FIG. 1.—THE BELL ROCK LIGHTHOUSE.
(THE ANEMOMETER MAST IS SEEN ON THE LEFT OF THE DOME.)

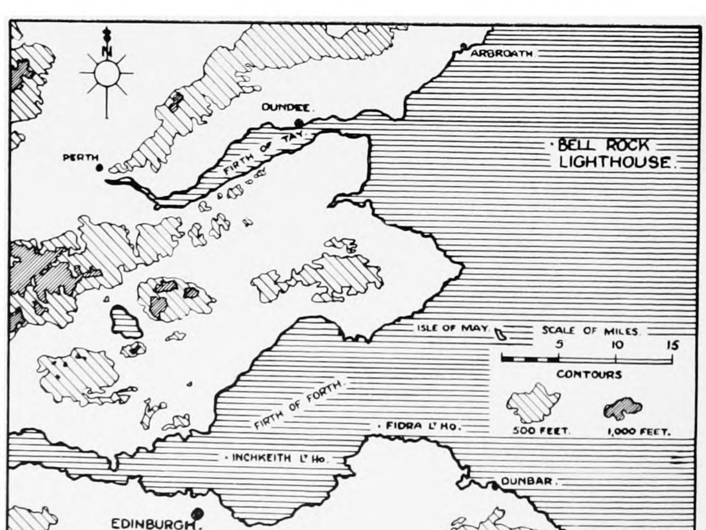

FIG. 2.—MAP SHOWING THE SITUATION OF THE BELL ROCK LIGHTHOUSE.

M.O. 356f. AIR MINISTRY

METEOROLOGICAL OFFICE

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WIND RECORDS FROM THE BELL ROCK LIGHTHOUSE

By A. H. R. GOLDIE, M.A., F.R.S.E.

WITH AN ACCOUNT OF EXPERIMENTS MADE BY THE AERODYNAMICS DEPARTMENT OF THE NATIONAL PHYSICAL LABORATORY

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WIND RECORDS FROM THE BELL ROCK LIGHTHOUSE

§ 1—INTRODUCTION

The need for having a well-exposed anemometer somewhere on the east coast of Scotland had been felt in the Meteorological Office for some years, and in 1927 a survey of possible sites was made by Lt.-Col. E. Gold and the present writer. It appeared that if only the engineering difficulties of erecting the instrument could be overcome the Bell Rock Lighthouse would provide an open sea exposure of quite unique character. The " Rock " strictly speaking covers an area of about six acres in extent and consists rather of a number of rocky ridges, none of which, even at low tide, emerges more than a few feet above the sea; at high tide the entire mass is submerged. The lighthouse was designed and built between the years 1808 and 1810 by Robert Stevenson and is a graceful structure, 100 feet high, built of freestone on a foundation of solid granite. The nearest coast is in the neighbourhood of Arbroath, 12 miles distant. The situation of Bell Rock is shewn in the map in Fig. 2 and a photograph of the lighthouse appears in Fig. 1.

In 1928 the Advisory Committee for the Meteorological Office, Edinburgh, proposed a research scheme which included the provision of anemographs at Bell Rock as well as at Butt of Lewis together with clerical assistance for the reduction of data. The scheme received official sanction. With the approval of the Commissioners of Northern Lights and the assistance of the Engineers' Department of the Northern Lighthouse Board, plans were then prepared for the erection of a pressure tube anemograph on the Bell Rock Lighthouse. The provision of access to the vane and of accommodation for the recording mechanism furnished difficult problems which were, however, solved by Mr. D. A. Stevenson, M.Inst.C.E., Chief Engineer to the Board, who also made the arrangements for the erection of the mast. The problems connected with the recording mechanism were tackled by Mr. E. G. Bilham and the staff of the Instruments Division of the Meteorological Office. On August 19, 1929, Mr. Bilham, with Mr. S. F. Stanley of the Instruments Division, and Mr. McLeod, the engineer who had actually erected the mast, proceeded to the Bell Rock to make the final connexions and adjustments. On the following day the recording commenced and since then the instrument, though in some respects of unique design, has continued to function in a remarkably consistent and successful manner. The instrument is in the care of the Lightkeepers.

The following description of the instrument was given by Mr. Bilham in the *Meteorological Magazine*, September, 1929 :—

" The photograph . . . (Fig. 1) was taken at low tide from the south-south-west extremity of the Rock. The mast is seen projecting above the dome on the left hand (i.e. north-west) side. Unfortunately, the vane does not show up well, and, on account of the foreshortening due to its high angular elevation, the mast appears shorter than it actually is. The vane is about 10 feet higher than the wind vane on the top of the dome and is supported on a mast made of 3-inch galvanised steam-piping bolted to the upper gallery. The spindle operating the direction recorder passes down the mast and then through a short length of smaller bore tubing into the top of a hollow casting, inside which it is connected through a universal coupling to a gear wheel about 4 inches in diameter. This gear wheel rests on a single steel ball at the bottom of a long bearing and transmits the movements of the vane to the recording mechanism.

"The gearing between the spindle from the vane and the direction recorder consists of three meshed brass wheels all in the same horizontal plane. The first, or driver, is attached to the spindle in the manner already described. The second is of 8 inches diameter and has a similar type of bearing. The third, which is identical in size with the driver, is coupled directly to the helix of the direction recorder. The need for this arrangement arose from the fact that the direction recorder could not be placed vertically under the vane. It was necessary to step across a horizontal distance of about 10 inches and gearing of some kind was, therefore, essential. The method actually adopted forms the simplest and least objectionable solution of the problem. Access to the instrument is obtained from the inside of the light-room by means of a door which, when closed, lies flush with and forms part of the wooden interior lining of the room.

"The only feature of the velocity recording arrangement calling for special mention is the fact that the pipes conveying the pressure and suction from the head to the recorder are of copper, 1-inch internal diameter, throughout. The head and vane are, of course, of the most recent pattern, incorporating the improvements mentioned on pp. 7–8 of the *Meteorological Magazine* for February, 1929. Access to the vane for cleaning and lubricating purposes is provided by means of an iron ladder, which can be seen in the photograph, inclined to the mast at an angle of about 45 degrees."

