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ON THE RELATION BETWEEN THE VELOCITY OF THE GRADIENT WIND AND THAT OF THE OBSERVED WIND.

BY

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WITH A PREFACE BY THE DIRECTOR OF THE METEOROLOGICAL OFFICE.

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ON THE RELATION BETWEEN THE VELOCITY OF THE GRADIENT WIND AND THAT OF THE OBSERVED WIND.

PREFACE

BY THE DIRECTOR OF THE METEOROLOGICAL OFFICE.

DURING the past ten years the Meteorological Office has devoted a good deal of attention to the study of what is called the gradient wind.

The idea originates with the deduction on theoretical grounds that in considering the motion of any body over the earth's surface, be it a gunshot, a locomotive, air or water, account has to be taken of a tendency in every case to deviate from the direction of motion towards the right of the path in the northern hemisphere and towards the left in the southern hemisphere. This universal tendency is due to the rotation of the earth, and, to a first order of approximation, is expressed algebraically as an acceleration $2\omega v \sin \lambda$, which acts at right angles to the direction in which the body happens to be moving at the time. In this algebraical expression ω is the angular velocity of the earth's rotation about its polar axis, v is the velocity with which the body is moving relatively to the earth, and λ is the latitude of the place in which, for the time being, the body finds itself.

It follows at once from the form of the expression for the acceleration that it is inoperative if there is no velocity, that is, if the body is at rest, or, in the case of air, if it is calm; and also at the equator where $\sin \lambda$ is zero. The factor ω representing the earth's angular velocity is, of course, the same for all bodies, and its numerical value is derived from the fact that the earth makes a complete revolution of 360° in one sidereal day.

Recognition of the effect of the earth in causing a deviation of the motion of bodies moving over the earth's surface dates back as far as George Hadley's explanation of the trade winds in the *Philosophical Transactions* of 1735; the most practical demonstration of it is to be found in the rotation of the plane of oscillation of a pendulum in the experiment devised by Foucault in 1851. According to Hann (*Lehrbuch der Meteorologie*, 1st edition, 1900, p. 423), the computation of the acceleration which represents the deviation in its most general form was made by Coriolis in 1835, and it finds a place in all analytical treatises on mechanics. It was first applied in meteorology in 1860 by W. Ferrel, apparently without knowledge of Coriolis's work, in a publication *On the Motions of Fluids and Solids relative to the Earth's Surface, comprising Applications to the Winds and Currents of the Ocean*; and to the same meteorologist may be attributed the recognition of the fact that the natural deviation due to the earth's rotation could

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be prevented by a suitable distribution of pressure, which, by its gradient, would provide an acceleration equal and opposite to that due to the rotation. By 1853 Coffin, an American author of a work on the winds of the globe, had noted that the prevalent winds had low pressure on their left-hand side; and in 1857 Buys Ballot, the Dutch meteorologist, had enunciated the law which bears his name, that "if you stand with your back to the wind, pressure is low on the left and high on the right." In 1860 he had connected that general law with the rotation of the earth, and as soon as maps with isobars were drawn, a close connection between barometric gradient and wind force was recognised and became a common subject of study. It was elaborately treated by Guldberg and Mohn, *Études sur les mouvements de l'Atmosphère*, 1^re^ partie, Christiania, 1876; 2^me^ partie, Christiania, 1880, in which the undisturbed relation of pressure gradient to wind velocity was discussed and the question of the disturbing effect of the surface friction upon the relation was dealt with.

Between that time and 1900 the relation of wind to pressure distribution has been discussed by many meteorologists, notably by Sprung and Weihrauch in Germany, Ekholm in Sweden, and W. M. Davis in the United States, and it has become a fundamental proposition of dynamical meteorology.

Thus on the theoretical side the subject was well understood; but in 1900, though one of the earliest of Dr. R. H. Scott's papers was on an inquiry into the connection between strong winds and barometric differences, and other papers were published elsewhere, little use was made of the proposition in the practical work of forecasting by means of weather charts at the Meteorological Office. Every weather chart illustrated the general truth of Buys Ballot's law, but gradient velocities were never calculated, nor was any apparent contradiction of the law regarded as anything else than a local circumstance without relation to dynamical theory. The disturbance due to surface friction was admitted as a qualitative explanation of any local peculiarity of either sign and any magnitude.

The attention of the Meteorological Office was first directed towards the calculation of the gradient wind and its relation to the surface wind in the work upon the *Life History of Surface Air Currents*, and in a paper on the general circulation of the atmosphere contributed to the Royal Society in 1903. From that time it has gradually come to be regarded as a real working principle which is applicable in practice in a great variety of ways. In 1902 Mr Dines began his work upon the upper air by means of kites, and it soon became evident from the results which he obtained that the change in the direction and magnitude of the velocity of air currents with height brought them more and more into agreement with the theoretical wind computed from the surface gradient, so that when one of the public departments asked for an effective estimate of wind velocities up to 3000 feet, it was arranged that the gradient wind should be supplied as representing a better estimate than anything that could be obtained from an anemometer with an empirical correction for height. Frequent applications were at that time received from aeronauts who wished to know their chances of a cross-Channel trip in a free balloon, and it was the gradient wind that was relied upon for the purpose, supplemented by the information contained in the *Life History of Surface Air Currents*.

When Mr E. Gold joined the Office staff in 1906 he was asked to examine all the information which we had collected on the subject of barometric gradient and wind force and to prepare a report upon it, with tables for computing the gradient wind and the correction for curvature. His report was published in 1908. It included an explanation of certain characteristics of any weather map, which was new and of great importance as indicating the dominance of the principle of the gradient wind in determining the actual meteorological conditions. The characteristics in question were the wide separation of isobars in the inner regions of an anticyclone as compared with the closeness of the lines in the central region of a cyclone; they were shown to be dependent upon the fact that in an anticyclone the curvature gradient acts in the opposite sense to the general rotation gradient, whereas in a cyclone the curvature gradient and rotation gradient are concurrent.

Thus the idea of the balance of barometric gradient by velocity as a primary law of the atmospheric circulation has been gradually strengthened. We have come to regard it as, generally speaking, inexorable for the horizontal motion of the atmosphere in the regions beyond the disturbances of the turbulent motions which are due to surface friction and local obstacles of various kinds. There still remained a tendency to regard the balance of gradient and velocity as likely to be disturbed in the upper air by convection and the consequent mingling of currents moving in different directions or at different speeds. But the more we know of the upper air the less likely does any such disturbance seem. Inversions of temperature and other sequels of convection are much less frequent above the four-kilometre level than below it, and such violent commotions as those of a thunderstorm or line-squall are local and generally infrequent. Consequently the disturbance of the balance between gradient and velocity becomes unlikely. Quite recently, in a paper contributed to the *Journal of the Scottish Meteorological Society* for 1913, I have shown that the principle of balance between gradient and velocity leads to the calculation of relationships between the distribution of wind and those of pressure and temperature which agree in many recognisable particulars with known facts, and that the same principle explains the falling off of wind velocity in the stratosphere, examples of which have often been observed.

These considerations lead us to regard the law of relation of the distribution of pressure and wind as a first law of atmospheric motion, the departures from which are either of an infinitesimal order or transient in character, though in either case they are deserving of close study.

We cannot attempt a verification of this law by actual observation, because it is not possible to determine with a sufficient degree of accuracy the distribution of pressure at any level, but we may approach the proof of the law in another way, by considering that the balance of gradient and wind velocity is the state to which the atmosphere always tends, except in so far as it may be disturbed by the operation of new forces. If we suppose the balance once established, any disturbance by convection or otherwise must act in the free air by infinitesimal stages, and during every stage the tendency to restore the balance is continuously operative. Hence the transition from one set of conditions to another must be conducted by infinitesimal stages during which the disturbance of balance is infinitesimal.

Consideration of these points and of some consequences which follow from them are set out in a paper entitled "Principia Atmospherica" in the *Proceedings of the Royal Society of Edinburgh*, vol. xxxiv. p. 77.

Meanwhile great difficulties have been experienced in the practical measure of wind velocity. Anemometers, which had been duly compared one with another, were installed at the official observatories and elsewhere for the purpose of obtaining information about the wind at different stations. After a while it became known that the constant used for interpreting the records of the anemometer was a good deal in error, but as all the instruments of the same pattern were similarly affected, that circumstance was of less importance than the uncertainty attaching to what we call the exposure of the anemometer, an uncertainty which had a paralysing effect upon the study of wind measurements. It was known that the actual readings obtained from the anemometer only gave the velocity of the air current at whatever height above the particular roof the anemometer cups were mounted; a few feet of height would certainly make a difference, though no one knew how much; the configuration of the building and of neighbouring buildings or country must also be accounted as having some influence, so that there was really no common standard to which to refer the wind velocities recorded at exposures of such different character as Deerness, Fleetwood, Holyhead, Scilly, Valencia, Falmouth, Armagh, Phœnix Park, Aberdeen, Glasgow, Stonyhurst, and Kew, to mention only the oldest anemograph stations of the Office.

The student of wind measurements had to imagine for himself an ideal air current flowing above the irregularities of the surface obstacles and undisturbed locally thereby; an undisturbed current into which the anemometer certainly did not penetrate at any but the most exposed stations, such as Deerness, Fleetwood or Holyhead, but which it might reach if it were high enough.

It will easily be understood what a serious addition the uncertainty of exposure makes to the difficulty of determining such a question as the velocity equivalents of the Beaufort scale, the answer to which depends upon the comparison of personal estimates of wind force with the readings of a neighbouring anemometer; a few feet of difference in the height of the anemometer cups or a difference in the configuration of the building which carries the instrument may affect the scale of comparison either for all directions or for some.

Since 1900 we have gradually come to regard the gradient wind as the real representative of the ideal, undisturbed current, at an unknown height, which the anemometer fails to measure. For its determination we require, in the first instance, only an accurate knowledge of the distribution of pressure at sea-level in the neighbourhood of the anemometer, and therefore we have been seeking to regard each meteorological station, whether for an anemometer or for Beaufort estimates, as being liable to local peculiarities which could be most properly represented by referring a sufficient series of measurements or estimations for winds from different directions to the gradient wind.

Mr J. Fairgrieve, who has followed the lectures and discussions of recent years at the Meteorological Office, found time, among the duties of a schoolmaster's life, to carry out this most needful investigation for a number of the stations of the Daily Weather Service, where the wind is noted by means of personal estimates on the Beaufort scale, and the results are set out in the memoir which follows; and I have the pleasure of placing on record the thanks of the Meteorological Committee for his contribution towards the discussion of a most interesting and important subject.

With the assistance of a number of workers we are gradually approaching a satisfactory solution, but we are not yet quite out of the wood. As we have seen already, when allowance is made for the curvature of the path there is reason for confidence in the calculation of wind velocity from the barometric gradient if the distribution of pressure is accurately known in all its details; but it is quite certain that the individual maps which we use do not give us that distribution with the accuracy which we desire and which is necessary for the purpose. Pressure is subject to local variations of small magnitude arising from causes about which we can make reasonable conjectures, but which we cannot at present verify, and which we are unable to represent even upon our most detailed maps, which are those of the working charts. Still less can they be represented on the charts of the Daily Weather Report, the larger of which are on a scale of one-half of that of the working charts. In various cases of line-squalls the effect of these variations of pressure has been represented. Mr Corless has prepared for me a set of maps for one particular occasion in which endeavour has been made to represent all the recorded variations of pressure shown on a series of barograms, and I hope shortly to present it for publication. Meanwhile, until our power of representation is more fully developed, the measure of the pressure gradient is always liable to error of unknown amount, and we have to trust that by the multiplication of observations the errors will disappear in the process of obtaining mean values.

But here another interesting point arises which is characteristic in greater or less degree of all methods of statistical treatment of the relation of two quantities, both of which are liable independently to errors of observation. The mean values obtained are different according as the observations are arranged in "columns" or "rows," the columns representing a grouping according to the progressive values of the one quantity and the rows the alternative grouping according to the progressive values of the other quantity. This point has been indicated in Mr Fairgrieve's Memoir.

APPENDIX.

I take this opportunity of adding two tables of information which have been compiled in the Office in answer to inquiries which have been made, and which provide material for consideration with regard to the question of certain extreme cases of the relation of wind force to barometric gradient.

TABLE A.

High Wind Pressure recorded by the Pressure Plate at Holyhead.

Date.	Time.	Force on Pressure Plate of 1 square foot.	Equivalent Pressure to nearest millibar.
		lbs.	mb.
1899 January 2	7·45 p.m.	20	10
January 12	3·40 p.m.	20	10
November 3	12·55 p.m.	18	9
1903 February 27	7·30 a.m.	21	10
September 10	9·30 p.m.	18	9
1905 March 15	7·0 a.m.	23	11
1906 February 11	10·0 a.m.	15	7
December 5	9·20 p.m.	18	9
1908 February 22	3·30 p.m.	16	8
1910 November 5	10·0 a.m.	15	7
November 5	1·0 p.m.	15	7
November 6	10·4 a.m.	15	7
1912 December 25	9·40 a.m.	15	7

The first is a table of maximum values of wind force indicated by a "pressure plate" anemometer which has been in operation at Holyhead since 1897. The instrument is described in the Report of the Meteorological Council for 1897–98. The force of the wind upon a circular plate one square foot in area is the subject of measurement. The yield of the plate to the force of the wind is restrained by a spring, but a ratchet is provided, which prevents the plate from returning after the spring has been compressed until it is released by the attendant. The plate is thereby prevented from oscillating and records only the greatest force that has been experienced since it was last released. The measures of extreme force thus obtained are believed, and probably justly so, to be free from the uncertainty attaching to the records of an oscillating plate.

The second table, Table B, gives some examples of very steep gradients measured on the working charts. They bear upon the question of the practical limits to be assigned to wind velocity in these islands, leaving out of account the violent squalls or tornados which are sometimes the local accompaniment of line-squalls and thunderstorms, and which may be regarded as outside the present limits of the calculation of the gradient wind. There seems no reason why the gradients set out in the table should not find expression in the observed wind when due allowance is made for the curvature of the path of the moving air and the frictional equivalent of the eddies due to the motion of the air over the surface.

TABLE B.

Steep Barometric Gradient over Short Distances.

Date.	Time.	Locality.	Distance over which Gradient was very steep.	Fall over Short Distance.			Gradient.	Character of Circulation and Radius of Curvature.
			Statute Miles.					
1907, February 20	8 a.m.	Between Iceland and Faeröes	86	29·4	28·9	·5	·52	Straight
" "	2 p.m.	Shetland Isles	77	28·5	28·2	·3	·39	Cyclonic 7° and 8°
" "	6 p.m.	S.W. Sweden	60	28·2	27·9	·3	·50	" 2°
1912, April 8	5 p.m.	N. of Scotland	70	29·1	28·8	·3	·43	" 2°
" August 26 (Norwich Floods)	1 p.m.	East Anglia	32	29·1	28·9	·2	·63	" 2°
1912, November 26	7 a.m.	W. of Scotland	82	29·0	28·7	·3	·37	" 6°
" "	1 p.m.	N. of Ireland	57	28·4	28·1	·3	·53	" 4° and 5°
" "	6 p.m.	W. of Scotland	54	28·6	28·3	·3	·56	" 10°

I append also a table of the highest wind velocities recorded in the British Isles from 1899 to 1910.

