beaufort Scale" at coast stations as freely exposed to the wind as Scilly, Yarmouth and Holyhead. Thus, we must abandon the idea that the Seewarte equivalents are low because they were based on observations made by inexperienced observers.

This leaves us with only one factor to consider, namely, the exposure of the anemometers used in the two investigations, and I think that it will not be difficult to show that this factor is at the root of the difference—at all events for the higher forces.

The anemometers used in the Meteorological Office investigation had unusually free exposures. At Scilly the actual anemometer used in the comparison was of the cup type with cups 5·8 metres above the ground, but the anemometer constant used in the determination was derived by comparing the run of the cups with the velocity recorded by a Dines pressure tube anemometer erected by its side. The head of the pressure tube was 10·0 metres above the ground and was carried on a slender mast. The Scilly record is, therefore, for all practical purposes that of the free air 10·0 metres above the ground. The site of the anemometer was the highest point of a small island and the ground level was 39 metres above the surrounding sea.

The anemometer used at Holyhead was of the Robinson type mounted on the top of a disused lighthouse on the end of a pier running some distance out to sea. The cups were 22·2 metres above sea-level, but there were certain sheds at the foot of the tower the roofs of which were about 10 metres below the cups. A pressure tube anemometer was also used at Holyhead. It was erected on a small island which may be described as an open stretch of grass about 5 metres above the level of the sea. The vane of the pressure tube was 13·5 metres above the ground and 19·2 metres above mean sea-level. A direct comparison showed that there was no material difference in the velocities recorded by the two anemometers. Therefore, at Holyhead, the exposure was equivalent to an exposure in the free air 13·5 metres above the ground and 19 metres above the surface of the sea.

At Yarmouth the anemometer of the Robinson type was mounted on the roof of a large building, the cups being about 4 metres above the nearly flat roof. The building was itself 14·6 metres above the ground and was much higher than the surrounding buildings—in fact, was the highest building in the town. The anemometer cups were, therefore, 4 metres above the roof, 18·6 metres above the ground and 22 metres above sea-level. As the building was nearly isolated and within a few metres of the sea the exposure was very good, especially for winds from the east.

It is impossible to reduce the exposure of the Yarmouth anemometer to a definite height in the free air as was possible at Scilly and Holyhead, but from the fact that the velocity equivalents for the higher Beaufort numbers derived from the Yarmouth anemometer are practically the same as those derived from the anemometers at Scilly and Holyhead we may infer that the exposure at all three anemometers was similar. The exposures of the anemometers at North Shields and Oxford were not so good as those at the other three stations, so we will limit this part of our discussion to the results obtained from the Scilly, Holyhead and Yarmouth anemometers, the mean exposure of which may be taken as that of the free air, 12 metres above the ground, in a perfectly open situation.

We have now to compare this exposure with the exposure of the anemometers used in the Seewarte investigation.

By far the most important series of observations used by the Seewarte was that made on the "Gazelle." The "Gazelle" was a large sailing ship of the type specified by Beaufort. In the years 1874 to 1876 she made a cruise for scientific purposes which took her into all oceans. An anemometer was carried and regular Beaufort estimates and simultaneous measurements of the velocity were made. As the ship was of the type specified by Beaufort the estimates were of particular value, for the conditions described by Beaufort could be controlled by the ship itself. In the reduction of the observations, only those estimates were used which were made when the ship was sailing as described by Beaufort in his specification.

There can be no doubt that these estimates were as nearly perfect as they could be made. The effect of the speed of the ship on the measurements has been discussed by Köppen (2), and found to be inappreciable, so that it need not be considered further. The exposure of the anemometer, however, was far from satisfactory. The anemometer was held in the hand by an observer on the weather side of the bridge, or in one of the boats on the weather side of the ship.