The head of the instrument is 130 feet above mean water level and its "effective height" for the purposes of the *Monthly Weather Report* is regarded as being 126 feet. With so remarkable an exposure it was felt that the records would always be regarded as having a particular value in problems of wind structure and might in future be used largely for such purpose. For the same reason it was considered that experiments should be conducted to see whether and to what extent, if any, the record obtained by the instrument was affected by the presence of the one and only obstruction in its neighbourhood, namely the dome of the lighthouse. To this end experiments on a scale model were carried out in 1931 at the National Physical Laboratory. An account of these experiments is given in § 2. It may be said that they disclose no evidence of any effects due to the presence of the dome. The head of the anemometer is about 14 feet higher than the top of the dome. The dome approximates to a smooth hemisphere of about 14 feet diameter, and according to the ordinary dynamical theory of the smooth flow of a fluid past such an obstruction, the effect at the distance of the head, even in the most unfavourable circumstances as to wind direction, ought not to exceed one per cent. on the wind speed record and should be quite negligible on the direction record. With turbulent flow the matter might be different and this was one of the questions the model experiments were intended to test.

In § 3 a short account is given of the salient features of the Bell Rock records in the matter of gustiness; records from Tiree are similarly analysed for purposes of comparison. In this section, the writer had the assistance of Mr. C. J. Boyden. § 4 deals with the longer period variations in wind and some typical examples of records are reproduced. The account is not intended to be more than preliminary and illustrative. § 5 contains some data regarding the diurnal variation of wind speed at Bell Rock, with comparative data, covering the same periods, at Tiree and Butt of Lewis; also a note on the annual variation.

§ 2—EXPERIMENTS AT THE NATIONAL PHYSICAL LABORATORY

Two series of experiments relating to the air flow over a model of the Bell Rock Lighthouse were made by the Aerodynamics Department at the National Physical Laboratory. The model was roughly made of a cardboard tube of 2·25 inches diameter and 6 inches in length (representing the upper part of the lighthouse to a scale of 1 : 135) and only those details of the structure which were likely to influence the flow markedly were included. Thus the lantern head, surmounted with the support for the vane, the upper and lower platforms, as well as the support for the Dines anemometer were reproduced to scale; while other parts such as railings, stays, and ladder were purposely omitted on the grounds of being too small to disturb the flow in the neighbourhood of the anemometer.

In the first series the model was attached to the floor of the 1-foot wind tunnel, with the anemometer mast on the leeward side, corresponding with the position where the anemometer in practice would be most exposed to the influence of the disturbances arising from the structure. Smoke used to render the flow visible was conveniently generated from a few drops of titanium tetrachloride spread over the surface of the model; and was illuminated for photographic purposes by an electric spark between two magnesium points placed on the far side of the model. The camera was situated on the near side and focussed on the median plane; hence the photographs obtained exhibit the flow conditions in this neighbourhood during the interval determined by the spark, probably about 1/100,000 second. "Over the range of speeds covered by the experiments, despite changes in detail of the flow structure, there is no sign of a marked alteration in the position of the boundary defining the upper limit of the disturbed region. Hence, if the flow past the model represents adequately the principal features of the flow in the vicinity of the lighthouse—and there is some evidence in support of this contention, based on a comparison of the flow conditions over a small-scale model and over a full-scale ship—it is reasonable to infer from the positions of the disturbed regions in the photographs that the Dines anemometer is well outside the disturbances due to the lighthouse even if it were possible for the wind to be inclined, on the average, at 20° upwards." The range of speeds was however only from 1·8 to 6·6 ft./sec., and as the technique adopted did not permit of a much larger range it was decided to perform a second series of experiments by different methods. The report on these further experiments is given in full below.

Regarding the recommendation in the last paragraph it has to be remarked that the possibility of conducting full scale experiments was explored. The dangers of the reef are such, however, that the discharge of smoke from a vessel to windward of the reef in strong winds would be attended by considerable risks. Also, the vessel in any case could scarcely approach sufficiently near for the lighthouse to be enveloped in a cloud of smoke suitable for photography. The matter of securing a satisfactory series of photographs even from aircraft also presents difficulties.

In the wind records there have been a few cases where there is some suggestion of instability of air flow. These cases have mostly been with winds from SSW. or SW. and with speeds below 20 m.p.h. and have mostly occurred within periods of otherwise very smooth flow. The effect is a marked broadening of the direction trace for perhaps 15 minutes and a reduction of mean wind speed accompanied also by greater gustiness. The anemogram of Fig. 23, for short periods after 18h. 30m. and 21h., shows effects which are probably, in part, of this nature. In this case however, the mean speed was fairly high. The cases have been too infrequent and too transitory for any effect to come out in the statistics.

The anemometer is situated at the north-west side of the dome; at low water the greater part of the uncovered reef lies to south-south-west of the tower and at half tide the whole reef is submerged. Normally at low tide a stretch of 350–400 feet of rock is uncovered; but a much greater stretch, over 1,000 feet long extending in this direction, consists of reefs "seen partially at low water of spring tides." Certainly it is in the south-south-west direction that the character of the surface is different from the character in other directions. Also, the cases seem to have been rather more frequent near times of low water. On the other hand, even with all conditions apparently favourable, the effects have mostly not been in evidence.

Report by the Aerodynamics Department of the National Physical Laboratory on Further Wind Tunnel Experiments Conducted with a Model of the Bell Rock Lighthouse.

The photographs appended at the end of the previous report (not reproduced in this memoir) on wind tunnel experiments clearly indicated that the eddying wake, produced by the model, was confined to a region lying below the top of the sphere and extending downstream. At the time of the experiments, the technique for rendering the flow visible restricted the observations to speeds below 10 feet per second.

But even though the experiments were conducted with a small model and at low speeds, it was thought reasonable, in view of past experience, that the conclusions drawn from the results would also apply to the conditions of flow over the dome of the lighthouse.

The results of more recent experiments made with a similar model, but at higher wind speeds than those formerly attainable, and with new methods for detecting the extent of the disturbed region of flow, furnish further information on the subject ; they also lend support to the views already expressed. While descriptions of the methods employed are reserved until later, for convenience, they are classified here under the following headings :

(i) Photographic methods of recording flow :
  (a) with the aid of smoke ;
  (b) with the aid of hot air.

(ii) Hot wire anemometer method of recording speed variations.