TABLE C.

Wind Velocities of Force 10 or upwards of the Beaufort Scale, recorded on Anemometers at Stations in connection with the Meteorological Office, 1899–1910.

Station.	Date.	Average Velocity during an hour or more.	Maximum Velocity in gusts.
		Metres per second.	Metres per second.
Holyhead	2nd January, 1899	—	42·0
Fleetwood	12th January, 1899	*33·5	—
Southport	12th January, 1899	—	40·2
Scilly	28th December, 1900	26·8	40·2
Shields	26th–27th February, 1903	24·6	—
Valencia	26th–27th February, 1903	28·2	—
Kingstown	26th–27th February, 1903	*29·5	—
Liverpool	February, 1903	*29·1	39·3, 38·4, 37·6, 36·7 and 36·2
Blackpool	February, 1903	—	38·9
Fleetwood	5th–6th July, 1903	26·4	—
Scilly	10th–11th September, 1903	*28·6	—
Scilly	13th–15th January, 1904	27·7	33·5
Scilly	12th–13th February, 1904	*29·1	34·4
Pendennis Castle, Falmouth	14th March, 1905	—	†46·0, 41·6
Holyhead	15th March, 1905	—	37·6
Scilly	6th January, 1906	26·4	36·2
Pendennis	6th January, 1906	*29·1	38·0
Scilly	18th January, 1906	24·6	34·0
Pendennis	18th January, 1906	25·0	31·3
Scilly	5th–6th December, 1906	27·7	38·0
Holyhead	5th–6th December, 1906	24·6	35·3
Roche's Point	5th–6th December, 1906	26·4	33·5
Deerness	26th–28th December, 1906	27·7	—
Deerness	28th January, 1907	26·4	—
Fleetwood	19th–21st February, 1907	26·4	—
Pendennis	16th–17th March, 1907	24·6	30·9
Southport	16th–17th March, 1907	26·8	36·2
Fleetwood	16th–17th March, 1907	25·0	—
Pendennis	18th–19th October, 1907	24·6	31·7
Fleetwood	12th–13th November, 1907	26·4	—
Fleetwood	13th–14th December, 1907	27·3	—
Pendennis	26th–28th December, 1907	26·4	31·7
Scilly	7th–8th January, 1908	24·6	—
Fleetwood	22nd February, 1908	24·6	—
Deerness	22nd–23rd February, 1908	26·4	—
Pendennis	5th–6th March, 1908	24·6	32·6
Pendennis	26th August, 1908	24·6	30·9
Pendennis	31st August, 1908	26·0	34·9
Scilly	1st September, 1908	25·0	30·9
Pendennis	1st September, 1908	25·0	33·5
Fleetwood	22nd–23rd November, 1908	25·0	—
Deerness	28th–29th December, 1908	25·0	—
Scilly	16th January, 1909	24·6	34·9
Edinburgh	18th January, 1909	25·0	—
Pendennis	7th October, 1909	25·0	30·0
Scilly	23rd October, 1909	*31·3	40·2
Pendennis	23rd October, 1909	24·6	32·6
Fleetwood	12th–13th November, 1909	24·6	—
Pendennis	18th November, 1909	25·0	33·5
Scilly	1st December, 1909	25·0	29·5
Pendennis	2nd December, 1909	24·6	33·5
Southport	3rd December, 1909	26·0	34·0
Fleetwood	3rd December, 1909	*29·5	—
Scilly	24th January, 1910	25·5	35·8
Pendennis	14th February, 1910	25·0	31·7
Kingstown	17th February, 1910	24·6	—

† On the wind record for this date there is an isolated mark which might be taken to indicate a velocity of 106·5 miles per hour, but careful examination at the time left the matter in doubt.

* Storm force reached.

TABLE C.—*continued.*

Station.	Date.	Average Velocity during an hour or more.	Maximum Velocity in gusts.
		Metres per second.	Metres per second.
Southport	17th February, 1910	24·6	34·0
Pendennis	18th–19th February, 1910	26·8	38·9
Plymouth	20th February, 1910	25·0	32·6
Pendennis	20th–21st February, 1910	27·7	36·7
Kingstown	21st February, 1910	26·4	—
Southport	21st February, 1910	28·2	38·0
Scilly	1st–2nd August, 1910	25·0	26·8
Scilly	2nd October, 1910	26·4	31·3
Pendennis	14th October, 1910	25·5	32·2
Deerness	7th November, 1910	25·0	—
Pendennis	7th December, 1910	24·6	30·0
Pendennis	9th December, 1910	25·0	31·3
Pendennis	16th December, 1910	28·2	38·0

It may be noted that the highest value recorded for an hour's run of a cup anemometer is 34·9 metres per second (78 ml/hr.) at Fleetwood on 22nd December, 1894, and the strongest gust recorded is 46 metres per second (103 ml/hr.) at Pendennis Castle on 14th March, 1905. The comparison of these values with the steep gradients recorded in the table leads to the question whether the effect of the eddy motion due to friction is necessarily always great enough to keep the surface wind within the limits of about 50 metres per second. To that question we cannot at present give a complete answer, but some progress towards a solution has been made by Mr G. I. Taylor in a paper on "Eddy Motion in the Atmosphere" contributed to the Royal Society in April 1914.

W. N. SHAW.

ON THE RELATION BETWEEN THE VELOCITY OF THE GRADIENT WIND AND THAT OF THE OBSERVED WIND.

PART I.

OBJECT AND METHODS.

Object.—The object of this memoir is to find what relation, if any, exists between the velocity of the gradient wind and the velocity of the observed wind for different points of the compass. The gradient wind * is that wind which in a particular latitude is in dynamical equilibrium under the action of forces due to the barometric pressure gradient, the rotation of the earth, and the curvature of the path in which the wind itself moves. A gradient wind of a particular velocity corresponds with a particular gradient and curvature in a given latitude. The investigation was suggested by an obvious weakness in the forecasting rules of M. Guilbert, who bases his forecasts to some extent on the difference of the velocity of the observed wind from that of "normal" winds: these "normal" winds he assumes empirically and considers constant for any given gradient at every observing station and for winds from all directions. It is, however, certain that stations vary greatly in exposure, and the same station has usually better exposure in some directions than in others: it is thus probable that M. Guilbert's assumption is not justified, but, as a test, data from certain stations have been examined and worked up.

Stations.—The stations dealt with are—

London, Brixton . .	1901–1904.
London, St. James' Park . . .	1905–1910.
Dungeness	1901–1912.
Jersey	1901–1912.
Holyhead	1901–1912.

The St. James' Park observations were chosen in the first instance because, owing to the greater number of stations comparatively near at hand, it seemed likely that the barometric gradient, and hence the gradient wind, could be more accurately determined there than elsewhere. The preliminary results were so interesting that it seemed well to choose other stations with, as far as possible, different kinds of exposures. London is an inland station; the others are on the coast: Holyhead is on the west, Dungeness is on the south, and Jersey has sea all round. It might have been better to have chosen an exposed station on the west or east, say Valencia or Spurn Head, but the uncertainties of knowing what the gradient really was would have

* See *Forecasting Weather*, W. N. Shaw, F.R.S., Sc.D., p. 38 *et seq*; M.O. 190, "Barometric Gradient and Wind Force," E. Gold, M.A., p. 5 *et seq.*

been greatly increased, especially in the former case, owing to the lack of any observing station to seaward.

Source of Data.—The data used are those given in the Daily Weather Report. The use of this as the source of data is somewhat unfortunate, since (1) the maps, though accurate enough for most purposes, suffer from some unavoidable defects; (2) only one map per day could be used; that constructed from the evening observations, besides being small, has isobars only for each ·2 inch. It might have been better to have obtained the gradient winds from measurements of the working charts at the Meteorological Office, but that would have entailed many more visits to the Office than was possible in the time at the disposal of the author.

Period.—At first, only three years' observations were worked out, but it was evident that for some of the less frequent directions there was not enough material to give any valid results, so that ten, and later twelve years' (1901–1912) observations were dealt with. In a sense, it is unfortunate that the London observations for these twelve years are divided among three stations, Brixton, St. James's Park, and Kew, for thus no one of the sets of results is so reliable as are the results from the other stations. At the same time, the results from two stations so close together as Brixton and St. James's Park allow of interesting comparisons.

Measurement and Tabulation.—Measurements of the gradient for each station were made in the following manner from the Daily Weather Report charts. This gradient was in general found by measuring across the station the distance between successive ·1 inch isobars; in some cases where the station lay on an isobar, the distance between ·2 inch isobars was measured; in a few cases the gradient was measured less directly by considering the height of the barometer at neighbouring stations. The values of the gradient wind corrected for temperature, latitude, and pressure were then read off in metres per second from tables amplified from those given in M.O. 190, "Barometric Gradient and Wind Force," by E. Gold. The readings were not corrected for curvature of the path; the extent of the error thus introduced is discussed later. The readings were then tabulated for each day opposite the corresponding wind direction—one of the sixteen points of the compass—and observed wind force in Beaufort numbers, thus:—

Day of Month.	Gradient Wind (Metres per second) corrected for Temperature, Latitude, and Pressure.	Observed Wind Direction.	Observed Wind Force in Beaufort Numbers.

Usually no direction was assigned to a "calm," as there was no means of knowing what the correct direction ought to have been; but when a steady current of air appeared, from the records of neighbouring stations, to be blowing over these islands, the direction of this current was taken as the observed direction at the station. The readings relating to a particular observed wind direction were then collected together and dealt with in a number of ways.

Result of Tabulation.—If there were no errors of observation or any other sources of uncertainty, then with a particular gradient wind from any fixed direction there would always correspond a certain observed wind; it would be sufficient to take only a few observations, and points plotted in any way from these observations would lie on curves which could be accurately determined. Many uncertainties, however, are introduced, and the result is that for any particular gradient wind as measured, nearly all the Beaufort numbers are recorded as corresponding values of the observed wind. As an illustration, take the case of the W.S.W. winds at Holyhead during the years 1901–1912.

Observed Winds, Beaufort Number.	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39
9	...	...	...	...	...	...		...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	1
8	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	1	1	...	1	...	...	...	...	...	2	1	...	...	...	...	1	...	...	...
7	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	1	1	1	4	3	...	2	...	...	3	1	1	...	1	1	1	2	...	...	...	...	...
6	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	1	3	3	1	3	3	2	1	1	...	1	1	2	...	1	1	...	1	1	...	...	...	...	...
5	...	...	...	...	...	...	1	...	1	...	...	3	2	4	3	1	2	5	8	...	2	...	2	2	5	...	...	1	...	1	...	...	...	...	1	...	...	...	...	...
4	...	...	...	...	...	2	...	2	...	3	4	6	3	2	9	4	6	8	9	2	3	5	3	2	1	1	1	1	...	...	1	1	...	...	...	...	...	...	...	...
3	...	...	...	...	...	2	2	3	4	4	12	10	11	11	6	4	8	8	4	2	1	2	...	...	...	...	1	...	...	...	...	...	...	...	...	...	...	...	...	...
2	...	...	...	...	2	...	1	3	2	7	2	3	7	1	4	2	2	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
1	...	...	...	...	...	3	...	4	2	2	...	...	...	1	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
0	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...

Gradient Velocity (metres per second).

Fig. 1.—Diagram showing Number of Winds for each Gradient and Observed Velocity, W.S.W., Holyhead, 1901–1912. (Metres per second.)

When the gradient wind was measured as being 16 metres per second, Beaufort number 2 was recorded as observed on two occasions, Beaufort number 3 on eight occasions, Beaufort number 4 on six occasions, Beaufort number 5 on two occasions, and Beaufort number 6 on one occasion.

Sources of Error, and how Errors are obviated.—Though rather perplexing, it is not wonderful that there should be this disagreement, for the values of the velocity of the gradient wind and of the observed wind corresponding with it are liable to be wrong for the following reasons :—

(1) While it is most improbable that the barometric height is wrongly recorded, it is quite possible that the isobars are incorrectly drawn simply owing to the lack of stations. With a few stations it is easy to draw isobars to fit the case, because there are many different possible forms which they may take, but it is more than likely that one of the wrong ones has been drawn on any particular occasion. Further, in the printed copy of the Daily Weather Report the maps are of necessity much less accurate than are those of the working chart, not only because the isobars have not been so carefully drawn, but also because the printing does not always register accurately on the maps. For the years 1901 to 1910, when the barometric readings were marked on the maps, it has been possible to check the isobars to some extent; but on the charts for 1911 and 1912 the heights are not so marked, and it has been correspondingly difficult to check inaccuracy. In cases where the isobars on the Daily Weather Report were unsatisfactory they have been redrawn; but it is obvious that it has been impossible to check every map; it would have taken little less time than redrawing the maps completely.

(2) Even if the isobars are correctly drawn for every tenth of an inch, it is quite possible that, owing to local inequalities of pressure and therefore of gradient wind, the gradient wind as measured between the isobars is not the gradient at the station. In order to obviate as many errors of this kind as possible, it has been thought better to reject readings of stations (*a*) within the central areas of cyclones or of anticyclones, (*b*) where the observed wind is very much opposed to the general

direction either of the isobars or of the main current of air as reported at neighbouring stations, (*c*) where great incurvature takes place, (*d*) or if there is a great distance between the isobars and there are indications that the gradient as measured between the isobars is not the gradient at the station.

(3) The observer's estimate of the wind force may not be correct.

(4) As will be shown later, the actual surface wind at a particular station corresponding with a particular gradient may be different for two adjacent wind "directions," and if the wind direction is wrongly observed there is a further cause of disagreement.

(5) As the gradient wind has not been corrected for curvature there must be for the same uncorrected gradient wind representatives of several other gradients.

(6) A few arithmetical mistakes may have remained undetected.

Methods of Reduction.—Having, then, tables for each wind direction as in fig. 1, it is necessary to deal with these in such a way as to obtain the most accurate results. There are three methods which may be adopted :—

(1) A smooth curve may be drawn through the figures as they stand. The method is referred to hereafter as Method I.

(2) We may average all the Beaufort numbers represented by the figures above each gradient wind, *e.g.* in fig. 1 the average for gradient wind 16 metres per second is $\frac{(2\times 2)+(8\times 3)+(6\times 4)+(2\times 5)+(1\times 6)}{19}$ Beaufort numbers. We may thus find the average Beaufort number for each gradient wind. These values may be plotted and a smooth curve drawn through the points. This method is referred to hereafter as Method II.

(3) We may average all the values of the gradient winds represented by the figures opposite each Beaufort number, *e.g.* the average for observed Beaufort number 1 is $\frac{(3\times 5)+(4\times 7)+(2\times 8)+(2\times 9)+(1\times 13)}{12}$ metres per second. We may thus find the average gradient wind for each Beaufort number. These values may again be plotted and a smooth curve drawn through the points. This method is referred to hereafter as Method III. Each of these methods has advantages and disadvantages.

Method I.—The method is easy but somewhat rough; if there were enough observations it would be most correct; it is probable that corresponding with any gradient wind there ought to be a certain definite value of the actual wind. One would expect this value to be reported most often, and that the correct value of the observed wind corresponding with any particular gradient wind should be easily obtained by noticing which Beaufort numbers are reported most often. Unfortunately it would require a much more extensive series of observations than it has been possible to work up, to obtain enough figures to give the probable maximum in all cases.