When one thinks what a great obstacle to the motion of the air a large ship with its masts, sails and riggings must be, it is not difficult to believe that even on the weather side of the ship there must be a considerable general reduction in the wind velocity, and, therefore, the velocity measured by an anemometer held in the hand—say 2 metres above the bridge—must have been much less than would have been measured 12 metres above the sea far removed from the ship. For the higher forces 7, 8. and 9, the observations on the " Gazelle " give velocity equivalents of 11·6, 14·0 and 17·0 m/s, respectively, which have to be compared with 15·1, 18·7 and 22·6 m/s derived from the Scilly, Yarmouth and Holyhead observations. It is significant that for each force, the ratio of the two equivalents is practically the same : 0·77, 0·75 and 0·75, respectively. This is quite satisfactorily explained by assuming that the estimates were correct in both cases and that the difference is entirely due to the difference in the exposure of the anemometers.

Turning now to the Seewarte, Group III, the five anemometers used at the lighthouses on the Norwegian coast were of the Wild pressure plate pattern and were erected in all cases on islands. With one exception, the islands were very small and in every case the exposure was quite free and open. Mohn gives the following details of the exposure :—

TABLE IV—EXPOSURE OF NORWEGIAN ANEMOMETERS

	Height of ground above sea level	Height of wind plate above ground	Support
Torungen	15 m.	5 m.	Post.
Hellisö	19 m.	5 m.	Post.
Ona	60 m.	1 m.	Point of rock.
Prestö -	10 m.	11 m.	Gable.
Andenes - - -	6 m.	3 m.	Post.

It is clear that these instruments are not so well exposed as those at Scilly, Yarmouth and Holyhead, but they are better exposed than the anemometer on the " Gazelle." The equivalents given by them for forces 7, 8 and 9 are 12·8, 15·1 and 17·4 m/s, respectively, which give a mean ratio with the Scilly, Yarmouth and Holyhead equivalents of 0·81. Thus, the better exposure corresponds with a nearer approach to the Meteorological Office equivalents.

Another series of observations used by the Seewarte, Group II, was based on observations and estimates made at five of their own stations, viz. :—Neufahrwasser, Swinemunde, Keitum, Borkum and Hamburg. Details regarding the individual exposures are not given, but Köppen gives the following information : The cups of the anemometers were between 1 and 2 metres above the roofs of buildings which were as free as the surroundings allowed. The exposure was the most free in Hamburg; moderately free in Borkum, Swinemunde and Neufahrwasser ; while at Keitum there were trees near the anemometer which towards the end of the period investigated had their small upper branches higher than the anemometer.

Such exposures are clearly much less free than those of the British stations and, therefore, it is not surprising to find that the equivalents deduced from them are less than the British equivalent—in fact they are practically the same as those of the "Gazelle."

It is clear from this discussion that the exposures of the anemometers used by the Seewarte were nothing like as free as the exposures of the anemometers used by the Meteorological Office, and that, examined individually, the difference in the velocity equivalents for the higher forces can quite satisfactorily be explained by the difference in exposure.

It is interesting to check this conclusion by using Hellmann's determination of the variation of wind velocity with height. From experiments made at Nauen, Hellmann found that the variation of wind velocity with height over a level grass surface of great extent can be expressed up to a height of 30 metres by the following formula :—

$$v = k\,(1{\cdot}00 + 2{\cdot}81 \log(H + 4{\cdot}75)\,)$$

in which v = wind velocity in metres per second, k = a constant and H = height above ground in metres.

We have seen that the exposure at Scilly, Holyhead and Yarmouth is equivalent to an unobstructed exposure at 12 metres above the ground. For force 8 these three stations have a mean equivalent of 18·7 m/s, while the Seewarte equivalent is 15·4 m/s. Putting the values for Scilly, Yarmouth and Holyhead in the above equation it is then found that the Seewarte equivalent corresponds with a height of 4 metres. In other words, the two sets of equivalents would agree at force 8 if the average exposure of the anemometers used by the Seewarte was equal to the exposure at 4 metres above a perfectly open level grass surface. This agrees well with the exposure of the Norwegian anemometers and is about the order one would expect for the anemometers exposed in the hand on a sailing ship, or for the anemometers 1 or 2 metres above the roofs of low buildings.*

* The effect of the exposure of an anemometer on board ship was discussed by Callé (4) and he arrived at similar results.