Methods (i)a and (i)b were similar in principle in so far that the air flow was rendered visible, in the former by the introduction of smoke into the current, and in the latter by means of hot air ; and the flow pattern photographically recorded either instantaneously or by time exposure. In the experiments grouped under (i)a, the smoke was introduced some distance upstream of the model in a manner to cause the minimum of disturbance in the general flow. The smoke stream was easily visible in a beam of light, when viewed at an angle. It was found, however, that the source of illumination had to be in a certain position in relation to the model before the intensity of the light, reflected from the smoke into the camera, reached a maximum ; and that only with the source in this position could satisfactory photographs be secured. By the use of a grid of fine wires electrically heated instead of the tube previously used for injecting the smoke into the stream, it was possible, in the second method, to use thin layers of air, heated by contact with the wires, for disclosing the flow conditions. When shadows of the hot filaments were illuminated by a point source and projected on a screen, they appeared as thin, dark bands, clearly visible for a length of several inches against a light background. Immediately above the top of the model the shadowgraphs of the filaments appeared continuous ; and no signs of dispersion were evident to indicate the presence of eddying motion. A similar conclusion was also drawn from the results of experiments made by the third method, in which continuous records of speed were obtained with a hot-wire anemometer traversed along lines in the wake, normal to the general wind direction. From the recorded speed fluctuations the boundary of the eddying wake was accurately located ; and on a comparison being made was found to coincide approximately with the limit reached by the smoke in the tests of the earlier report.

Tests with smoke introduced upstream of the model.—Smoke is used in two ways to indicate the air flow pattern near a model ; in one, it is introduced into the boundary layer for the purpose of disclosing the eddying motion originating there ; in the other, it is injected some distance upstream of the model and in the course of its passage reveals the stream lines in the region of steady flow, and, in certain circumstances, the boundary separating the two states of motion. The first method has already been described with special reference to some tests made at speeds below 10 feet per second ; the second method can be employed at higher wind speeds, provided certain precautions are taken to ensure the smoke remaining visible over a reasonable distance, and a special system of illumination adopted for photographically recording the lines of flow. To this end it is necessary to avoid undue interference by injecting the smoke into the air current through a small pipe, the size of which is determined by the needs of the supply, which must be at such a rate that the losses caused through diffusion do not seriously impair the visibility of the smoke stream. Experience shows that the smallest pipe that can be used for chemical smoke, without becoming blocked too quickly, has an internal diameter of 0·125 inch. But though the " critical speed " for a pipe of this diameter is as high as 34 feet per second, the eddies created in the wake cause the smoke jet to be turbulent at lower speeds. There is thus some danger that the appearance of the jet may create a false impression of the nature of the flow it is intended to reveal. To avoid this it is therefore necessary to compare the results of experiments made with, and without, the model.

In the experiments on the new model, smoke was generated by forcing a current of air, delivered from a fan, over the surface of titanium tetrachloride contained in a Woulff's bottle. The smoke mixture produced by the chemical reaction between the salt and the atmospheric moisture was thence led to a small nozzle in the wind tunnel, about 4 inches forward of the model, and projected as a jet in a downstream direction. Instantaneous photographs of the jet were taken with the aid of an electric spark, produced by the discharge of a condenser between two magnesium points. After a number of trials, the best position for the spark source was found to be about 5 inches on the far side of the model and about 3 inches below the level of the smoke. The model thus served as a screen to shield the camera from the direct rays emitted by the spark, without obstructing the light reflected downwards from the smoke ; which could itself be focussed on the camera screen, situated on the near side of the wind tunnel, about 2 feet from the model. As the outline of the model formed by the oblique rays was too faint to register the shape, the plan ultimately adopted consisted of photographing the model in still air, by means of a lamp held in front ; afterwards superimposing a spark photograph of the smoke on the same negative. For other records, wherein some advantage was gained by masking the turbulent nature of the smoke stream, time exposures were used varying between 5 and 10 seconds. In such cases the same procedure of double exposure was followed as formerly, except that the spark was replaced by a small flash lamp.

Photographs obtained at wind speeds ranging from 10 to 80 feet per second are reproduced in Figs. 3–7. Figs. 3 and 4 show instantaneous records of the smoke taken in the unobstructed tunnel

INSTANTANEOUS PHOTOGRAPHS OF SMOKE STREAM IN THE WIND TUNNEL MAGNIFICATION RATIO 0·7

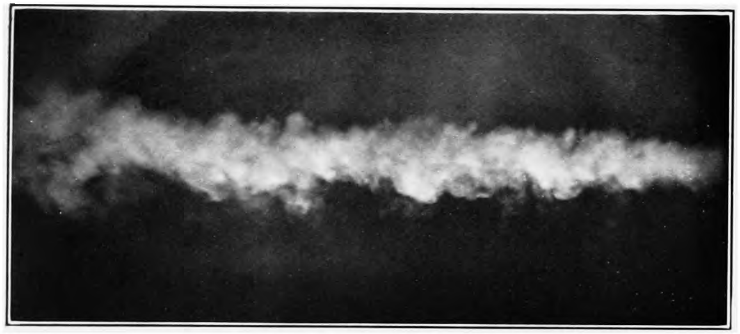

FIG. 3.—WIND SPEED 20 FT. PER SEC.

FIG. 4.—WIND SPEED 40 FT. PER SEC.

INSTANTANEOUS PHOTOGRAPHS OF THE SMOKE STREAM NEAR THE TOP OF MODEL. MAGNIFICATION RATIO 0·7

FIG. 5.—WIND SPEED 10 FT. PER SEC.

FIG. 6.—WIND SPEED 60 FT. PER SEC.

FIG. 7.—WIND SPEED 80 FT. PER SEC.

NOTE - DIRECTION OF FLOW IS FROM RIGHT TO LEFT.

TIME EXPOSURES OF THE SMOKE STREAM AT THE TOP OF THE MODEL. MAGNIFICATION RATIO 0·7

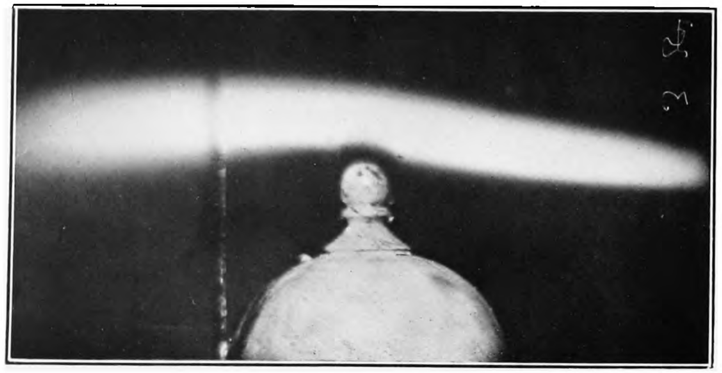

FIG. 8.—WIND SPEED 20 FT. PER SEC.