Method II.—It may be assumed that observers underestimate the actual value of the wind the same number of times as they overestimate it, *i.e.* the curve drawn by plotting the numbers reported for any particular gradient ought to be symmetrical about the maximum, *i.e.* the higher numbers ought to balance against the lower, and the actual value ought to be given by averaging all the values reported. If the values of the Beaufort numbers in metres per second formed an arithmetic series, this assumption would be correct, but as the higher Beaufort numbers represent a greater range of values in metres per second than the lower Beaufort numbers, they will be reported less frequently, and the average Beaufort number will be lower than the true value required, especially for the greater values of the gradient wind.

Further, for the smaller values of the gradient wind 0 to 9 or 10 metres per second, where the correct value of the actual wind is Beaufort number 1 or 2, there is a much greater possibility that higher values (Beaufort numbers 3, 4 or 5) than that lower values will be recorded, *i.e.* the average Beaufort number for the lower gradient winds is likely to be too high. Thus the curve drawn by this method will have its upper end too low and its lower end too high.

It ought to be correct at some intermediate point. The curve obtained by this method from the numbers in fig. 1 is shown in Plate 37, due weight having been given in drawing the curve to points representing the greater number of observations.

Method III.—On considering the values of the gradient wind with which one particular observed Beaufort number has been found to correspond, it will be seen again that the numbers ought to form a series which rises to a maximum and then decreases; but it is not at all obvious that the series will be symmetrical about this maximum, *i.e.* there is no reason why the higher numbers should balance the lower and the actual value be obtained by averaging all the values reported. This is a serious objection to the use of this method. In any case, the fact that some gradient winds occur much more often than others, implies that this maximum will be displaced, and that the value of the average gradient wind will lie nearer the position of this maximum than it ought to do.

Further, the lower values of the gradient winds have in many cases had to be rejected, since it is in those cases that the uncertainty arises as to what is the local gradient. For these reasons, then, the curve drawn by this method has its upper end too high and its lower end too low. This curve also ought to be correct about some intermediate point.

The curve obtained by this method from the numbers in fig. 1 is shown in Plate 38, due weight having been given in drawing the curve to points representing the greater number of observations. It will be observed that the two curves drawn together on Plate 39 are by no means the same.

Non-Use of Statistical Methods.—The difference of method is indeed fundamental, and curves showing similar differences may be drawn to show the relation between any two sets of connected phenomena. Of the two lines drawn to represent regression equations, one has too steep and one has too gentle a slope; it may be thought that the statistical method of correlation might have been employed in this investigation to obtain accurate results. The means of the observed Beaufort numbers and of the corresponding gradient winds, and the lines corresponding to the two regression equations, have been found in a few cases, but the value of the results would have been quite incommensurate with the labour involved in working these out for each wind direction. Apart from the fact that when figures are based on comparatively few data correlation methods give too much weight to large accidental departures from the true mean line, there are two reasons why these methods are inapplicable in this investigation.

(i) The true values of the Beaufort numbers are not in arithmetical progression, so that the values of the regression equations are only approximate.

(ii) There is some evidence that the lines are not straight but curved, so that the straight lines corresponding to the regression equations do not represent the facts of the case.

The results obtained by statistical and mechanical methods are shown in Plate 40. In this case the theoretical mean happens to lie at the point of intersection of the curves obtained by Methods II. and III. This does not usually occur. It is to be noticed that the curves obtained by the mechanical methods are more accordant than are the lines obtained by statistical methods.

In the few cases worked out, the correlation co-efficients lie between ·6 and ·7. In view of what has been said above, this statement is not of much value.

Methods finally Adopted.—After a careful examination of the three possible methods of investigation, and from an inspection of a considerable number of pairs of curves such as those shown in Plate 41, it seems probable that *the values of the average Beaufort numbers given by Method II., corresponding with gradient winds of* 10 *to* 14 *metres per second, are more likely to be correct than are any others* obtained by other methods, and indeed are likely to be accurate within narrow limits.

Curves, therefore, have been drawn in all cases according to Method II., i.e. *the average values of the observed winds in Beaufort numbers have been plotted against the corresponding gradient winds in metres per second, and smooth curves drawn through the points thus obtained.* This gives the average Beaufort number (usually a fraction) corresponding with any gradient wind.

The investigation has thus taken two forms, as there are two questions that require answers.

Method for Question 1.—Relation of Observed to Gradient Wind.—(1) The first of those questions is: What ratio do the observed winds bear to the gradient winds for different directions and for different stations? The answer to this is best obtained by taking the most accurate results that are comparable, and comparing these results. As above stated, the values of the *observed wind corresponding with gradient wind* 10 *to* 14 *metres per second found by Method II. are most nearly correct, so that the value* 12 *metres per second has been selected for comparison.*

Method for Question 2.—Value of Normal Wind.—(2) The second question is: What is the value of the normal observed wind which corresponds with *any* given gradient wind from any direction? This cannot be answered in the same way. The results obtained by Method II. are probably correct for gradient winds of 12 metres per second, but we have seen (p. 201) that the curves are certainly too high at the lower ends and too low at the upper ends. We have seen also that the curves obtained by Method III. are too low at the lower ends and too high at upper ends. The curves obtained by Method I., however, are seen to lie for the most part between the curves obtained by Methods II. and III., and it may be supposed that they represent the actual facts more truly on the whole, though in the particular case selected for comparison (a gradient wind of 12 metres per second) the results may not be so accurate as those obtained by Method II.

The chief disadvantage of Method I. is that when the observations are comparatively few in number it is difficult to say *precisely* how the curve should be drawn. If, however, we assume that the value for 12 metres per second obtained by Method II. is correct, we obtain one point through which the curve obtained by Method I. may be supposed to pass. Thus to find the value of the normal wind corresponding with any gradient wind, or to find the value of the gradient wind with which any given observed wind should correspond, *the curves found by Method I. have been carefully compared with the curves drawn by Method II., and slightly adjusted when necessary,* so that, unless there is evidence to the contrary, the values given for a gradient wind of 12 metres per second should be nearly the same in either case.

The values obtained are not, however, always in agreement, though there is never any very great difference.

Effect of Curvature of Path.—Some work has been done to obtain material for an estimate as to how far the neglect of correction for curvature of the isobars has affected the correctness of the results. It is probable that in the cases of gradient winds of from 0 to 13 or 14 metres per second, the corrections that require to be applied for anticyclonic curvature just balance those for cyclonic curvature, but that for gradient winds above 14 metres per second it is likely that the values of the observed winds are slightly higher (*i.e.* slightly nearer the values of the gradient winds) than the present results indicate.

It is difficult to say how much higher they are, since a theoretical correction for curvature, which assumes that the trajectory of the winds follows the isobar, generally speaking, makes too much allowance. The absence of this correction certainly introduces a considerable element of doubt into the result of this investigation, but if the correction had been made there would still have been a considerable, if not as great, element of doubt as to how far the corrections made represented facts.

PART II.

RESULTS OF INVESTIGATION.

Question 1.—Ratio of Observed to Gradient Wind.—Even by a glance at Plate 42, showing how the points found by Method II. may be plotted for N.E. and N.W. winds at Dungeness, it is obvious that the idea that even at the same station the strength of the observed wind varies with different directions is seen to be fully justified. Even allowing for the greatest possible errors in each case, it would be impossible to conclude that the strengths of observed N.E. and N.W. winds for the same calculated gradient wind are the same.

To test the validity of the 12 years' results, however, the material for Dungeness was divided into two portions and separate curves drawn for each direction of each set by Method II. On taking out the values of the observed wind in Beaufort numbers corresponding to a gradient velocity of 12 metres per second, values which it has been pointed out are most probably correct, and plotting these on radial paper, it is seen (Plate 43) that the two curves so obtained are remarkably similar, *i.e.* there is a distinct type of curve for this station. As a wind of strength represented by Beaufort number 6 has a velocity of 12·1 metres per second, the gradient velocity is represented by a circle in the position of Beaufort number 6.

In the same way curves have been drawn in Plates 44–47 to show similar relationships for the 12 years 1901–1912 at Dungeness, Jersey, and Holyhead, and for 1901–1904 at Brixton, and 1905–1910 at St. James' Park.

It is now obvious that the types of curves, and therefore the character of the exposure or whatever reduces the value of the actual wind relative to the gradient wind, are different for each station. The winds over London have lost much more of their velocity than have those at other stations; but whether at London or elsewhere winds from some directions have lost more than those from other directions.

The evidence is cumulative: it does not depend on the accuracy of the plotting of this or that point on such diagrams as Plate 37. A considerable number of points in that diagram would require to be plotted differently in order that the value of the observed wind, corresponding to a gradient wind 12 metres per second, should be read as having an appreciably different value. But, further, the belief in the accuracy of the value obtained is strengthened by noting that the values obtained in a similar way for the directions S.S.E., S., S.W., and W.S.W., and plotted in Plate 46, give a smooth curve. In general, the values obtained for any one direction are in agreement with those obtained for the directions on either side of it.

It may be noted as a rather remarkable fact that though the Brixton and St. James' Park curves are for different sets of years, they are not only remarkably similar to each other, but very different from the curves for the other stations, except Dungeness. It may perhaps be noted, also, although probably the matter has no significance, that if these two curves be compared with those for Dungeness 1901–1906 and 1907–1912, the differences between each pair are of the same kind.

Partly to test farther the validity of results, but also to see if there was any suggestion of seasonal difference, the material for Dungeness, Jersey, and Holyhead was divided into two portions, one dealing with observations during the months from April to September inclusive, and the other dealing with the observations during the months from October to March inclusive. The results are shown in Plates 48–50.

The pairs of curves are very similar, and, as there are no very striking differences, the belief in the general accuracy of the curves of Plates 44–47 is still farther strengthened.

If they are assumed to be correct, the percentage which the true "normal" wind is of the gradient wind may now be determined. The values are shown in Table I. These values are seen to vary from 81 per cent. for Holyhead N. to 11 per cent. for St. James's Park, S.E. The "normal" wind of M. Guilbert is about 45 per cent. of the gradient wind. This may perhaps be taken as an average value, but there are many cases where this value would seem to be very incorrect, and forecasts based on the assumption that 45 per cent. was correct would be wrong. Taking the sixteen directions at four stations chosen (Brixton being omitted as weighting London unduly), there are sixty-four values in Table I. Of these, only twenty-one, or one-third of the total, lie between 40 per cent. and 50 per cent.

TABLE I.—SHOWING WHAT PERCENTAGE THE "NORMAL" WIND IS OF THE GRADIENT WIND.

	Dungeness.	Jersey.	Holyhead.	Brixton.	St. James' Park.
N.	49	54	81	28	25
NNE.	57	55	75	29	29
NE.	70	56	44	36	29
ENE.	68	54	43	38	29
E.	61	56	35	31	24
ESE.	56	48	17	17	13
SE.	48	46	14	17	11
SSE.	48	47	34	23	12
S.	49	47	39	24	13
SSW.	53	47	49	25	23
SW.	56	48	48	24	24
WSW.	48	56	40	23	22
W.	41	57	48	23	18
WNW.	39	50	60	20	18
NW.	38	49	68	23	24
NNW.	46	56	80	...	19

Question 2.—Values of Normal Winds.—So far, attention has been focussed on the results for a gradient wind of 12 metres per second obtained from curves drawn by Method II., as it is probable that by so doing the most accurate comparable results are obtained for different stations. It is a matter of practical importance, however, to know what are the "normal" winds for any direction corresponding to *any* given gradient wind. These facts are given in Table II. for Dungeness, Jersey, and Holyhead. These values have been taken out not from the curves drawn by Method II., but from curves drawn by Method I. (see p. 200). They are probably nearly correct for gradient winds from 0 to 14 metres per second; for higher values of the gradient wind the corresponding values of the true normal winds should probably be somewhat greater as no account has been taken of the curvature of the path in measuring the gradient wind.

The relation of the observed to the gradient wind when the latter is 5, 10, 15 or 20 metres per second is shown graphically by the curves in Plates 51–53. These curves have been drawn from curves constructed by Method I., and thus show the same facts as those in Table II. in a slightly different form.

Causes of Variation of Normal Winds.—The object of this investigation has been to find out what ratio the observed winds has to the gradient winds for different directions and for different stations, and to arrive at some estimate of the values of the true normal winds for different directions and gradients at those stations.

This has now been done, but it may not be out of place to consider tentatively why these normal winds vary. The "exposure" has been spoken of as a cause, but there are at least four distinct causes which may affect the strength of the observed wind.

(1) Meteorological conditions.
(2) Large geographical conditions.
(3) Local geographical conditions, *i.e.* exposure.
(4) Psychological effects on observers of winds of different character.

If meteorological conditions are held to have weight, it must be remembered that the directions considered are observed directions, and that gradient winds will differ from those appreciably, the gradient direction veering from the observed by 1 or 2 points at least. Farther, it is probable that the veering is greater at some stations than at others and for some directions than for others. Thus the gradient direction corresponding to the observed N.E. direction is on the average probably E., but it need not be the same for London as for Jersey.

That local exposure is not the only cause of difference seems probable from the similarity of the two London curves (Plate 47). It would be extraordinary if two stations some miles apart should have such nearly similar local conditions as would require to be assumed if exposure is considered as the only cause of difference. At the same time, local conditions may be expected to have some effect. The dropping of the force for E.S.E. and S.E. must surely be caused, at any rate partly, by local conditions.

In the curves for Dungeness and London, and to some extent in the curves for Jersey also, the greater relative strength of the normal north-easterly winds is noticeable. This suggests causes not entirely local; these causes may be meteorological; but against this supposition must be placed the fact that in the curves for Holyhead

TABLE II.—SHOWING FOR DUNGENESS, JERSEY, AND HOLYHEAD THE "NORMAL" OBSERVED WIND ON THE BEAUFORT SCALE CORRESPONDING WITH ANY GIVEN GRADIENT WIND VELOCITY AND ANY GIVEN OBSERVED WIND DIRECTION.