Thus the difference between the equivalents found by the Seewarte and the Meteorological Office for the higher Beaufort numbers is completely explained by consideration of the exposure of the anemometers.

Turning now to the lower forces we should expect the effect of the exposure to show itself throughout the scale and the Seewarte equivalents of the lower forces also to be below those of the Meteorological Office. As a matter of fact the Seewarte equivalents are greater than those of the Meteorological Office at all forces below force 4. The differences are not large and practically they are not important, but it is interesting to investigate them somewhat further.

In the following table are given the differences between the successive equivalent velocities for the Beaufort numbers according to the Seewarte and Meteorological Office scales.

TABLE V—DIFFERENCE OF SUCCESSIVE EQUIVALENTS

Beaufort Scale	Seewarte m/s	Met. Office m/s
0 to 1	1·7	0·8
1 to 2	1·4	1·6
2 to 3	1·7	1·9
3 to 4	1·9	2·4
4 to 5	2·1	2·7
5 to 6	1·9	2·9
6 to 7	2·2	3·2
7 to 8	2·5	3·4
8 to 9	2·6	3·7
9 to 10	3·0	3·8

From this Table it will be seen that the steps of velocity according to the Seewarte equivalents are not regular. From force 0 to force 1 the velocity change is 1·7 m/s; but from force 1 to force 2 it is only 1·4 m/s; similarly the step from force 4 to force 5 is 2·1 m/s, but from force 5 to force 6 it is only 1·9 m/s. The irregularity of the difference is best seen in Figure 2 on which the Seewarte figures given in Table V are plotted.

This figure shows that on the whole the differences increase as the Beaufort numbers increase—as one would expect—but the curve is not regular. One cannot help feeling that the curve ought to be regular with steadily increasing differences, although, of course, this would not necessarily follow from Beaufort's original specifications. It is difficult to believe that a perfect observer would make the difference between forces 0 and 1 greater than the difference between forces 1 and 2, or the difference between forces 4 and 5 greater than the differences between forces 5 and 6.

In this particular the Meteorological Office equivalents are definitely better than the Seewarte equivalents. The differences

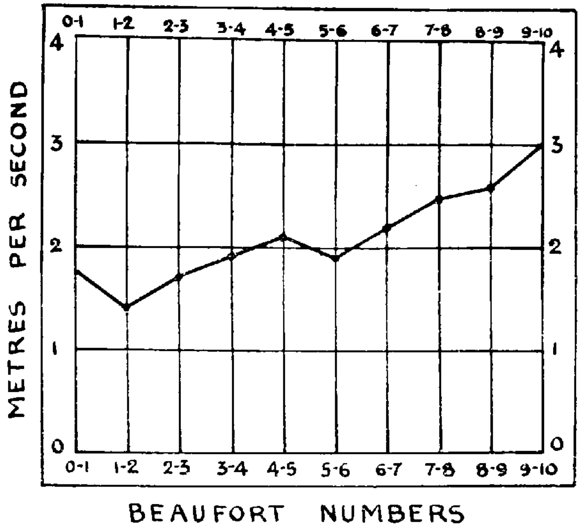

Fig. 2.

given by the Meteorological Office equivalents as shown in Table V steadily increase. This, however, is the natural consequence of the use of the expression $v = 0\cdot836B^{3/2}$ for obtaining the Meteorological Office equivalents. The observations, however, are nearly as regular as the calculated values, as is shown in Figure 3, in which both the calculated and observed values of the equivalents are plotted.