FIG. 9.—WIND SPEED 10 FT. PER SEC.

HOT AIR STREAMS FOR INDICATING THE NATURE OF THE AIR FLOW OVER THE TOP OF THE MODEL MAGNIFICATION RATIO 0·7

FIG. 10.—WIND SPEED 20 FT. PER SEC.

NOTE.—DIRECTION OF FLOW IS FROM RIGHT TO LEFT.

at speeds of 20 and 60 feet per second respectively; and, in addition to illustrating the turbulent nature of the smoke, they provide standards of comparison by which the disturbing influence of the model on the flow can be ascertained from Figs. 5–7. Such comparisons leave little doubt that the eddying wake in the rear of the model is confined to a region lying below the level of the stream of smoke. Perhaps a better idea of the average flow conditions during a period of about 8 seconds is conveyed by the photographs of Figs. 8 and 9, obtained by time exposures. These clearly indicate the upward inclination of the flow forward of the model, as well as the downward deflection which takes place on the leeward side. But the most noteworthy feature of the photographs is the absence of any marked dispersion of the smoke during the course of its progress, such as would have been evident had the smoke encountered the eddying wake.

*Hot air as a means of revealing air flow.**—An interesting variation of the previous method consists of the use of streams of hot air, produced by a grid of fine wires heated electrically to a temperature of about 500°C. The grid consists of a number of parallel wires stretched between two vertical supports at equal intervals of 0·5 inch; and when in use is held some distance upstream of the model, where it causes the minimum interference with the general flow. Each wire imparts heat energy to the air which makes contact with it; thus a number of thin streams of hot air are produced to be carried along by the air current. If the streams are illuminated by a point source placed on the far side, the light passing through the heated layers is refracted to a greater extent than that passing through the neighbouring layers. Consequently, shadowgraphs of the hot streams can be made clearly visible as dark filaments on a screen placed on the side opposite to the source. The contrast between the images formed in this manner and the light background is, however, generally so weak that the effective length of the filaments in the spark photographs are appreciably shorter than those observable on the screen. Fig. 10 serves to illustrate this point. Four of the six streams used in the experiments are here shown; and it is to be noted that the length of each filament does not exceed 1·6 inches whereas on the screen each image appeared continuous over at least twice this distance, in a manner consistent with the presence of stream-line flow immediately above the model.

Records of speed variations.—Undoubtedly the most convincing evidence relating to the present subject was provided by galvanometer records representing the speed variations at points lying in a number of transverse sections through the wake. Each record exhibited the changes occurring during an interval of 8 seconds, and was obtained with a platinum wire, 1 cm. in length and 0·002 mm. diameter, heated to a temperature of 100°C. in excess of the surrounding air. Due to the variable cooling of turbulent flow, the change of potential across the ends of the wire generated small out-of-balance currents in the circuit containing a sensitive string galvanometer. The movements of the string caused by the currents, after being suitably magnified, were registered on a falling plate, to provide a permanent record of the speed fluctuations, in view of the relationship existing between the current and the speed at any instant. It is necessary to add that such records were only faithful reproductions of the speed changes when the thermal lag of the wire was small; either because the changes occurred slowly, or because the "time constant" of the wire was small. Such conditions were not always fully observed; but, with the exception of the small and fast fluctuations, there is no doubt that the larger and more important disturbances were recorded with small loss of accuracy.

A typical set of records, obtained at a wind speed of 40 feet per second by traversing the wire along the line corresponding to the position occupied by the anemometer mast when on the leeward side, are given in Figs. 11–16. On inspection it is seen that along the line of exploration the nature and magnitude of the speed fluctuations indicate clearly the regions of steady and turbulent flow. Some difficulty is, however, experienced in determining from the records the upper boundary of the wake, since the position varies from time to time following an occasional deviation of an eddy to one side or other of its normal path: this is well illustrated in Fig. 13 by the relatively long periods of quiescence followed by the short and irregular periods indicative of disturbed flow. Figures in the table below, taken from the records, indicate the maximum recorded variations observed at various heights above and below the top of the model.

Height above the top of the sphere. (inches)	Maximum range of speed variations. (ft./sec.)
1·5	0·8
0·25	5·8
0	32
−0·13	40·4
−0·25	29
−0·5	23

It is clearly evident from the figures tabulated above that the free stream conditions are attained, at the section explored, near the horizontal tangent touching the top of the small sphere surmounting the dome of the model.

Visual observations of the current changes were also made with the wire supported at various positions in the wake; from these it was established that the eddying wake (the boundary of which could be determined to within 0·25 inch) comprised the region lying below a plane passing through the top of the model and inclined downwards, as shown by the smoke stream in Figs. 8 and 9.

General conclusions and recommendations.—The results of the foregoing experiments described in the report are in general agreement in showing that, at normal speeds and under the steady conditions

* *Aeronautical Research Committee Reports and Memoranda*, No. 1349. On rendering air flow visible by means of hot wires. By H. C. H. Townend.

characteristic of wind tunnel flow, the disturbances produced by the lighthouse model are confined to the region lying below the top of the sphere and extending backwards from the model. There are reasons, based on experience acquired from the study of flow problems of a somewhat similar kind to that discussed, for inferring that the conclusions drawn from the present series of experiments also apply to the flow over the actual lighthouse. But without full-scale experiments as a check some doubt must remain of the validity of this inference, especially in view of the higher Reynolds Numbers involved, and the disturbed conditions prevailing in natural winds. Much useful information concerning the problem, it is suggested, could be obtained from a few simple, full-scale, smoke experiments on the lines of those described in the earlier report.