"Normal" Observed Wind Force (Beaufort).	Observed Wind Direction.															
	N.	NNE.	NE.	ENE.	E.	ESE.	SE.	SSE.	S.	SSW.	SW.	WSW.	W.	WNW.	NW.	NNW.
	Gradient Wind Velocity in Metres per Second.															
	DUNGENESS.															
0	0–1	1–1·2	1–1·2	0–1	0–1	0–1·2	0–1·6	0–1·6	0–1·4	0–1·4	0–1·2	0–1·4	0–1·4	0–1·8	0–1·8	0–1·4
1	1–3·8	1·2–3·6	1·2–3·5	1–3·4	1–3·5	1·2–3·8	1·6–5	1·6–4·8	1·4–4·2	1·4–4·6	1·2–4·2	1·4–4·6	1·4–4·6	1·8–5·4	1·8–5·6	1·4–4·8
2	3·8–6·6	3·6–6·2	3·5–6	3·4–5·8	3·5–6·2	3·8–6·2	5–8·2	4·8–8·2	4·2–7·4	4·6–8	4·2–7·4	4·6–8·2	4·6–8	5·4–9	5·6–9·2	4·8–8·6
3	6·6–10·5	6·2–9·2	6–8·4	5·8–8·2	6·2–9	6·2–9·2	8·2–11·6	8·2–11·8	7·4–11·2	8–11·6	7·4–10·8	8·2–12	8–11·6	9–13	9·2–13·4	8·6–12·6
4	10·5–12·5	9·2–13·4	8·4–11·3	8·2–11	9–12	9·2–12·6	11·6–15·8	11·8–16	11·2–15·6	11·6–15·4	10·8–14·8	12–16	11·6–15·6	13–17·4	13·4–17·6	12·6–16·8
5	12·5–17	13·4–18	11·3–14·4	11–14·6	12–15·8	12·6–16·2	15·8–20·4	16–20·2	15·6–21·2	15·4–20	14·8–20	16–21	15·6–20·6	17·4–22·2	17·6–22·6	16·8–21·4
6	17–22	18–23·2	14·4–17·6	14·6–18·2	15·8–20·2	16·2–20	[20·4–26]	20·2–25	21·2–29	20–25	20–26	21–26	20·6–26	22·2–28	22·6–29	21·4–26
7	[22–28]	[23·2–30]	[17·6–21·2]	18·2–23	20·2–25	[20–25]	[26–33]	[25–31]	[29–	[25–30]	[26–33]	[26–32]	[26–	[28–	[29–36]	[26–31]
8	[28–	[30–	[21·2–	[23–	[25–30]	[25–30]	…	[31–	…	30	[33–	[32	…	…	[36–	[31–
	JERSEY.															
0	0–1	0–1·2	0–1	1–1·2	0–1	0–1·2	0–1·4	0–1·4	0–1·2	0–1·2	0–1·4	0–1	0–1	0–1	0–1	0–1
1	1–3	1·2–4·6	1–3·4	1·2–3·6	1–3·8	1·2–4	1·4–4·8	1·4–4·4	1·2–4·4	1·2–4	1·4–4·2	1–3·6	1–3·4	1–3·5	1–3·6	1–3
2	3–6	4·6–7·6	3·4–6·2	3·6–6·4	3·8–6·2	4–7·2	4·8–8	4·4–7·8	4·4–8·2	4–7·4	4·2–7·5	3·6–6·4	3·4–6	3·5–6·2	3·6–6·5	3–5·4
3	6–9	7·6–11	6·2–9·2	6·4–9·4	6·2–9	7·2–11	8–11·4	7·8–11·6	8·2–12·8	7·4–11·2	7·5–11·2	6·4–9·2	6–9	6·2–9·8	6·5–10	5·4–8·4
4	9–12·8	11–15	9·2–12·4	9·4–12·6	9–11·8	11–15	11·4–15	11·6–16·6	12·8–18·8	11·2–16	11·2–15·2	9·2–12·8	9–12·4	9·8–14·2	10–14·6	8·4–12·4
5	12·8–17	15–17·4	12·4–16	12·6–16	11·8–14·8	15–19	15–19	16·6–21·8	18·8–26	16–21·6	15·2–19·8	12·8–17	12·4–16	14·2–19	14·6–20	12·4–17·4
6	…	[17·4–23]	16–20	16–19·2	14·8–18	19–24	19–23	21·8–27·4	26–34	21·6–28	19·8–25	17–21·6	16–20·2	19–25	20–26	17·4–23
7	…	[23–	[20–23]	29·2–23·6	[18–	24–31	23–28	[27·4–	[34–	[28–	[25–	21·6–27	20·2–25	25–32	[26–	[23–
8	…	…	[23–	[23·6–	…	[31–	[28–	…	…	…	…	[27–	[25–	[32–	…	…
	HOLYHEAD.															
0	0–1	0–1	0–1·4	0–1·6	0–2·2	0–3·5	0–3·8	0–2·5	0–2	0–2	0–1·6	0–1·8	0–1·5	0–1·2	0–1·2	0–1
1	1–3	1–3	1·4–4·4	1·6–5	2·2–6	3·5–9·2	3·8–10·8	2·5–7·2	2–6·5	2–5·8	1·6–5·2	1·8–5·5	1·5–4·6	1·2–4	1·2–3·8	1–3·2
2	3–4·8	3–5·6	4·4–7·6	5–8·5	6–9·8	9·2–12·2	10·8–15·4	7·2–12·2	6·5–9·6	5·8–9	5·2–8·6	5·5–9·6	4·6–8	4–6·8	3·8–6·2	3·2–5·4
3	4·8–6·8	5·6–8	7·6–10·8	8·5–11·8	9·8–13·5	12·2–17·4	15·4–19	12·2–17·2	9·6–12·6	9–12	8·6–12	9·6–13·8	8–11·2	6·8–9·5	6·2–8·5	5·4–7·6
4	6·8–9	8–10·8	10·8–14·2	11·8–15	13·5–17	17·4–21·4	19–22	17·2–22	12·6–15	12–14·8	12–15·6	13·8–18	11·2–14·8	9·5–12·4	8·5–10·6	7·6–10·2
5	9–11·6	10·8–13·6	14·2–17·6	15–18·4	17–20·4	[21·4–]	22–25	[22–]	15–17·5	14·8–18	15·6–19·2	18–21·8	14·8–18·8	12·4–15·4	10·6–12·8	10·2–12·6
6	11·6–14·2	13·6–16·8	17·6–21·4	18·4–22·4	20·4–24	…	25–28	…	17·5–20·2	18–21·2	19·2–23·6	21·8–25·8	18·8–23	15·4–18·6	12·8–15·4	12·6–15·4
7	14·2–17·6	16·8–20	21·4–26	22·4–27	[24–]	…	[28]	…	[20·2–]	21·2–25	23·6–29·4	25·8–30	23–28	18·6–22·6	15·4–18·4	15·4–18·4
8	17·6–21·2	20–24	[26–32]	[27–]	…	…	…	…	…	25–29	[29·4–]	[30–]	[28–]	[22·6–]	[18·4–]	[18·4–21·8]

there is no suggestion of the greater strength of these winds. It is possible, of course, that some other cause may be operating to mask the effect at Holyhead.

At Holyhead the greater strength of northerly winds suggests that these may be over-estimated and southerly winds under-estimated on account of their temperatures, but the London, Dungeness, and Jersey results seem to show that this is not the case: nor are easterly winds of a greater, or less, strength than westerly, though N.E. seem on the whole the strongest. It is to be noted, however, that westerly or south-westerly winds are on the whole stronger than north-westerly. As the latter are colder than the former, the opposite result would be expected if temperature exercised a controlling effect on the observer.

The differences are so radical that one is forced to look for other than local causes to explain some of those differences, and it may be suggested that the larger geographical conditions help to give form to the curves.

It is, then, significant that Holyhead on the West Coast should have strongest winds north and south, and that south-east winds after coming across the great mass of England and Wales should be the weakest, while Dungeness, with land to the north-west and at some distance to south-east, should have these winds weaker than north-east winds which might come over a great expanse of sea. So also the London curves might be partly explained by similar conditions. But such considerations do not suggest any reasons why east winds at Jersey should be stronger than others, though they might seem to explain why west winds are stronger than north and north than south.

Thus there does not appear to be any one set of causes which can be taken to explain all the facts, but there is some suggestion that

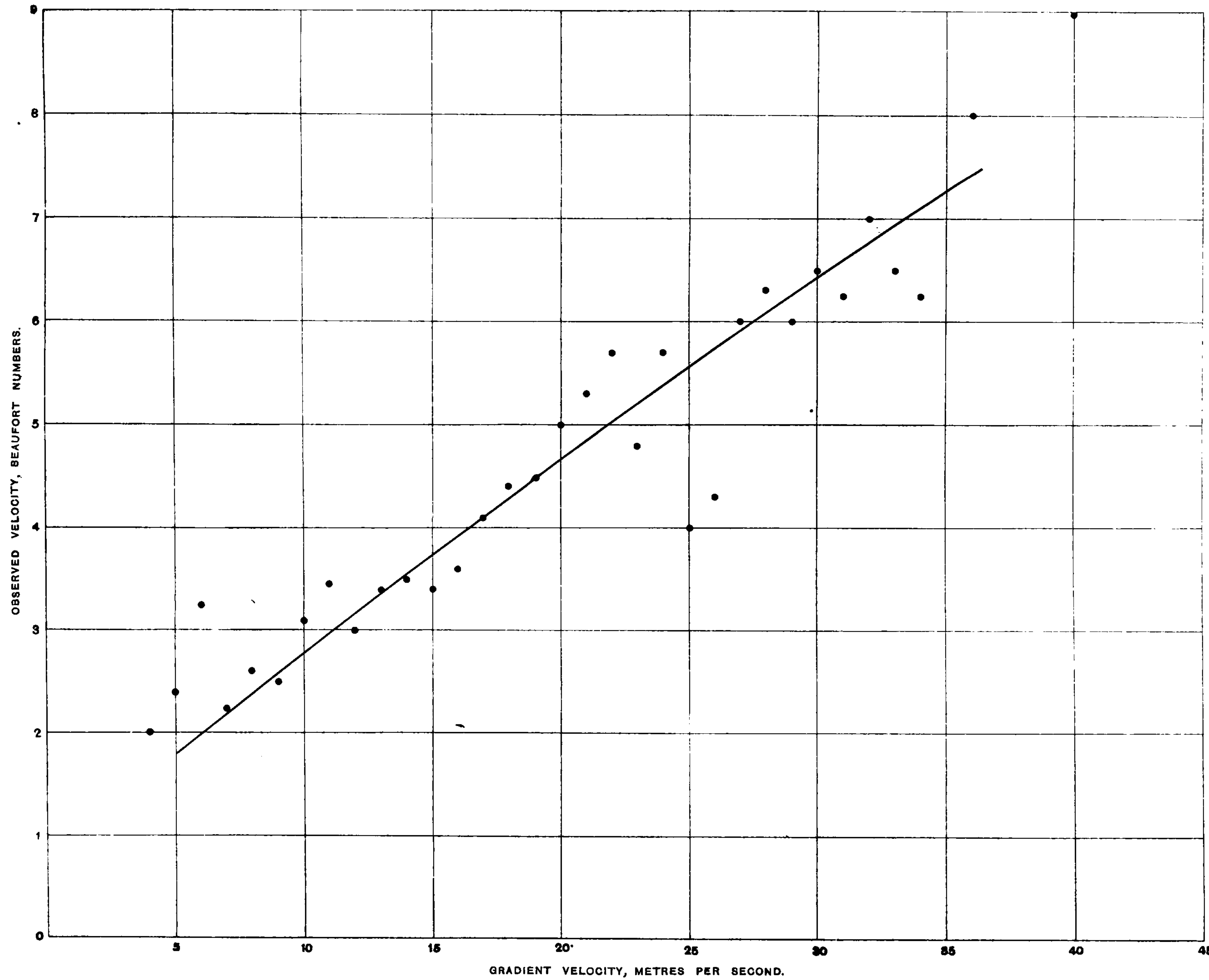
(i.) North-easterly winds are normally nearer the gradient velocity than others.

(ii.) The larger geographical conditions have some effect, *i.e.* if winds come over a large expanse of water they are nearer the gradient velocity than if they come over land, notwithstanding local conditions.

(iii.) Local geographical conditions, *i.e.* exposure, may serve to modify to some extent the strength of the wind.

These conclusions are very tentative: material from a considerable number of stations requires to be worked out before any conclusions can be regarded as valid. As it would appear to be advantageous for forecasting to find what really are the normal winds at all telegraphic reporting stations, this theoretical investigation may be helped by work of a practical character.

HOLYHEAD, 1901-1912.
W.S.W. OBSERVED WINDS.



Curve showing relation between gradient winds and observed winds, obtained by averaging all Beaufort numbers corresponding to particular gradient winds.

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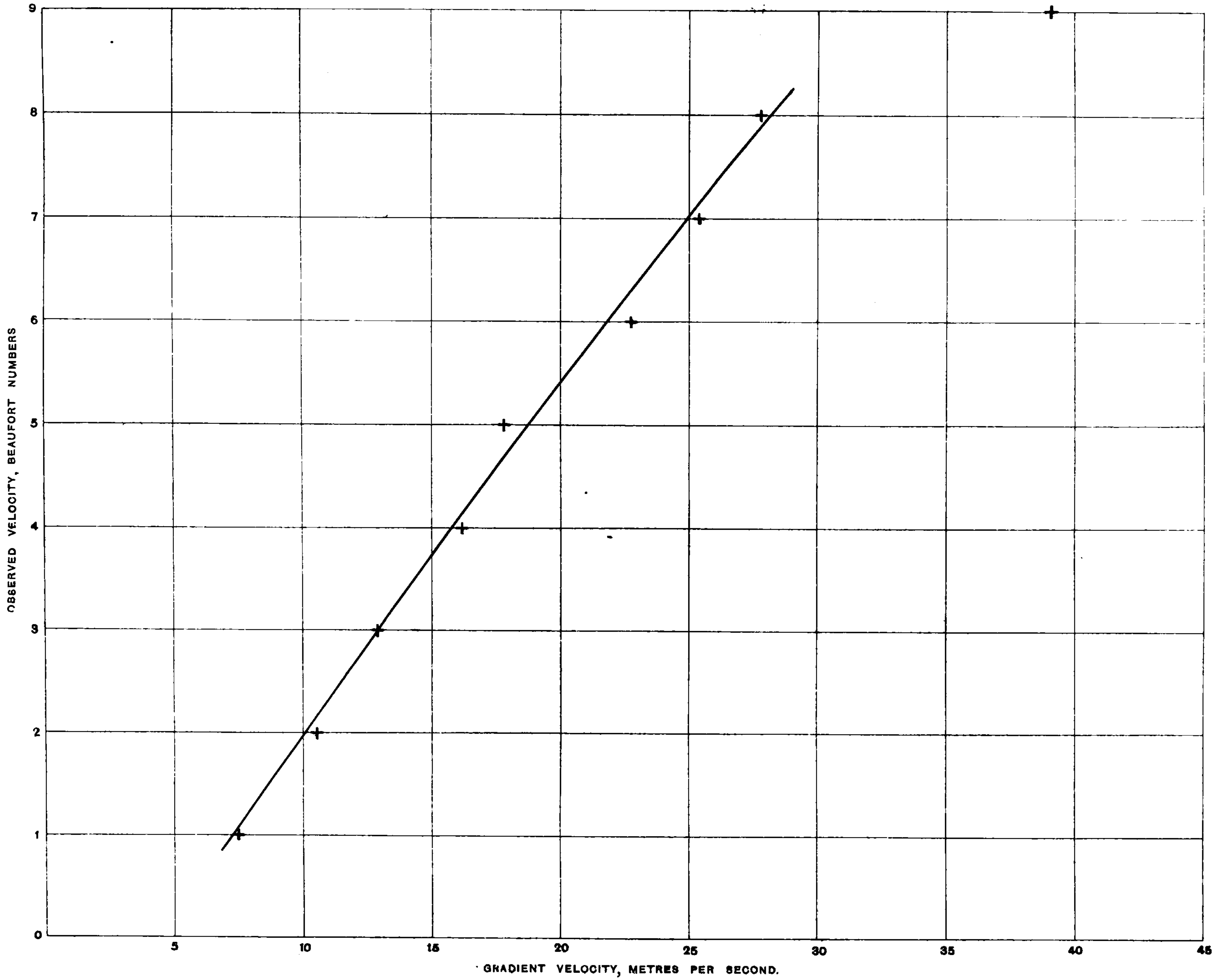
[illegible]

HOLYHEAD, 1901-1912.
W.S.W. OBSERVED WINDS.