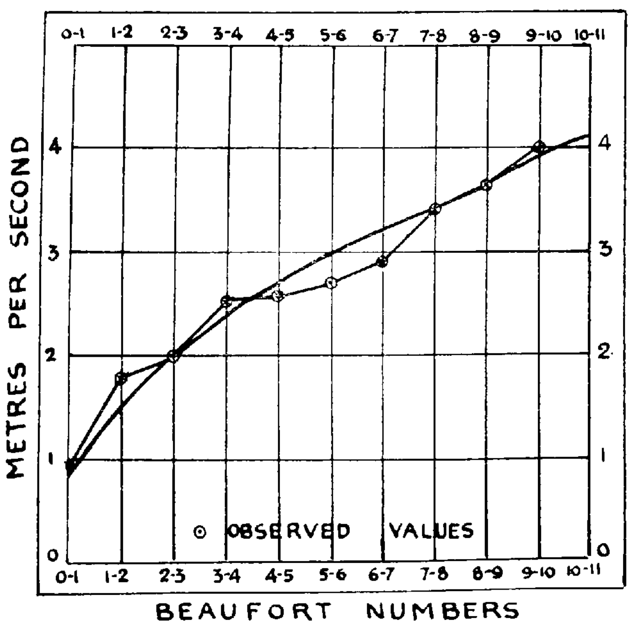

Fig. 3.

The results of this discussion so far may be summarized as follows :—

(*a*) There is no reason to believe that the observers whose observations were used by the Seewarte over-estimated the wind strength on the Beaufort Scale as compared with the British observers.

(*b*) The difference between the Seewarte equivalents and the Meteorological Office equivalents at the higher forces can be accounted for by differences of exposure of the anemometers.

(*c*) The cause of the difference between the two sets of equivalents for the lower forces is not obvious. The absolute values of the differences are, however, small, and are of little practical importance. From consideration of the differences between successive equivalents it would appear that the Meteorological Office equivalents give a better and more regular scale than the Seewarte equivalent for the lower forces.

If the above conclusions are generally accepted we may say that the problem of the true velocity equivalents of the Beaufort Scale is solved. For all practical purposes the Seewarte equivalents and the Meteorological Office equivalents are identical if the exposures of the anemometers are taken into account. This can be expressed in a more formal way by saying that there is no unique set of wind velocities equivalent to the estimated wind forces on the Beaufort Scale. The velocity equivalents depend on the exposure of the anemometer, so that the relationship between velocity and Beaufort numbers is represented by a family of curves of which exposure is a parameter. The set of equivalents published by the Meteorological Office gives one curve of the family and the equivalents of the Seewarte give another curve of the family.

It would appear further that the two curves obtained by plotting the Seewarte and Meteorological Office sets of equivalents are the extreme curves of the family which are likely to be met with in practice.

The exposures of the anemometers used in the determination of the Seewarte equivalents were typical of the ordinary exposure of anemometers. They were anemometers held in the hand in the most convenient place on a ship, anemometers erected on poles up to five metres above the ground and anemometers exposed one or two metres above the roofs of buildings. The Seewarte equivalents may, therefore, be assumed to represent an exposure procurable at most stations, and an exposure which would probably be attained by nearly all anemometers used at meteorological stations.

On the other hand the Meteorological Office equivalents represent an exposure which is very nearly the best procurable. To obtain it the head of the anemometer must be exposed in an open situation at least 10 metres above the general ground level.

It will be only in exceptional cases that a meteorological observatory will have an anemometer with an appreciably better exposure.

Thus, normally, anemometer exposures will be at least as good as those represented by the Seewarte equivalents and not better than those represented by the Meteorological Office equivalents. Hence the curves for all anemometers which have not obviously exceptional exposures will fall between the curves for the Seewarte and Meteorological Office equivalents.

This is a most important conclusion, which will be of direct use in the discussion of the further problem which we have now to take up.

IV.—Telegraphic Code for Wind Velocity

The method of determining the wind strength by making an estimate on the Beaufort Scale is not entirely satisfactory.