§ 3—GUSTINESS OF WIND

Having regard to the considerable height of the Bell Rock instrument and the unique exposure, it was considered important in the discussion of its records to have the data of some other instrument for purposes of comparison. The Tiree anemograph was selected. Like the Bell Rock instrument it has one inch tubing. The head is 75 feet above M.S.L., 50 feet above the ground and 41 feet above the roof of the small hut housing the recording mechanism. Its "effective height" is regarded as being 42 feet. The site is on a slight ridge on open ground separated from the shore by low sand dunes some 10 to 15 feet high and rough sea grass, and only some 350 yards from the sea. Fig. 17 gives an indication of the surroundings.

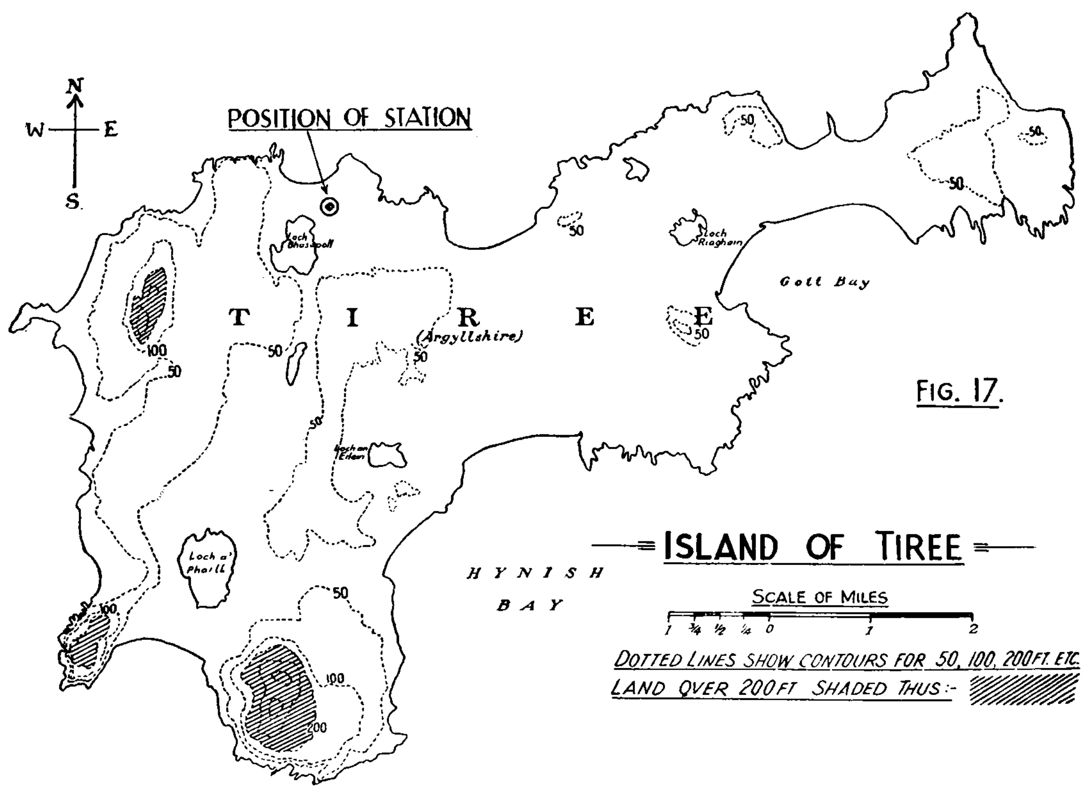

FIG. 17.

Winds from the north-east quadrant cross on the average about half a mile of dune land, winds from the north-west quadrant on the average about ¾ mile of similar land, winds from south-west about 3½ miles, including a small hill rising to 388 feet above M.S.L., and winds from south-east about 3 miles of almost flat land. The small hill to the south-west and other slight elevations in that quadrant may introduce slight effects, but the exposure generally may be taken as approximating closely to that of a small flat island, with the anemometer near the north shore.

Anemograms for three summer months and three winter months were examined for Bell Rock and Tiree, the actual months being December 1929–February 1930 and June 1930–August 1930 for Bell Rock; December 1930–February 1931 and

HOT WIRE ANEMOMETER RECORDS OF SPEED AT POINTS ON THE LINE OF EXPLORATION. AVERAGE WIND SPEED 40 FT. PER SECOND.

FIG. 11. HEIGHT 1·5 IN. ABOVE THE TOP OF THE SPHERE.

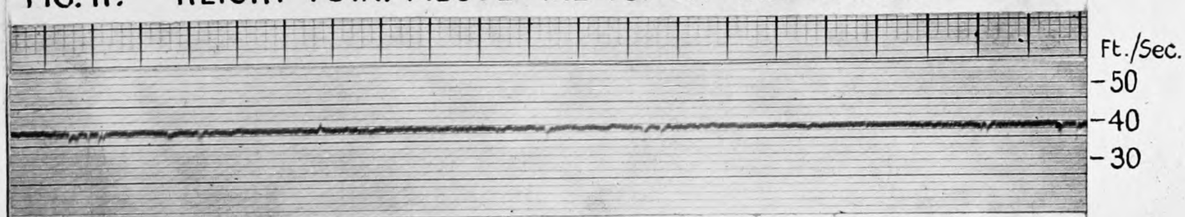

FIG. 12. HEIGHT 0·25 IN. ABOVE THE TOP OF THE SPHERE.