Curve showing relation between gradient winds and observed winds, obtained by averaging all gradient winds corresponding to particular Beaufort numbers.

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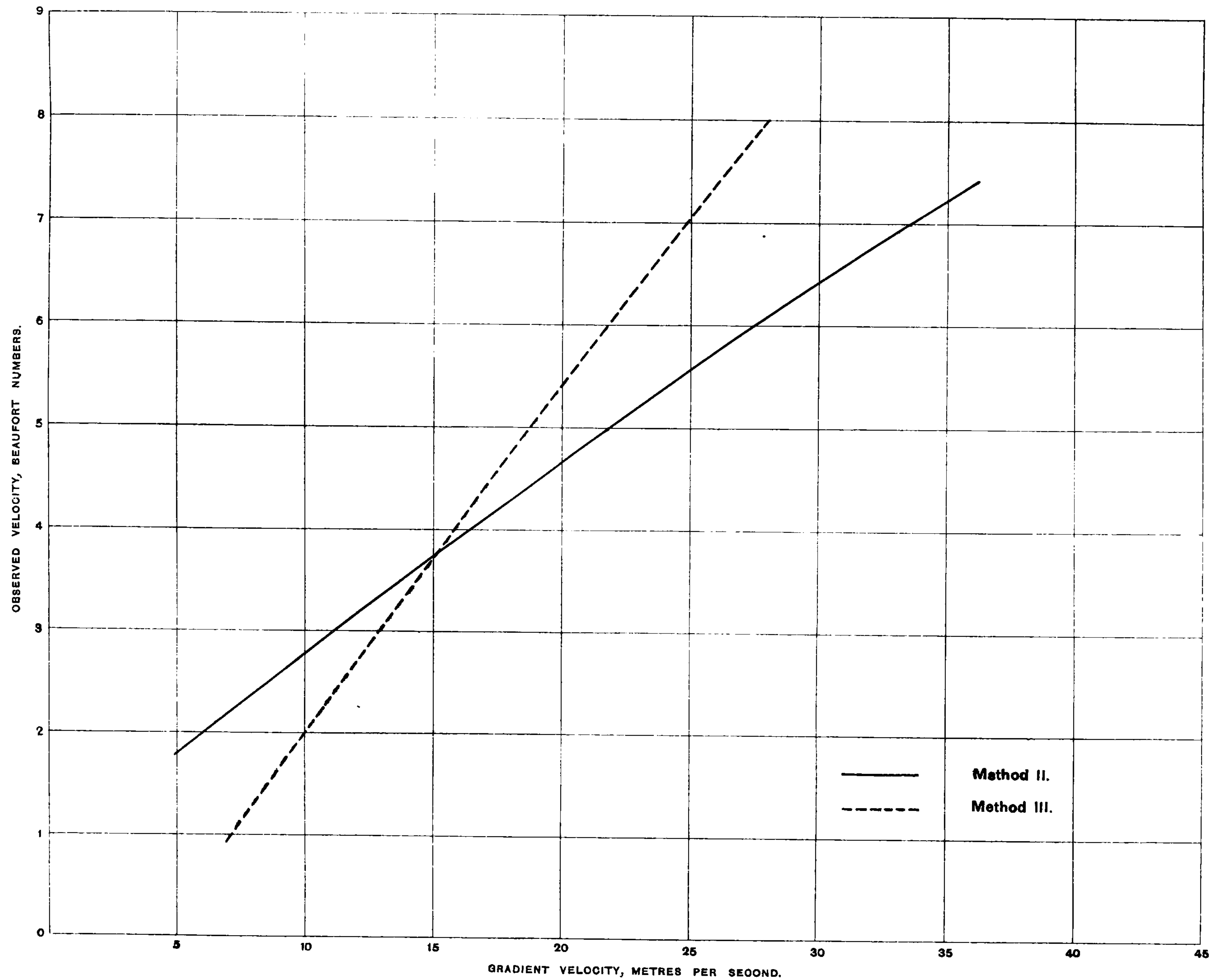
HOLYHEAD, 1901-1912.
W.S.W. OBSERVED WINDS.



Curves of Plates 37 and 38 compared.

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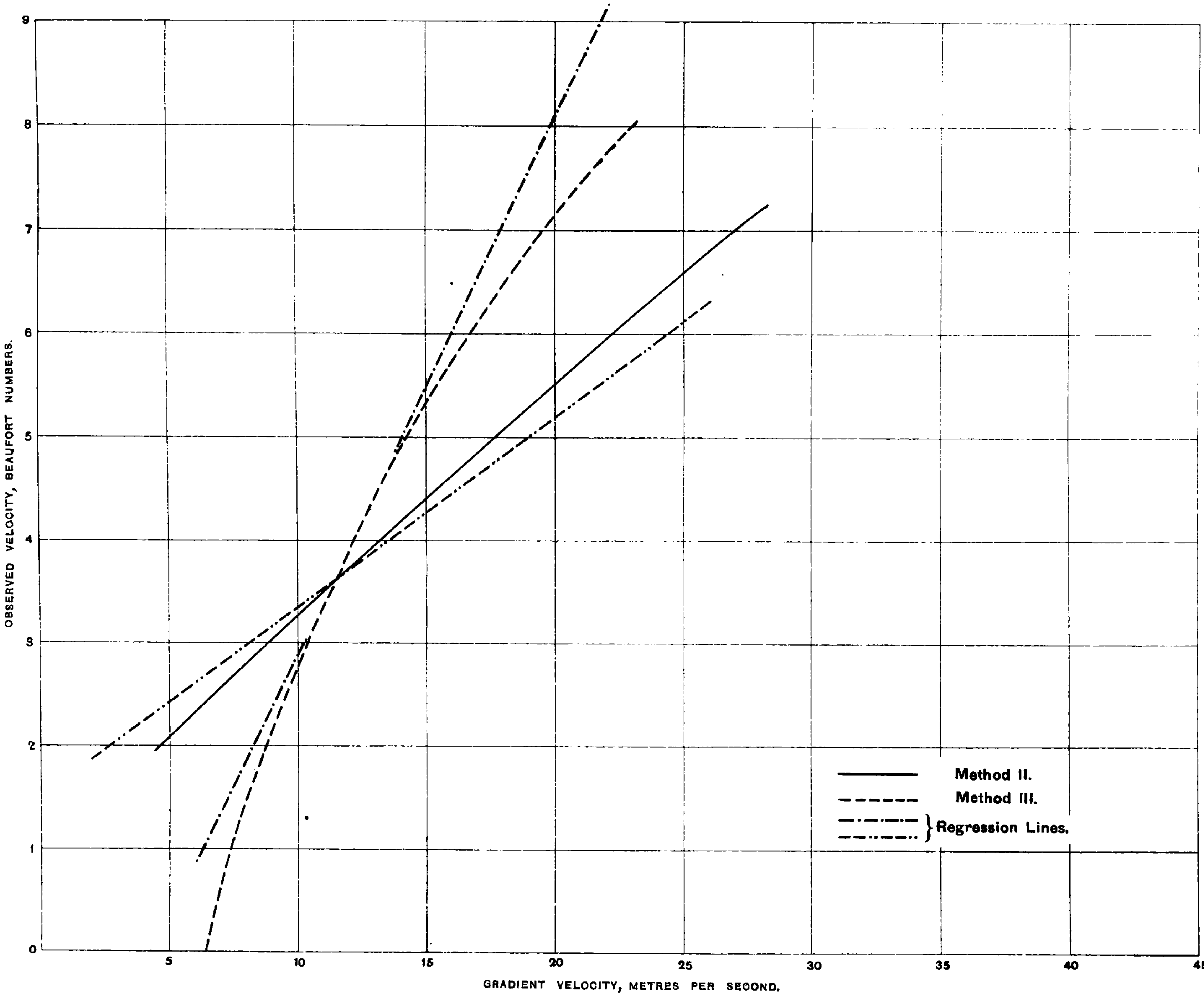
HOLYHEAD, 1901-1912.

N.E. OBSERVED WINDS.



Diagrams showing regression lines, and curves obtained by methods of plotting points.

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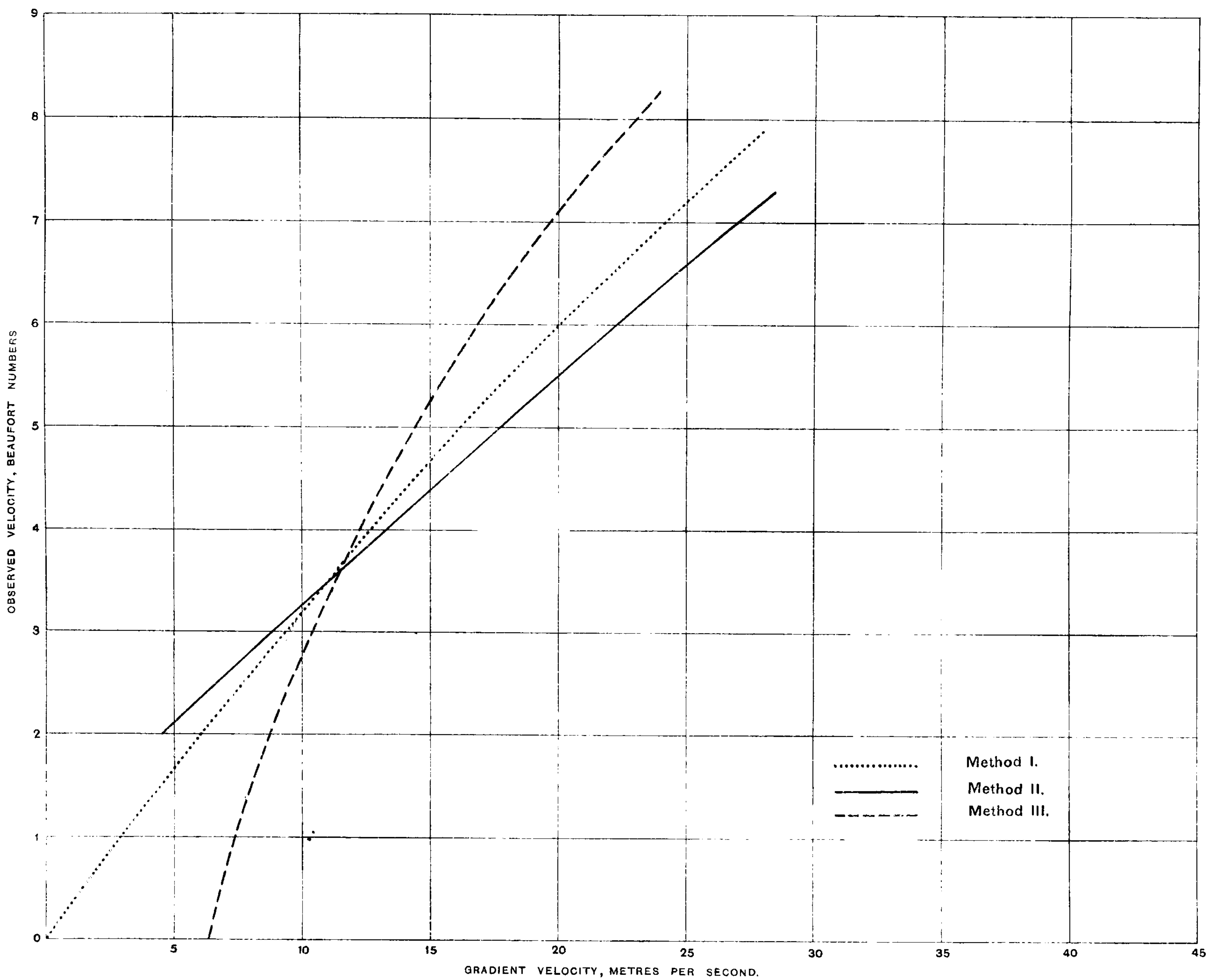
To face p. 208.

HOLYHEAD, 1901-1912.
N.E. OBSERVED WINDS.



Curves showing relation between gradient winds and observed winds, obtained by Methods I., II. and III.

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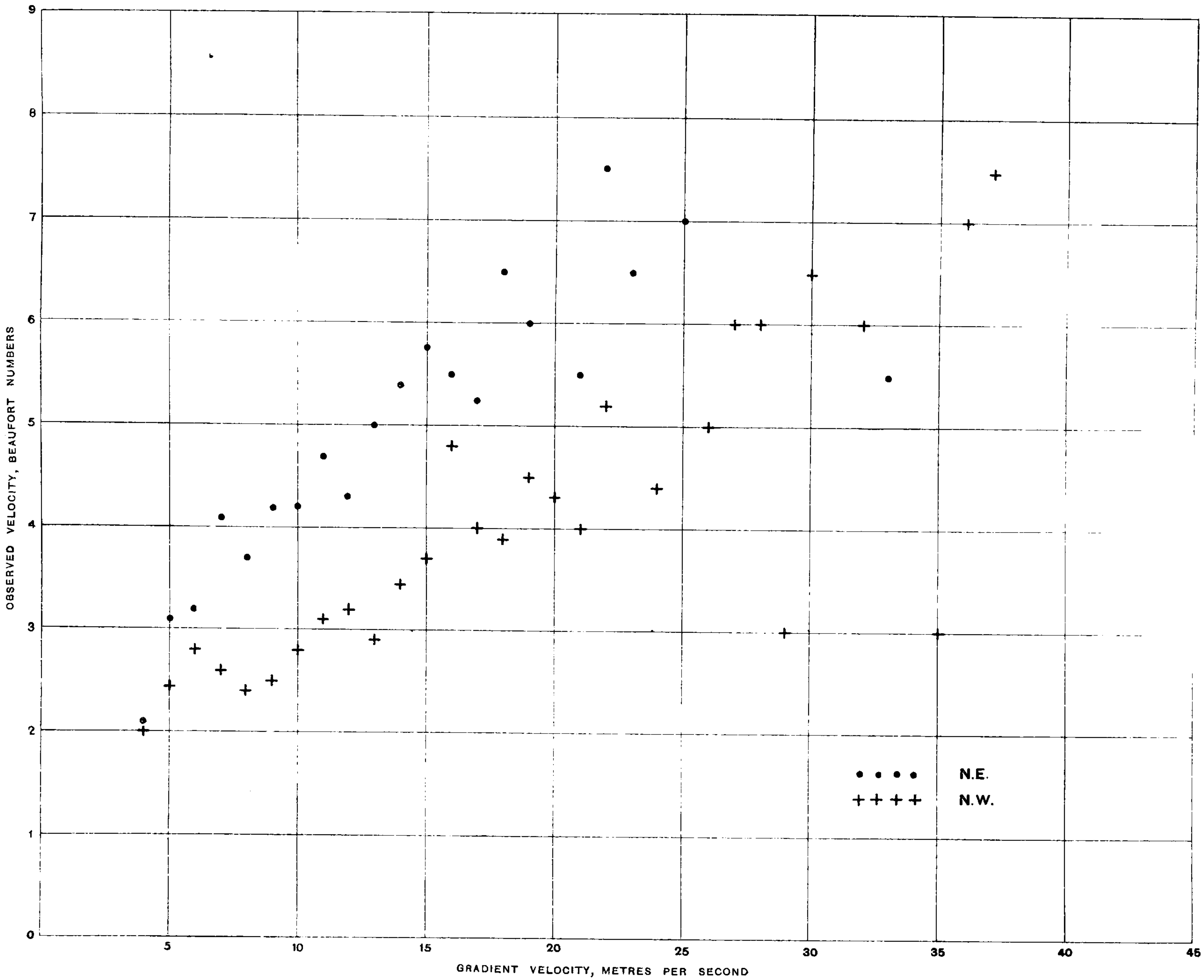
GEOPHYSICAL MEMOIRS, No. 9.