Even an experienced observer who has had a long training at sea finds considerable difficulty in estimating the strength of the wind to one Beaufort number. The estimates of two experienced observers will agree when the mean of a large number of observations is considered, but individual observations may well vary by one or even two Beaufort numbers. The difficulty which the best of observers feels in estimating on the Beaufort Scale is seen by the frequent entry of two Beaufort numbers in the records of observations. The experienced observers on the "Gazelle" estimated a single Beaufort number in only 44 per cent. of their observations. Their estimates extended over two numbers in the form 0–1, 1–2, etc., in 50 per cent and over three numbers in the form 0–2, 1–3, etc., in 5 per cent and over more than three numbers, 0–3, 1–4, etc., in 1 per cent.

The observer at Scilly—one of the most experienced of the British observers—estimated force 7 with measured velocities as low as 10 m/s. and as high as 20 m/s., showing the great uncertainty of estimates.

If experienced seamen have this difficulty, how much greater must be the difficulty of observers who have lived all their lives at inland stations! For this reason and others equally well understood the tendency has been to rely more and more on anemometers in meteorological work.

A properly calibrated anemometer does give the actual wind velocity at the place where the instrument is exposed, and if the anemometer record is higher at the second of two readings one can be sure that there has been a real increase in wind strength during the interval and that the difference is not due to an error of estimation.

Most meteorological observatories are now equipped with anemometers and the number of stations at which Beaufort estimates are made is rapidly decreasing. At the same time consideration of expense and difficulty of exposure prevent anemometers being used at all stations and anemometers cannot well be used at sea. Thus both methods of determining wind strength are likely to be employed for some time to come, and provision must be made for telegraphing the results of the observations, whichever method of determining the wind strength may be used.

The strength of the wind is now reported by using the Beaufort numbers from 0 to 9 as the code numbers in the telegrams. Special arrangements are made for reporting the higher forces, which, however, seldom occur at land stations.

The use of the Beaufort Scale for specifying wind strength has proved very useful in synoptic meteorology. It is possible to represent the various forces clearly on the charts by adding flèches to the arrows which are used to indicate the wind direction. As force 9 is seldom exceeded the number of flèches to be drawn when this method is adopted is not inconveniently large. The Scale has the further advantage that the scale divisions are small for the lower forces, where small variations in strength (as measured by velocity) are important, and large at the higher strengths, when small variations are of little significance. If there were no problems of reporting Beaufort estimates as well as wind velocities, and we were dealing with velocities alone, we should in all probability devise a code in which the velocities were grouped under code numbers, small groups at first and larger groups with the higher velocities. This would be a more practical method than telegraphing the actual wind velocities in metres per second.

The principle, then, of using the Beaufort Scale as the telegraphic code of wind velocity is satisfactory and it is only necessary to be able to convert the velocities into the appropriate Beaufort numbers in order to have a satisfactory method of telegraphing wind strength. Most meteorological services are using this method now, but, as already explained, serious difficulty has arisen because inappropriate sets of equivalents are being used for effecting the conversion.

There has always been a strong impression amongst meteorologists that there is in reality a definite wind velocity for each Beaufort number if only it could be determined; and that if an observer was actually at the position occupied by the anemometer his estimate would agree with the velocity recorded, no matter what the exposure of the anemometer. That this is not so has been made clear above, where it was shown that an experienced observer estimates the wind strength quite independently of his own situation, and does not change his estimate as he moves from place to place. This means that the exposure of the anemometer must be taken into account if it is desired to convert wind velocities recorded by an anemometer into Beaufort numbers.

From the researches of the Seewarte and the Meteorological Office we now know the true velocity equivalents for two types of exposure sufficiently accurately for practical purposes, and velocities recorded on anemometers in either of these two types of exposure could be converted into Beaufort numbers in a completely satisfactory manner. It might, therefore, be suggested that these two sets of equivalents should be approved and the velocities recorded by all anemometers converted into Beaufort numbers by using one or other of these sets of equivalents, that one being chosen which it is considered is most appropriate to the exposure of the anemometer.