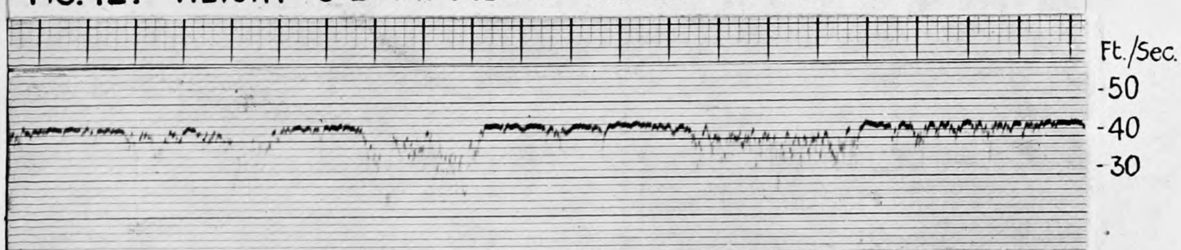

FIG. 13. POSITION AT THE SAME LEVEL AS THE TOP OF THE SPHERE

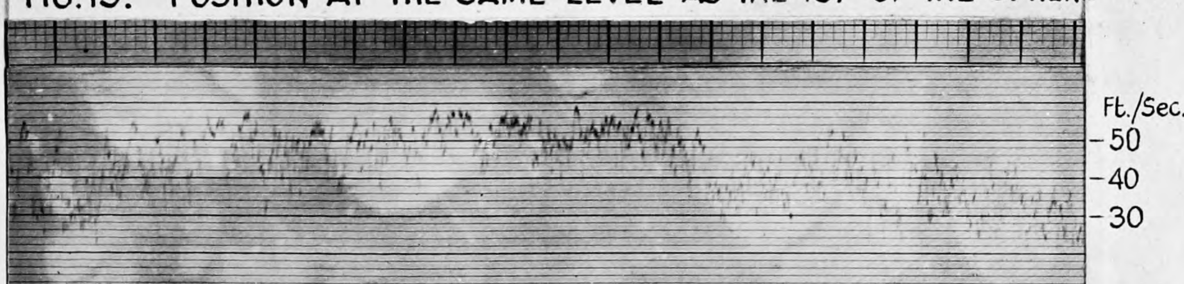

FIG. 14. HEIGHT 0·13 IN. BELOW THE TOP OF THE SPHERE.

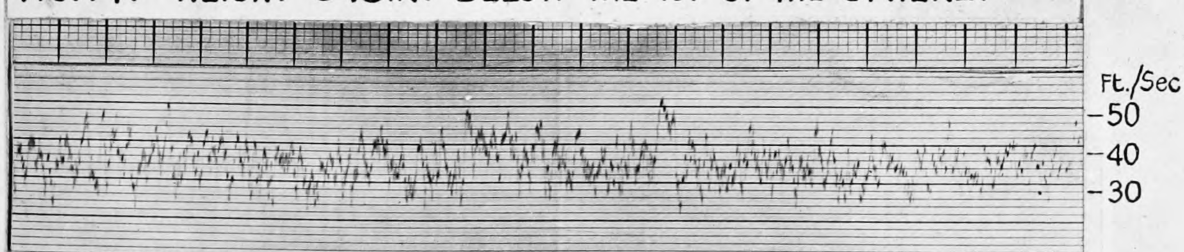

FIG. 15. HEIGHT 0·25 IN. BELOW THE TOP OF THE SPHERE.

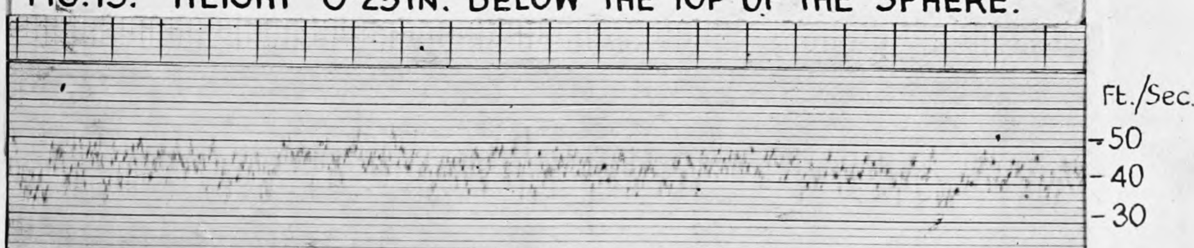

FIG. 16. HEIGHT 0·5 BELOW THE TOP OF THE SPHERE.

June 1931–August 1931 for Tiree. The total number of hours read in the first instance were 1,994, 1,769, 1,774 and 1,239 respectively. For each hour (centred at exact hours) were measured (*a*) the mean velocity of the wind, (*b*) the mean gustiness of velocity and, (*c*) the range of wind direction. The mean gustiness was measured as follows. In the velocity trace a line was taken between the upper edge of the darkest part of the trace and the upper edge of the trace (excluding any isolated strong gusts) ; and a similar line was taken between the lower edge of the darkest part of the trace and the lower edge of the trace. The difference in the velocities represented by these two lines was measured, and was taken to represent the mean gustiness, represented by G in the tables and diagrams below. The ratio of G to the mean wind velocity V for the same hour, here called the " gustiness factor," is represented by G/V in the tables and diagrams below. The range of wind direction was measured from the direction trace in precisely the same manner as the gustiness was measured from the velocity trace. It is represented by θ in the tables and diagrams below.

If the instantaneous wind be represented by $V + u$ along the mean wind direction and v transverse to the mean wind, then, approximately,

$$\bar{u} = \tfrac{1}{2} G \qquad\qquad \bar{v} = \tfrac{1}{2} V \theta$$

Thus $V\ \theta$ may be regarded as a measure of the transverse gustiness, comparable with the ordinary gustiness G. In practice it is perhaps more convenient to compare G/V and θ.

Cases of sudden change of velocity or direction within the hour were rejected. The results were classified in the four direction groups, N–W, W–S, S–E and E–N, and were also divided into groups of velocities, 0–3, 3–5, 5–10, 10–15, 15–20 and over 20 m/sec. The numbers of observations in the two last groups, in the case of Tiree, were small. With a view to making the averages more reliable, the additional cases of winds exceeding 15 m/sec. were therefore extracted from the records for the remaining summers and winters of the years 1926–31. By this means the numbers of cases available finally for analysis became as under.

Mean Hourly Speed m/sec.		0–3	3–5	5–10	10–15	15–20	>20	Total
Bell Rock ..	Summer	146	258	917	403	45	—	1,769
	Winter	55	150	623	695	343	128	1,994
Tiree ..	Summer	237	304	589	109	24	—	1,263
	Winter	99	267	779	476	477	87	2,185

The results of the classification are set out in Table I and in part graphically in Figs. 18 and 19. In both cases the gustiness factor shows considerable variation with wind speed, but for the moment we may set that aside and compare the mean values with those for other stations. At Tiree the mean gustiness factors at 5, 10 and 20 m/sec. are respectively ·40, .42 and ·46 ; at Bell Rock the corresponding values are ·17, ·20 and ·28. Sir Napier Shaw has remarked (1)* that the most gusty exposure for Meteorological Office stations with tube anemographs is that at Dyce, Aberdeenshire, where the mast of the instrument projects fifteen feet above surrounding tree tops ; the mean coefficient of gustiness in this case is 1·3. The most openly exposed stations in the British Isles show mean gustiness factors of ·3, but in the majority of cases quoted by Sir Napier Shaw the factor is considerably higher. The factors for Bell Rock are thus lower, in the mean, than any others determined so far.