DUNGENESS, 1901-1912.

OBSERVED WINDS.

N.E. AND N.W. DIRECTIONS



Points plotted by Method II., showing relation between gradient winds and observed winds.

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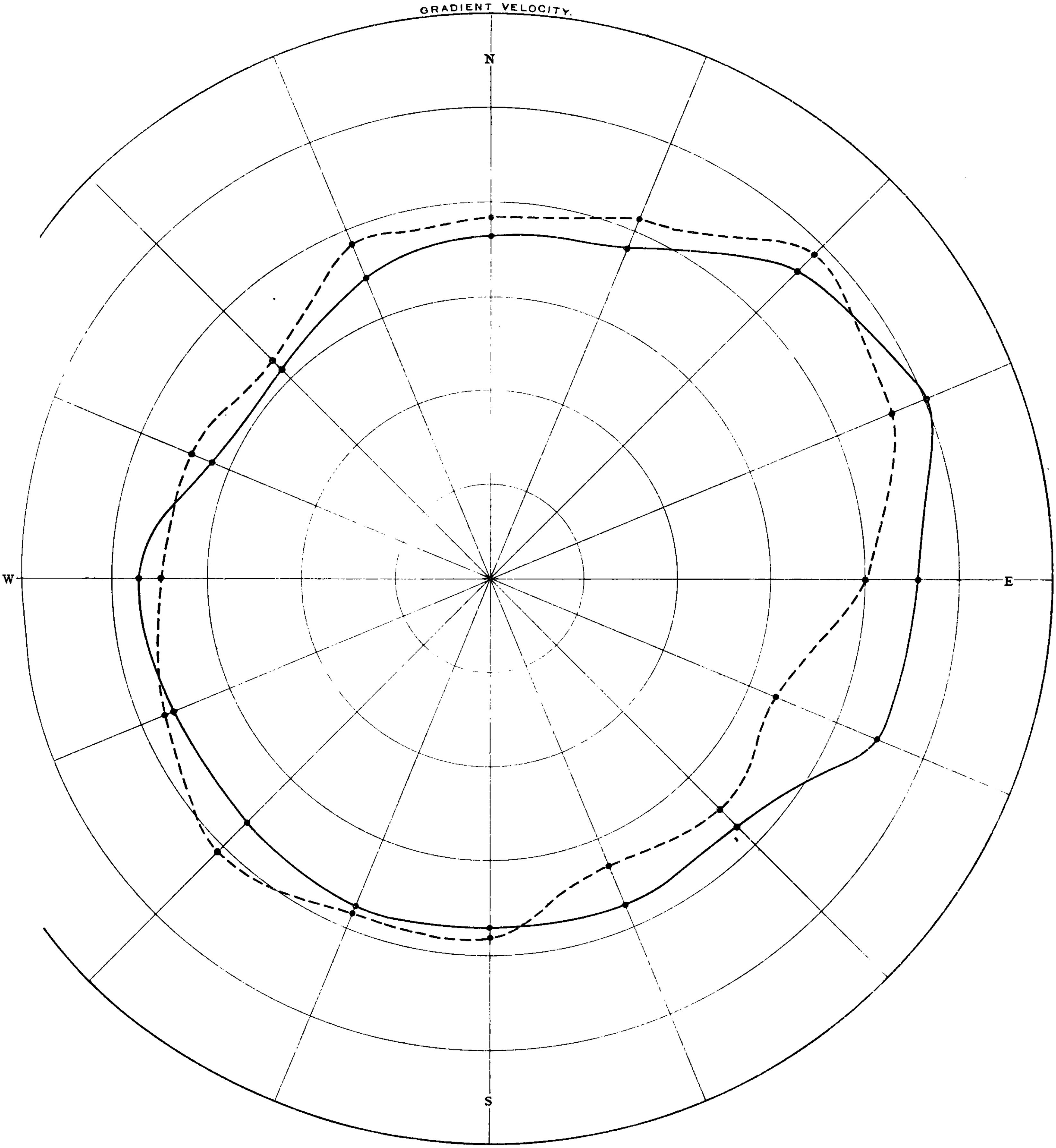
DUNGENESS.

——— 1901-1906.
– – – – 1907-1912.



Curves showing relation of observed wind in Beaufort numbers to gradient wind of 12 metres per second (Beaufort number 6). The circle of smallest radius represents Beaufort force 1 for the different points of the compass. The remaining circles denote forces 2, 3, 4, 5, 6 respectively, the last being outermost and representative of the gradient velocity

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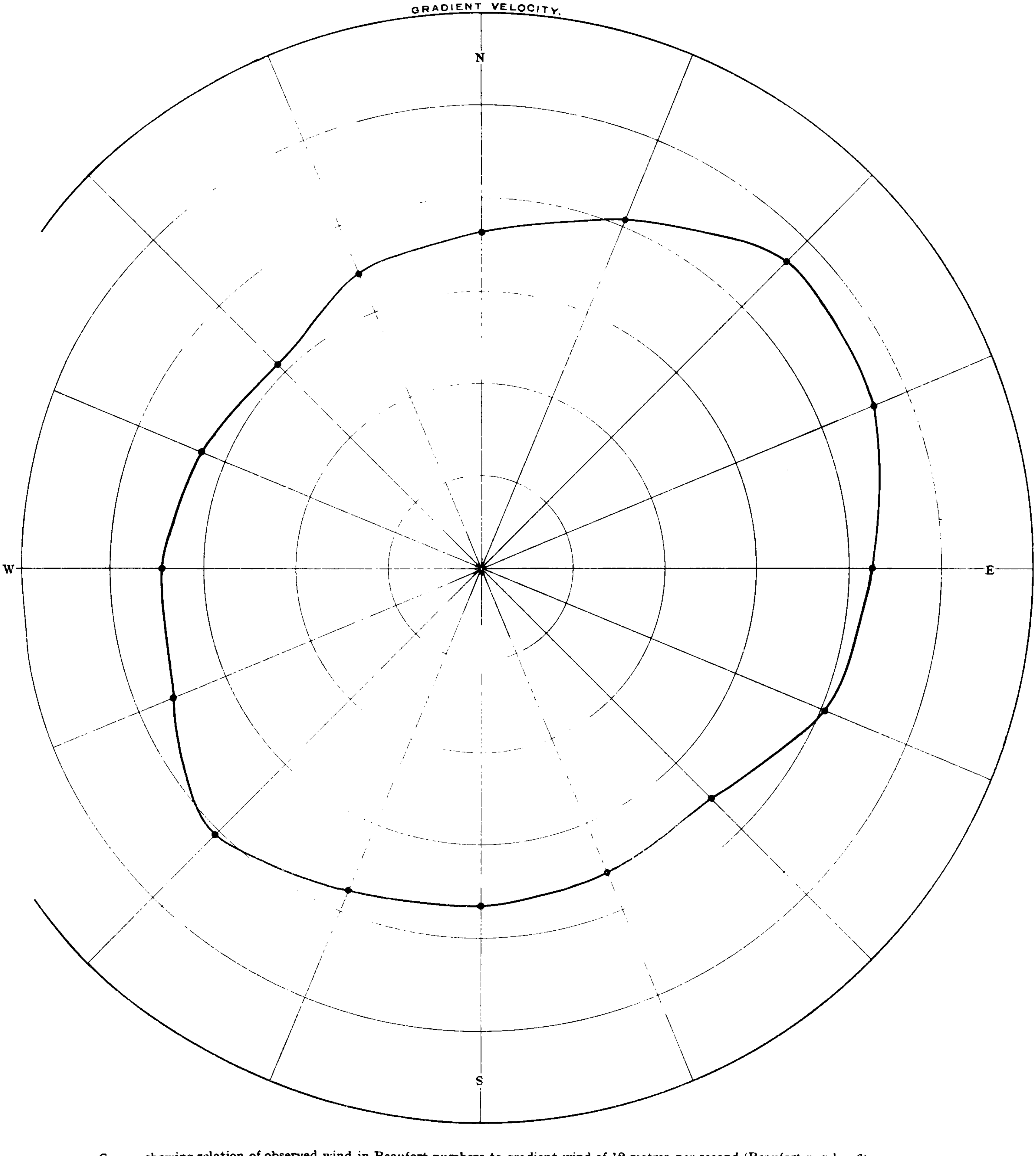
DUNGENESS, 1901-1912.



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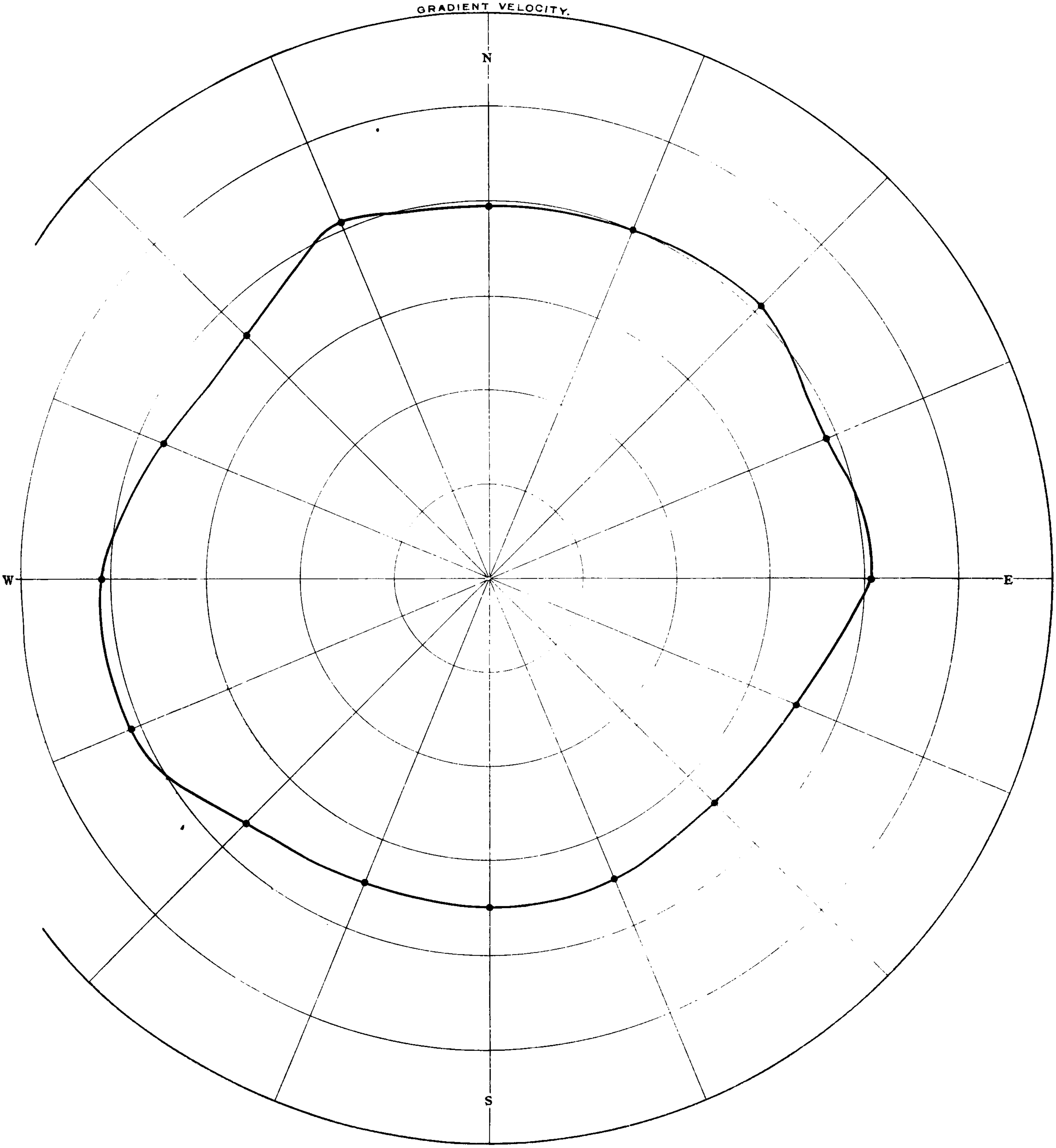
P.O. 51941. 30652 370 S O P 800 S. 4/14

JERSEY, 1901-1912.



Curves showing relation of observed wind in Beaufort numbers to gradient wind of 12 metres per second (Beaufort number 6). The circle of smallest radius represents Beaufort force 1 for the different points of the compass. The remaining circles denote forces 2, 3, 4, 5, 6 respectively, the last being outermost and representative of the gradient velocity

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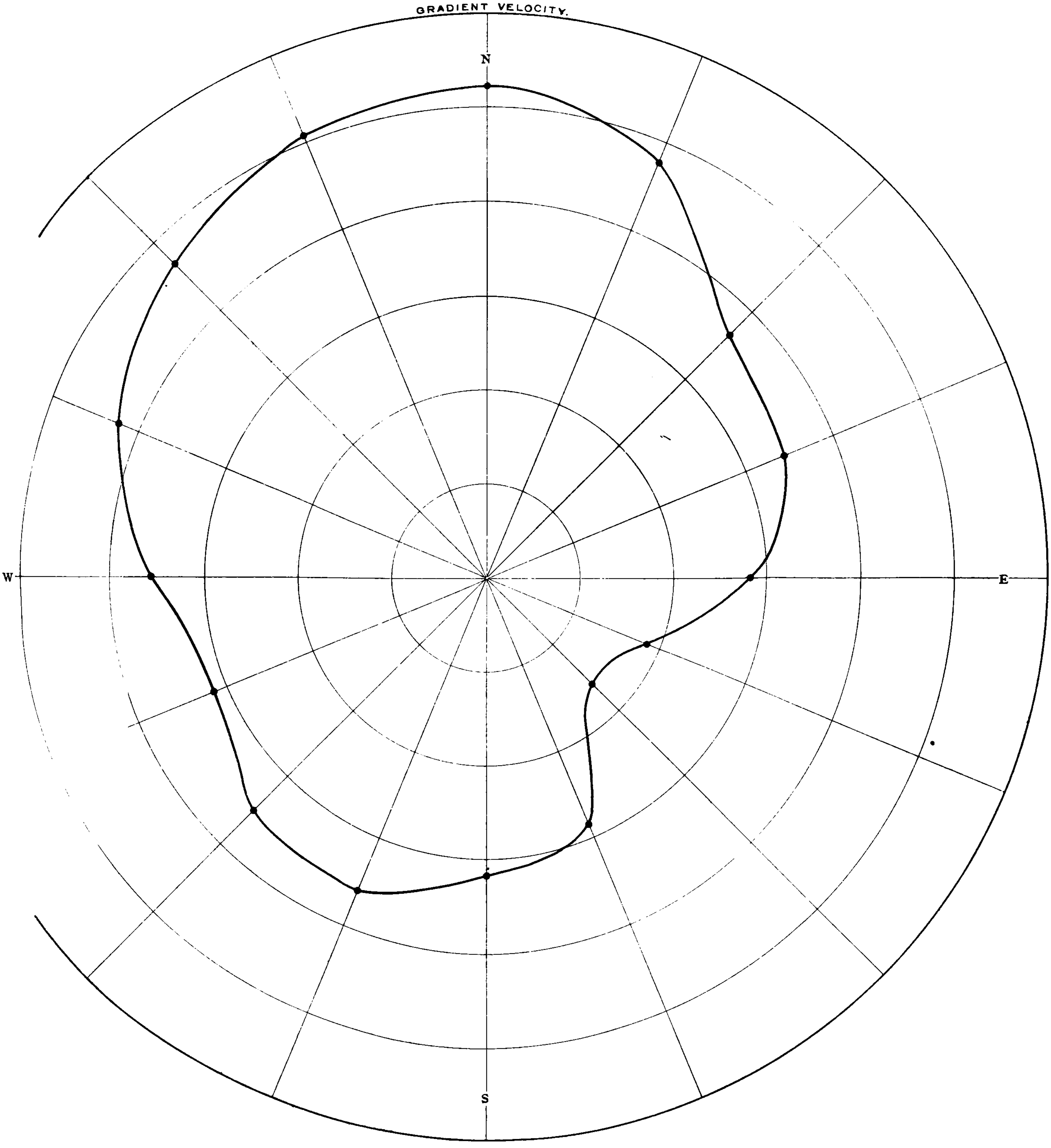
HOLYHEAD, 1901-1912.