The objection to this proposal is that alternatives of this nature are very unsatisfactory in practice. If we could depend on the exposure of every anemometer being critically examined and then the appropriate set of equivalents issued to the observer to be used in preparing his weather telegrams the method would be satisfactory. But experience has shown that such schemes are seldom carried out as they should be. If such a scheme were adopted, in a few years the reason for two sets of equivalents would probably be overlooked and the wrong set of equivalents used at some stations. There would always be a natural tendency for each meteorological service to adopt one or other of the sets of equivalents for use at all the observatories under its control. This would introduce serious errors, for the Meteorological Office equivalents are not suitable for use with anemometers having the exposure of the Seewarte anemometers or *vice versa*.

Figure 4 (*b*) has been prepared to exhibit the errors which would be involved if the Meteorological Office equivalents were

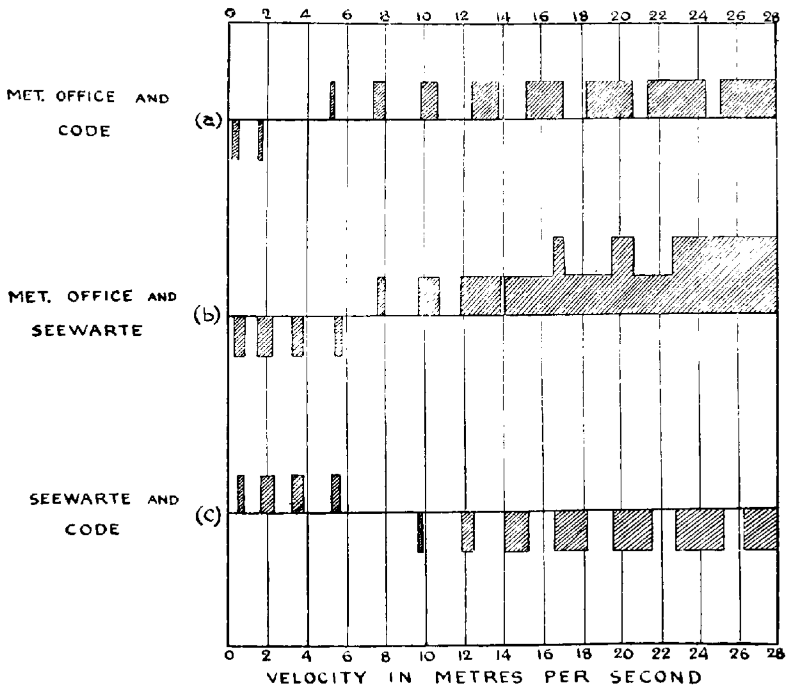

FIG. 4.

used for an anemometer having the Seewarte exposure or *vice versa.* The abscissæ are velocities in m/s as recorded by an anemometer. The shaded areas show where errors would result in the Beaufort numbers and the ordinates give the amount of the error. It will be seen that for velocities above 12 m/s. there would always be an error of at least one Beaufort number, while above 16 m/s. the error would frequently be two.

Thus if the Seewarte equivalents were employed for the Scilly anemometer a recorded velocity of 17 m/s would be reported as force 9, while in reality the force would be only 7.

On the other hand, if the Meteorological Office equivalents were adopted with a Seewarte exposure the same errors would occur, except that then the sign would be reversed. This is the difficulty which has been felt all along: the differences between the Seewarte and Meteorological Office equivalents are too large to make it possible to adopt either for general use.

There is one alternative left, and it is one which, in my opinion, offers a satisfactory solution to the problem. It is to specify a wind velocity code, in which the code numbers 0 to 9 are assigned to groups of velocities, small groups at first, but larger as the velocities increase. The groups of velocities in the code should be so chosen that the group corresponding with a given code number would be between the limits of the velocity equivalents found by the Meteorological Office and the Seewarte for the Beaufort number equal to the code number.