* The numbers in brackets refer to the list of references on p. 22.

TABLE I—RELATION OF GUSTINESS TO WIND SPEED AND DIRECTION

			Mean Values of $\frac{G}{V}$						Mean Values of θ (expressed in circular measure).					
		Speed m/sec.	0–3	3–5	5–10	10–15	15–20	20–25	0–3	3–5	5–10	10–15	15–20	20–25
Bell Rock	Winter	NW Winds	·213	·185	·201	·246	·264				·082	·157	·185	·214
		SW ,,	·240	·209	·214	·225	·268	·297			·105	·152	·197	·260
		SE ,,	·194	·190	·197	·220	·264	·306			·094	·146	·204	·250
		NE ,,	·155	·158	·177	·208	·230				·052	·129	·192	
		All Directions	·22	·195	·205	·225	·265	·298	·012	·035	·093	·148	·199	·253
	Summer	NW Winds	·085	·146	·175	·209	·273				·113	·152	·220	
		SW ,,	·141	·106	·138	·187					·096	·148		
		SE ,,	·137	·136	·162	·191	·249				·091	·146	·209	
		NE ,,	·176	·129	·175	·201					·098	·153		
		All Directions	·139	·125	·155	·195	·262		·031	·051	·098	·150	·214	
Tiree	Winter	NW Winds	·305	·313	·384	·405	·460				·361	·398	·476	
		SW ,,	·235	·258	·365	·385	·478				·335	·396	·458	
		SE ,,	·279	·264	·341	·348	·420				·352	·389	·450	
		NE ,,	·341	·300	·378	·379	·356				·289	·340	·602	
		All Directions	·285	·282	·369	·383	·455	·473	·100	·209	·347	·392	·462	·553
	Summer	NW Winds	·68	·45	·452	·492					·412	·534		
		SW ,,	·65	·48	·525	·448					·400	·464		
		SE ,,	·52	·43	·515	·499					·437	·533		
		NE ,,	·55	·40	·490	·451					·389	·442		
		All Directions	·617	·447	·506	·464	·435		·129	·275	·415	·482	·490	

It was thought that it would be of interest to examine whether the factor at the very gusty exposure at Dyce showed any variation with wind speed. Mr. M. T. Spence, who had once examined the Dyce records in detail, made available some measurements from which the following mean factors were deduced :—

Speed m/sec.	0–3	3–5	5–10	>10	All Speeds Mean
Summer	1·55	1·50	1·56	—	1·51
Winter	1·24	1·32 (3–5 and 5–10 combined)		1·28	1·31

There is thus at Dyce practically no variation of the factor with wind speed, but an appreciable variation with season. There is also a variation between day and night as shown in the following table :

Mean factor Summer day ..	1·53	Mean factor Winter day ..	1·35
,, ,, ,, night ..	1·47	,, ,, ,, night ..	1·29

Very markedly at Tiree and quite distinctly though less markedly at Bell Rock, the variation of gustiness with season is greater than the variation with wind direction ; also the seasonal effects at the two stations run in opposite directions. With winds up to 15 m/sec., at any rate, the winter gustiness factor is higher than the summer one at Bell Rock, whereas the reverse is very definitely shown in the Tiree curves. Apparently at Tiree the seasonal variation of turbulence is that of a land station with its higher lapse rate of temperature and higher turbulence in the lower layers of atmosphere in summer. Even with NE.ly and NW.ly winds which have, in the mean, crossed only half and three quarters of a mile of land respectively after leaving the sea, this seems to be the case ; further, of the different directions, the NW. winds show the least and SE. the winds show the greatest seasonal variation. At