Curves showing relation of observed wind in Beaufort numbers to gradient wind of 12 metres per second (Beaufort number 6). The circle of smallest radius represents Beaufort force 1 for the different points of the compass. The remaining circles denote forces 2, 3, 4, 5, 6 respectively, the last being outermost and representative of the gradient velocity

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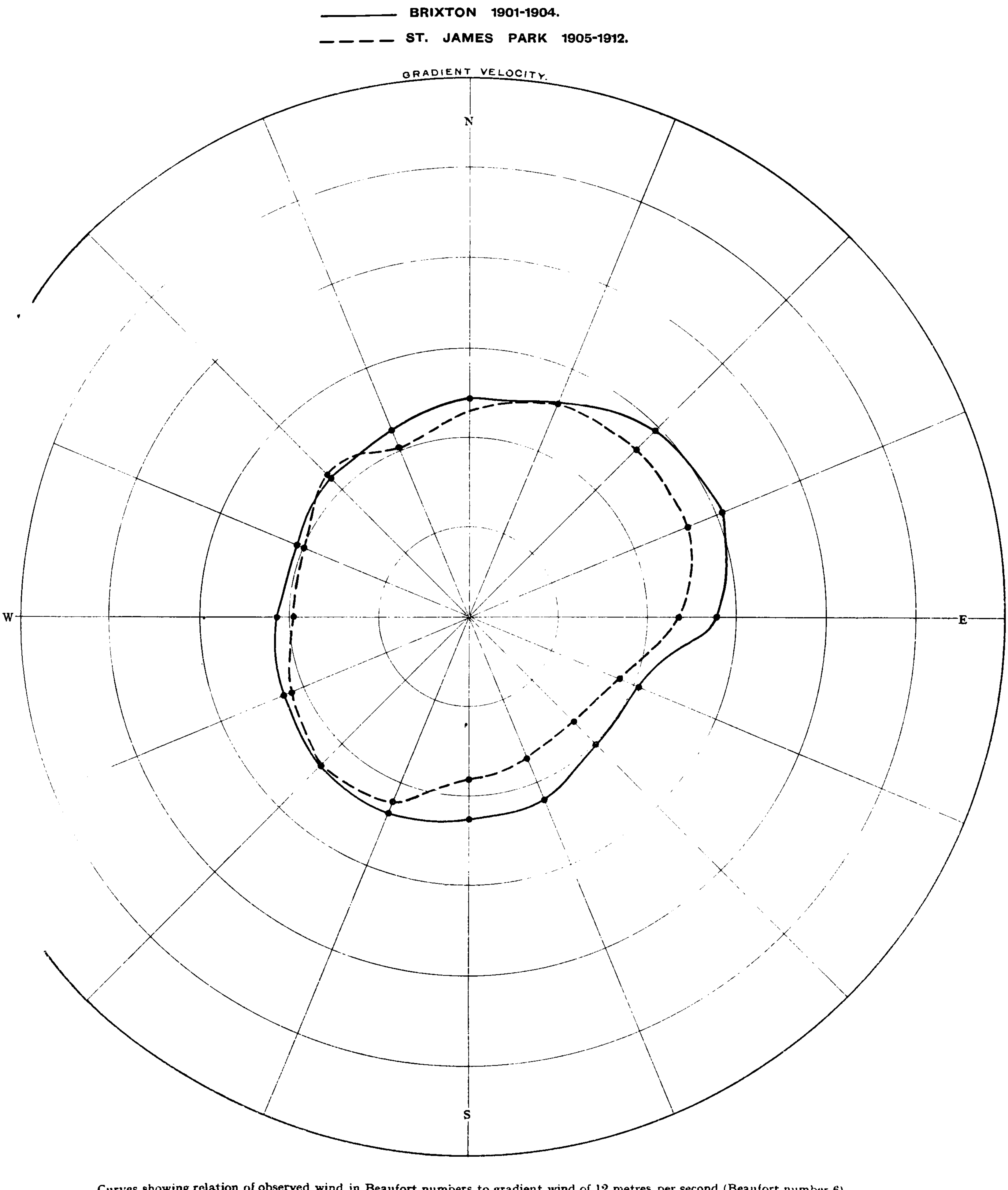

Curves showing relation of observed wind in Beaufort numbers to gradient wind of 12 metres per second (Beaufort number 6). The circle of smallest radius represents Beaufort force 1 for the different points of the compass. The remaining circles denote forces 2, 3, 4, 5, 6 respectively, the last being outermost and representative of the gradient velocity.

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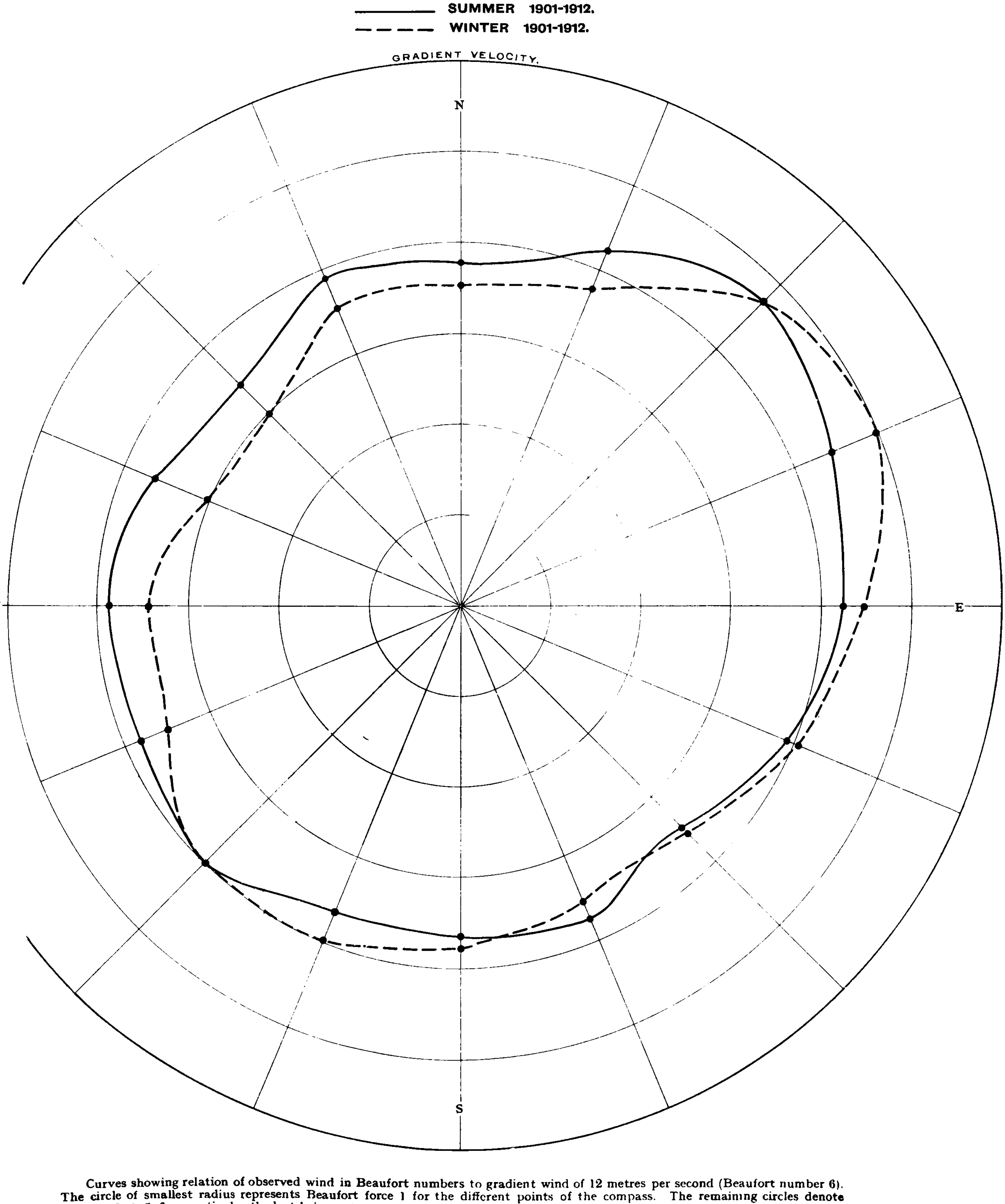
DUNGENESS.



Curves showing relation of observed wind in Beaufort numbers to gradient wind of 12 metres per second (Beaufort number 6). The circle of smallest radius represents Beaufort force 1 for the different points of the compass. The remaining circles denote forces 2, 3, 4, 5, 6 respectively, the last being outermost and representative of the gradient velocity

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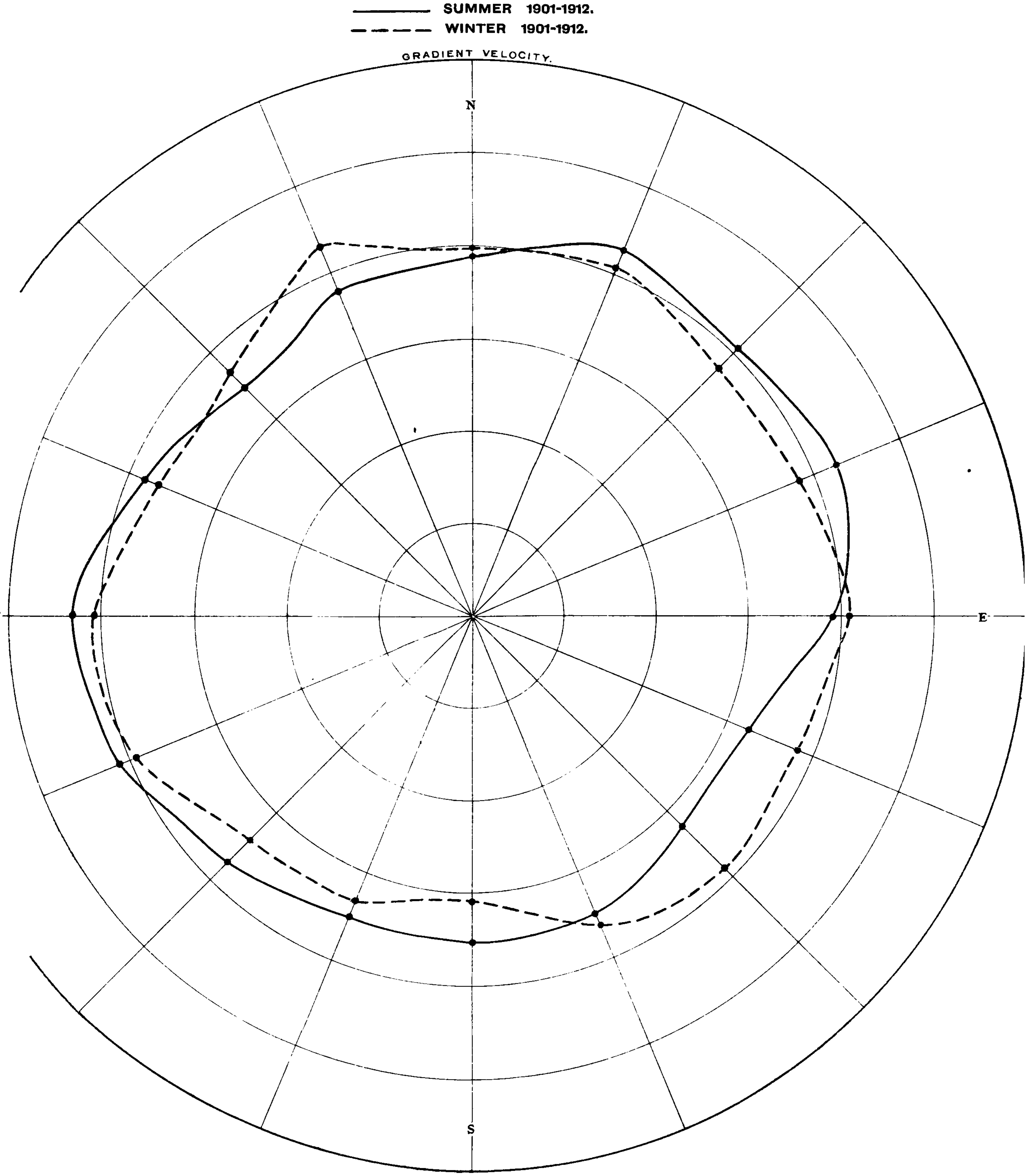
JERSEY.