This is not the same thing as taking the mean between the two sets of equivalents and approving that as the velocity equivalents of the Beaufort Scale. I propose a code pure and

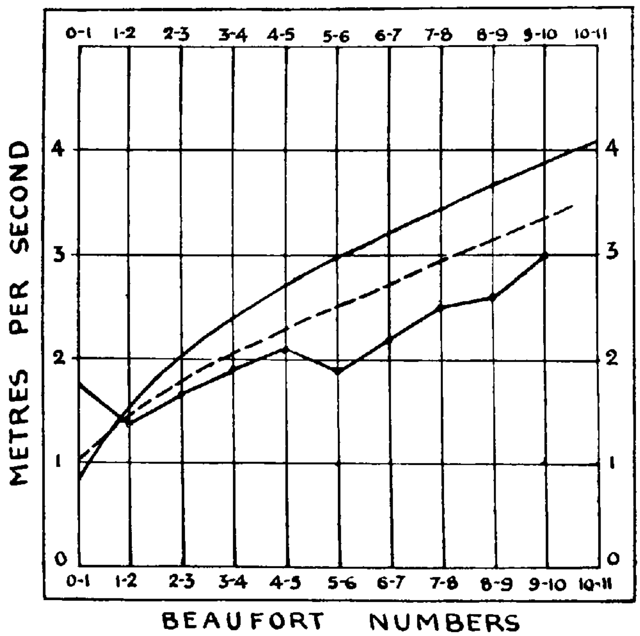

FIG. 5.

simple, but a code the numbers of which may be used alternatively with Beaufort estimates *with the least possible error.* Treated as a code the groups of velocity should, as already stated, have successive groups increasing regularly from number to number. I have prepared such a scale in the following way :—

The differences between the successive equivalent velocities, given in Table V, for the Seewarte and Meteorological Office determinations, were plotted in two curves on the same diagram, (*see* Figure 5). A smooth curve was then drawn by eye, to be the best fit to the two curves ; this curve is shown dotted in Figure 5. From this curve the successive steps for the new scale were read off, thus ensuring that the steps increase regularly over the whole scale.

Having obtained the successive steps of the new scale in this way, the scale itself was determined, for it was only necessary to add the steps together to get the values corresponding with each code number. These values were then plotted and a smooth curve drawn through the points. From this curve the limits for each number were read off at the ordinates half way between each whole number. In this way the following code scale was obtained :—

TABLE VI—PROPOSED CODE SCALE FOR WIND VELOCITY

Code number	*Limits of velocity*	
—	m/s	miles per hour
0	0— 0·5	0— 1
1	0·6— 1·7	2— 3
2	1·8— 3·3	4— 7
3	3·4— 5·2	8—11
4	5·3— 7·4	12—16
5	7·5— 9·8	17—21
6	9·9—12·4	22—27
7	12·5—15·2	28—33
8	15·3—18·2	34—40
9	18·3—21·5	41—48
10	21·6—25·1	49—56
11	25·2—29·0	57—65

I propose that this code should be adopted for reporting all wind velocities measured by anemometers. The International Meteorological Conference adopted the following resolution at Utrecht in 1923 :—

> 41.—(II) A description of the meteorological stations used in its collective synoptic messages should be published by each meteorological service.

If this resolution is carried out it will be possible for everyone receiving a message in the code to estimate for himself whether the anemometer at a station is under or over exposed and to make allowances accordingly.

Stations which do not use an anemometer will continue to telegraph the Beaufort number, and there will be nothing to distinguish an estimate from a measured velocity. We have now to consider whether this will lead to error or confusion.