Curves showing relation of observed wind in Beaufort numbers to gradient wind of 12 metres per second (Beaufort number 6). The circle of smallest radius represents Beaufort force 1 for the different points of the compass. The remaining circles denote forces 2, 3, 4, 5, 6 respectively, the last being outermost and representative of the gradient velocity

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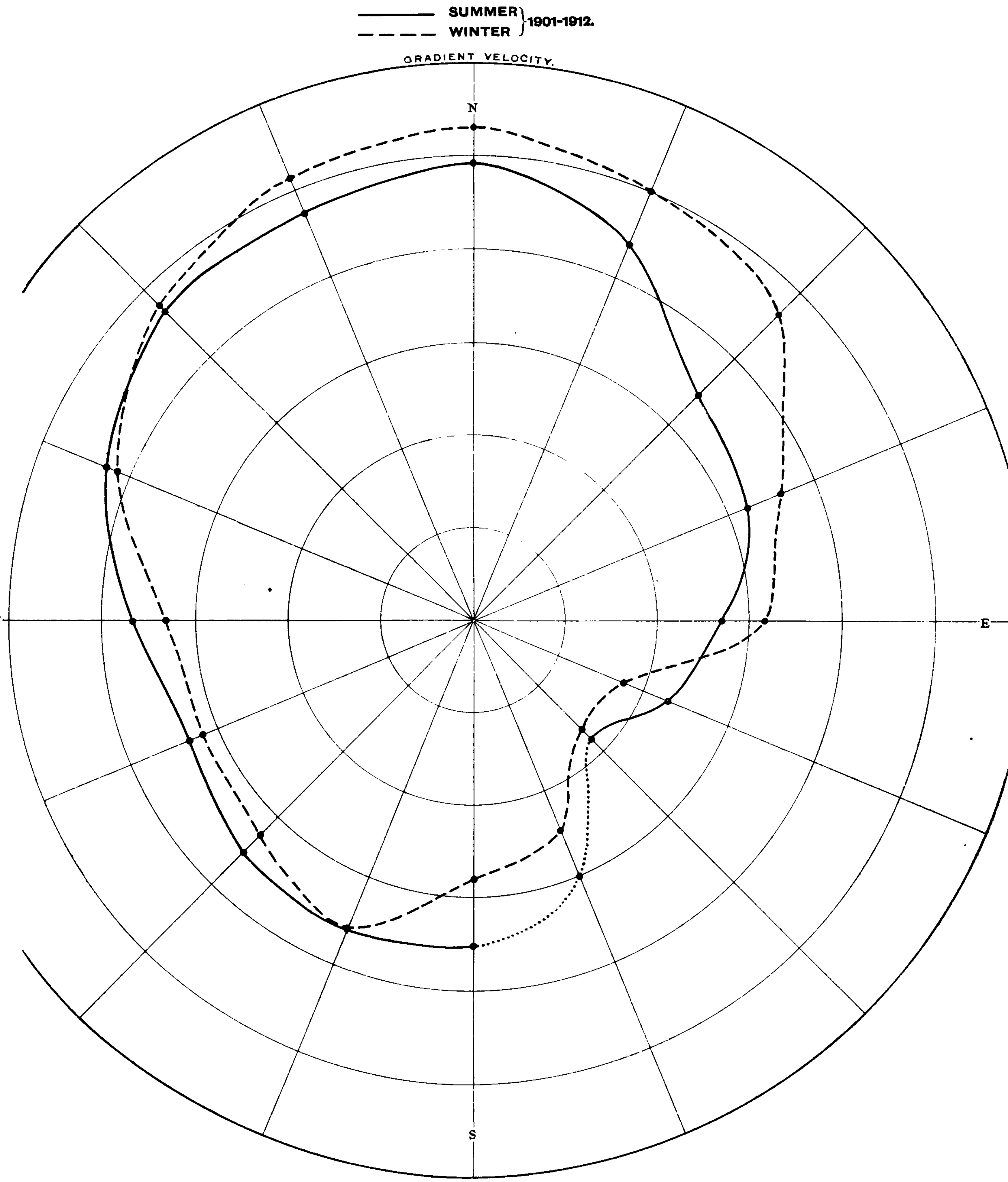
HOLYHEAD,



Curves showing relation of observed wind in Beaufort numbers to gradient wind of 12 metres per second (Beaufort number 6). The circle of smallest radius represents Beaufort force 1 for the different points of the compass. The remaining circles denote forces 2, 3, 4, 5, 6 respectively, the last being outermost and representative of the gradient velocity

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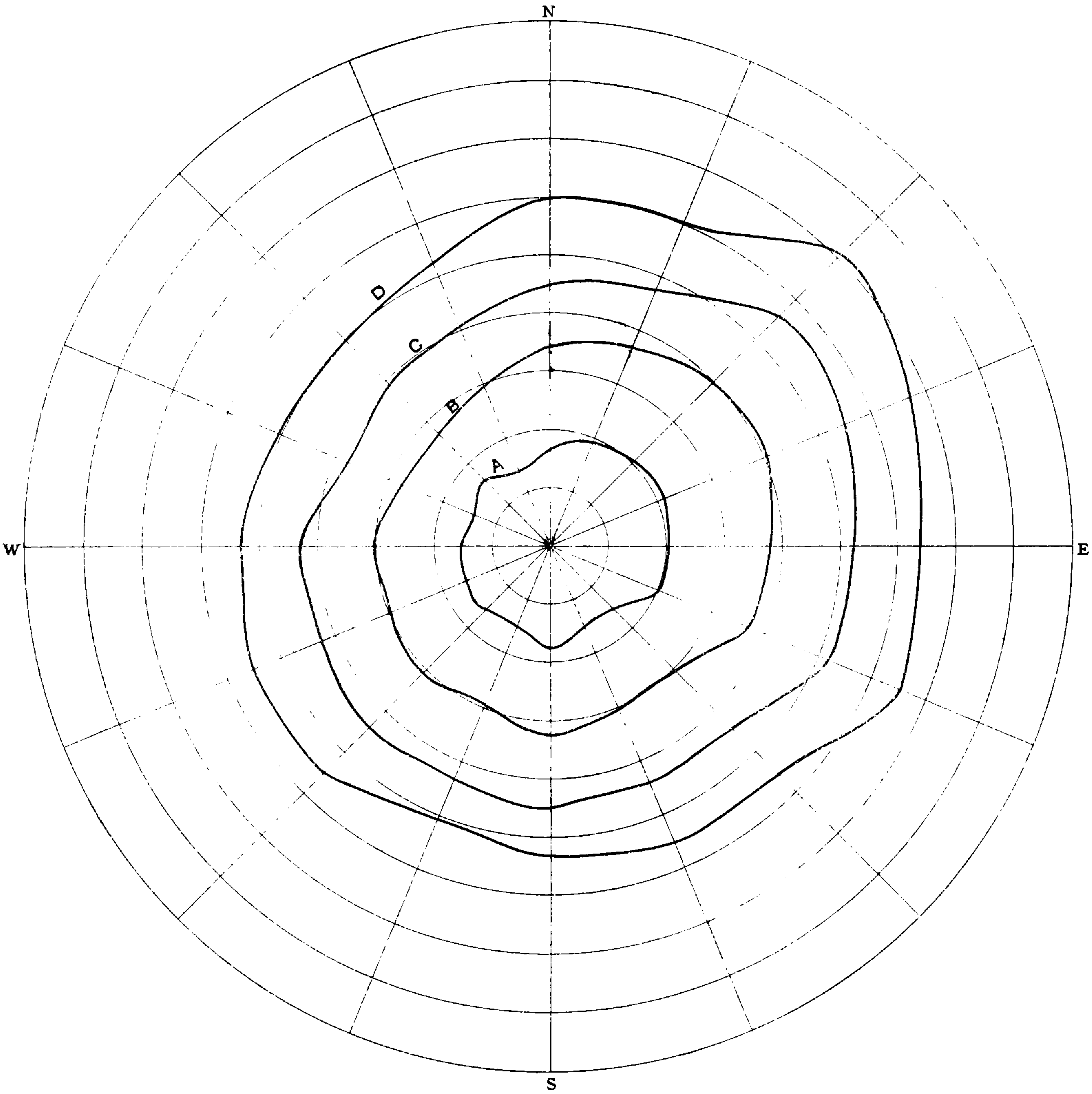
DUNGENESS.
1901 — 1912.



The curves A, B, C and D show the relation between the observed winds in Beaufort numbers and the corresponding gradient winds of 5, 10, 15 and 20 metres per second respectively. The concentric circles represent consecutive Beaufort numbers from 1 to 9, the former being innermost.

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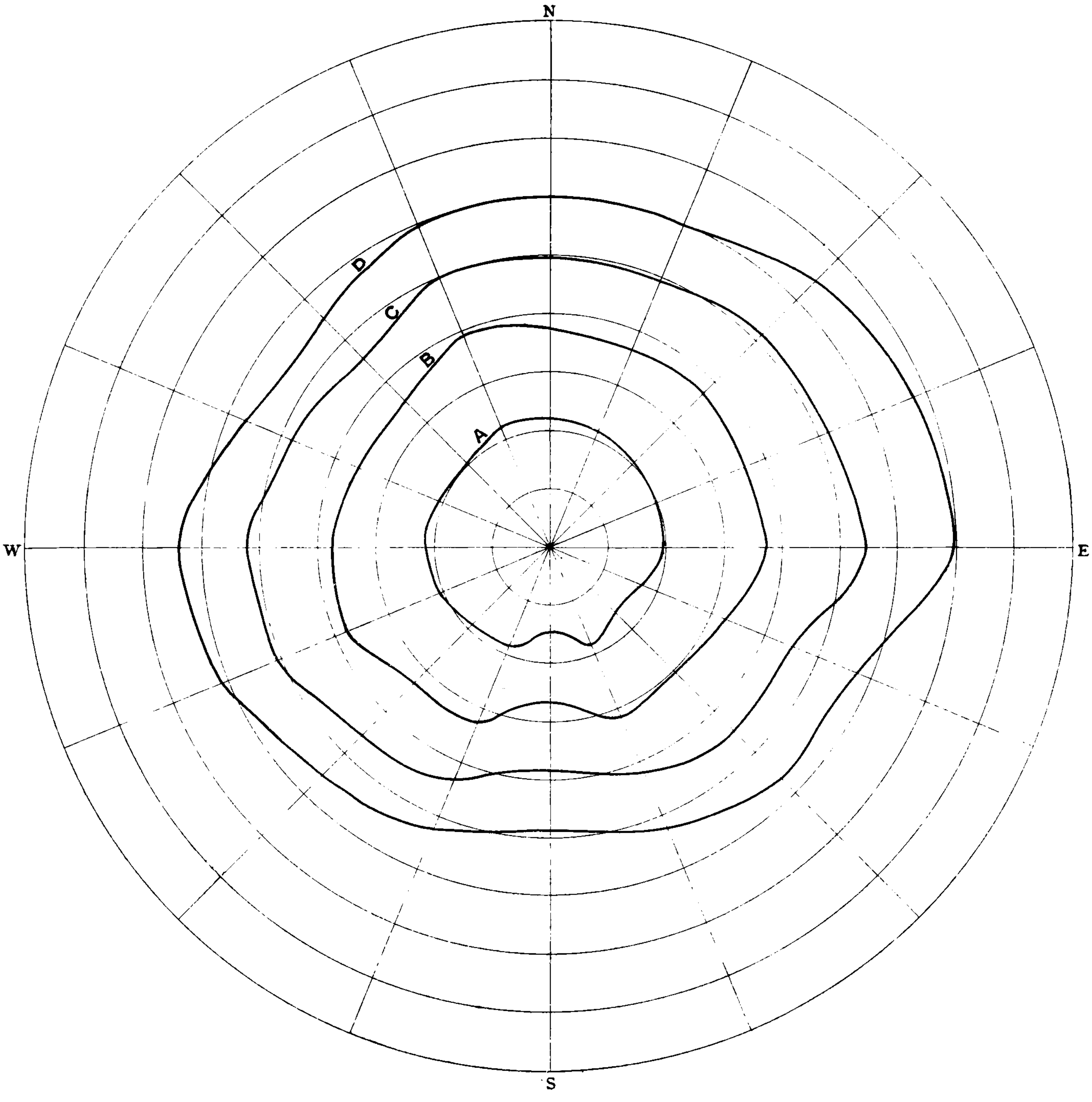
JERSEY,
1901–1912.



The curves A, B, C and D show the relation between the observed winds in Beaufort numbers and the corresponding gradient winds of 5, 10, 15 and 20 metres per second respectively. The concentric circles represent consecutive Beaufort numbers from 1 to 9, the former being innermost.

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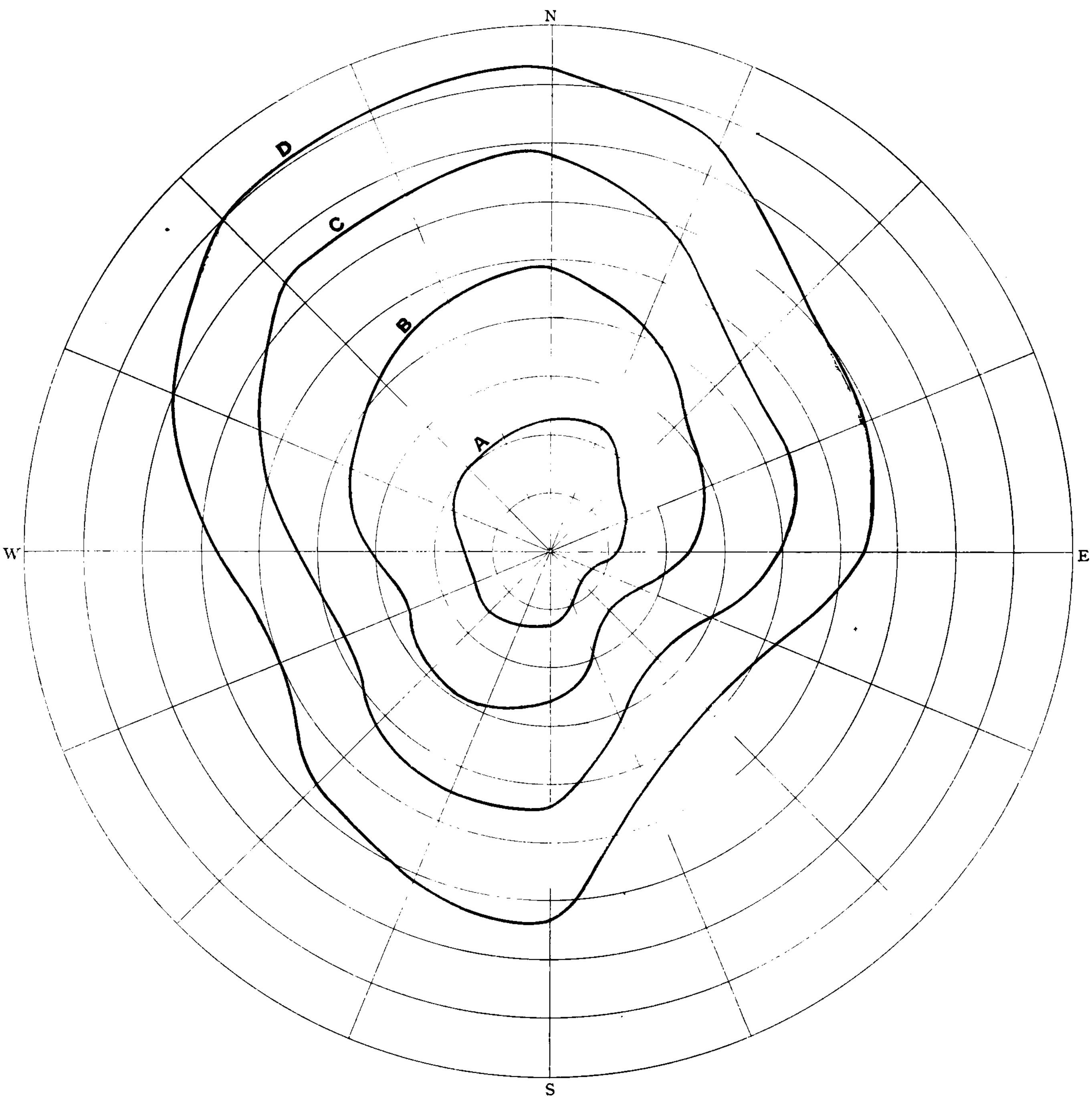
HOLYHEAD.
1901 — 1912.



The curves A, B, C and D show the relation between the observed winds in Beaufort numbers and the corresponding gradient winds of 5, 10, 15 and 20 metres per second respectively. The concentric circles represent consecutive Beaufort numbers from 1 to 9, the former being innermost.

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