We may for a moment consider that all Beaufort estimates are correctly made, so we have only to determine what would be the difference between the code numbers reported from anemometer stations and the estimate which would have been made if there had been no anemometers. I have already shown above that the exposures represented by the Meteorological Office and the Seewarte equivalents are opposite extremes. The true Beaufort estimates will, therefore, lie between those which would be obtained by using the two sets of equivalents. Figure 4 (*a*) and Figure 4 (*c*) show for what velocities there would be differences between the code number and the Beaufort estimate appropriate to the two standards of exposure. If the anemometer has the Meteorological Office exposure so that the Meteorological Office equivalents give the true Beaufort numbers, then Figure 4 (*a*) shows that over no part of the possible range of wind velocities will the code number depart by more than unity from the true Beaufort number. Below a velocity of 15 m/s. complete agreement occurs more frequently than disagreement, above 15 m/s. the code number is generally higher than the Beaufort number by unity; but over small ranges of velocity even this difference does not occur.

Figure 4 (*c*) gives the same information at the other extreme, *i.e.*, in cases where the exposure is that of the Seewarte anemometers. Here the divergence from the true Beaufort number is even less than in the case with the Meteorological Office exposure. Below 14 m/s the agreement is very good and above 14 m/s. there is complete agreement over a third of the scale, and nowhere is the difference more than one Beaufort number.

In other words, if the exposure of the anemometer is not very exceptional the code numbers will not depart from the true Beaufort number by more than unity, while up to velocities of 15 m/s the code numbers and the Beaufort numbers practically coincide. For practical purposes this is sufficient accuracy and is much closer than estimates can usually be made.

The advantage of adopting the code over adopting either the Seewarte or the Meteorological Office equivalents for general use can be seen at a glance by comparing Figures 4 (*a*) and (*c*) with Figure 4 (*b*).

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

* For comparison with the Meteorological Office and Seewarte exposures the code values correspond to an exposure at 6 metres.

yet reached by the Meteorological Office and the Seewarte. Nor does it prevent anyone converting anemometer records into Beaufort numbers by a suitable set of velocity equivalents. Thus in England we shall continue whenever necessary to convert the records of our freely exposed anemometers into Beaufort numbers by the use of the Meteorological Office scale of equivalent velocities. Similarly the Seewarte would no doubt continue to use their scale of equivalents when discussing the records of their type of anemometer. All that has been attempted has been to devise a method of telegraphing information about the strength of wind which is for practical purposes independent of the method of observation. This the proposed code appears to do quite satisfactorily.

V.—Conclusions and Recommendations

(*a*) There is no unique relationship between wind velocity as recorded by anemometers and estimates made on the Beaufort Scale.

(*b*) Wind velocities measured by anemometers can be converted into Beaufort numbers only if the equivalent velocities appropriate to the exposure of the anemometer have been previously determined. The Seewarte has determined a satisfactory set of equivalents for anemometers having one type of exposure and the Meteorological Office another set of equivalents for anemometers with a much freer exposure.

(*c*) It is recommended that when wind velocity is measured by an anemometer the velocity should be reported in weather telegrams by the code set out as Table VI. If this code is used no difficulty will be experienced when the code numbers are plotted on synoptic charts along with Beaufort numbers.

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APPENDIX I

NUMBER OF OBSERVATIONS USED IN THE DETERMINATION OF THE EQUIVALENT VELOCITIES GIVEN IN TABLE VIII AND TABLE IX OF THE METEOROLOGICAL OFFICE PUBLICATION NO. 180.

Beaufort Numbers	0	1	2	3	4	5	6	7	8	9	10	Total
Scilly - -	54	187	199	416	700	631	245	125	57	12	4	2630
Yarmouth -	20	130	549	992	849	351	186	35	24	1	0	3137
Holyhead -	93	622	703	651	336	100	126	180	84	6	2	2903
N. Shields -	98	330	1102	1174	284	68	15	10	1	0	0	3082
Oxford - -	87	619	735	526	137	52	16	7	4	0	0	2183
Total - -	352	1888	3288	3759	2306	1202	588	357	170	19	6	13935

Printed under the authority of His Majesty's Stationery Office
By Eyre and Spottiswoode, Ltd., East Harding Street, E.C. 4
Printers to the King's most Excellent Majesty.