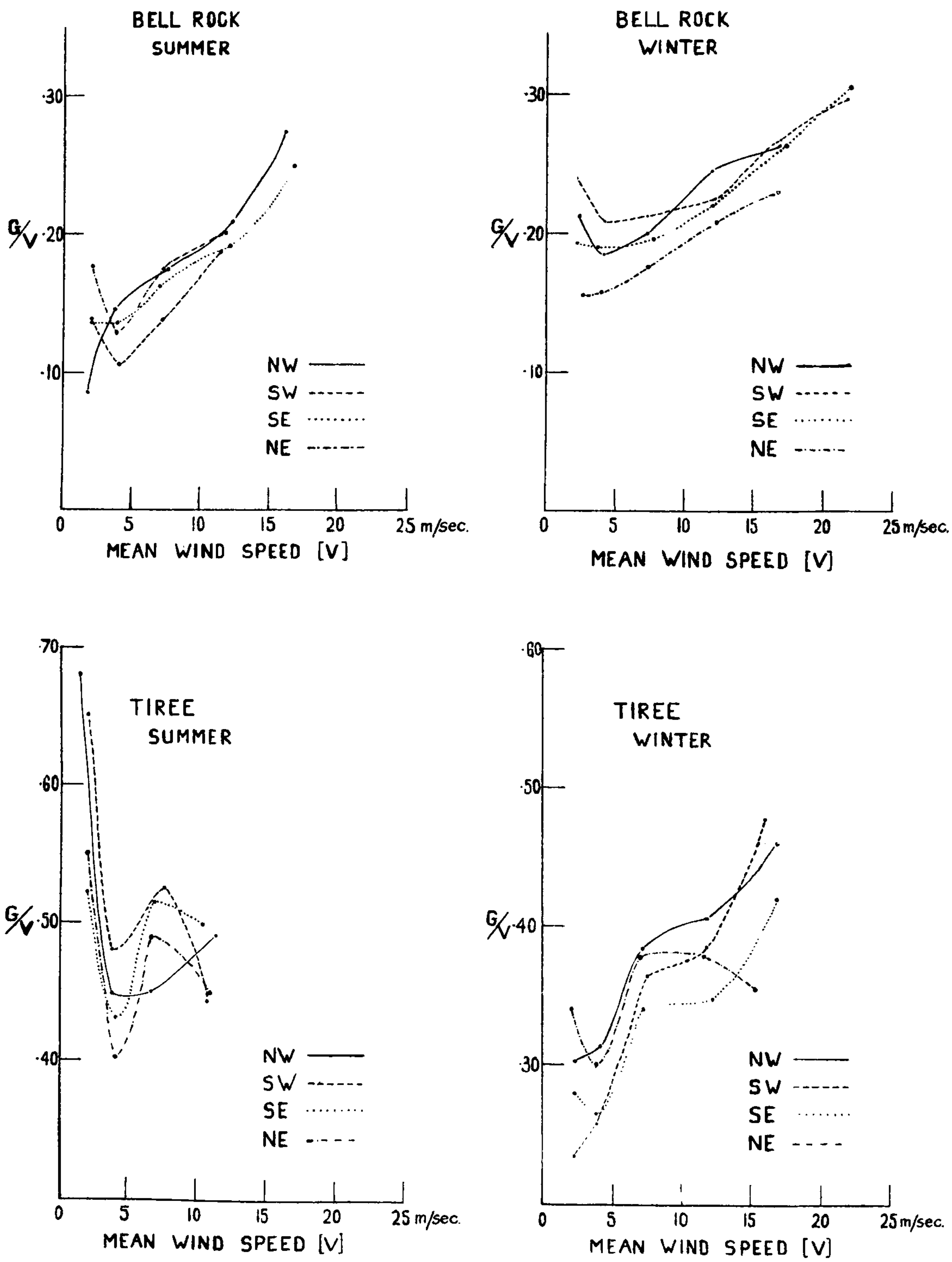

FIG. 18. RELATION OF GUSTINESS TO WIND SPEED AND DIRECTION

To Face p. 11

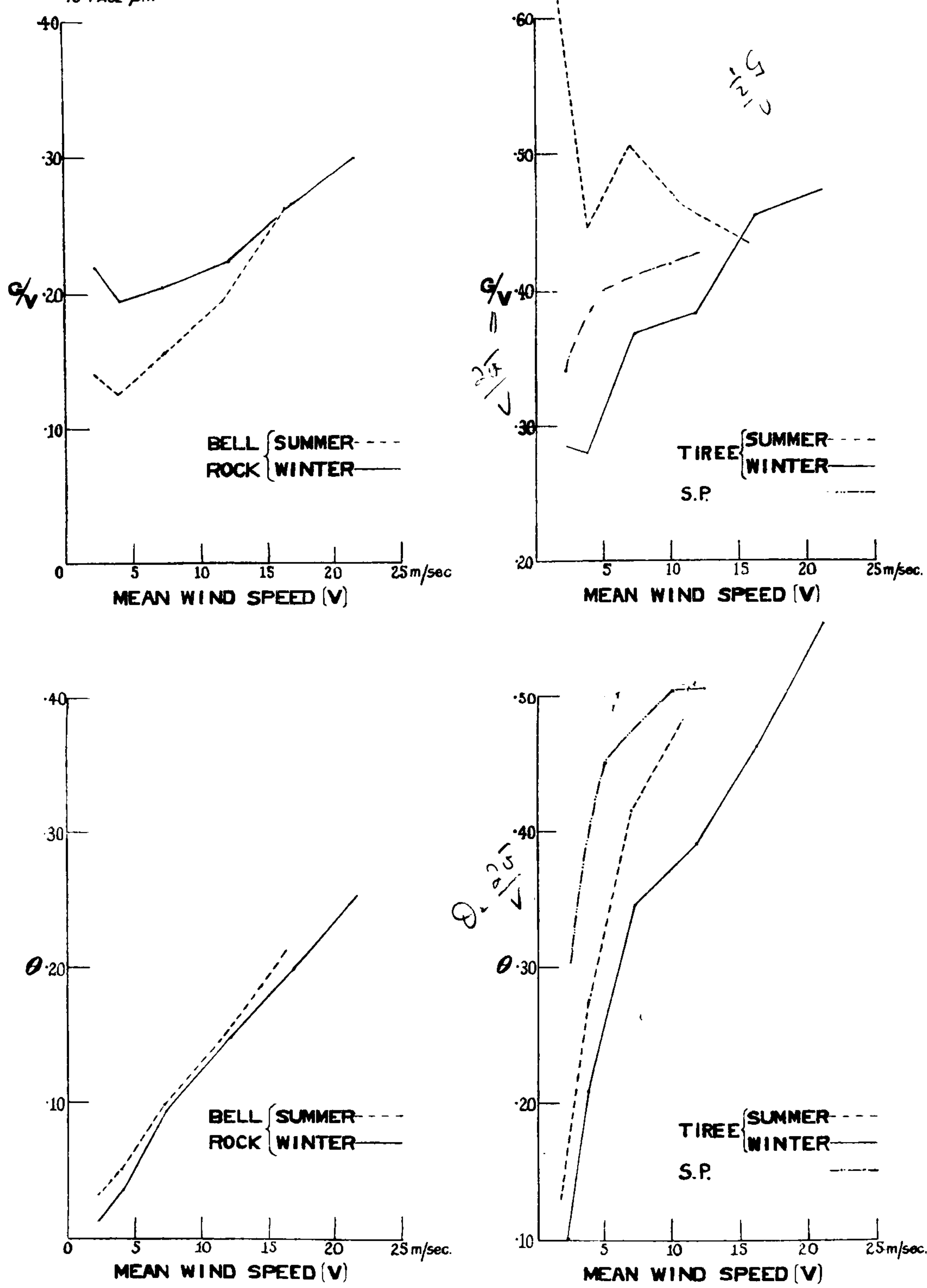

FIG. 19. RELATION OF GUSTINESS TO WIND SPEED

both places it would seem that seasonal effects are wiped out when wind speed rises to 15–20 m/sec. A mean gustiness factor of ·26 then applies at Bell Rock and a mean factor of ·45 at Tiree. At 20–25 m/sec. the factors become ·30 and ·47. Thus the gustiness at the Bell Rock anemograph is, for high speeds, of the order of 60 per cent. of the gustiness at Tiree.

If we can assume that at these high speeds convectional eddies contribute relatively little and gustiness represents almost entirely a wave effect between the wind and water surface, then in theory (2) the gustiness factors at the two heights h_1 and h_2 should be in the ratio

$$\frac{\exp(-2\pi h_1/\lambda)}{\exp(-2\pi h_2/\lambda)}$$

The values of h_1 and h_2 regarded as " effective heights above water " may perhaps be taken as approximately 130 feet and 65 feet. Thus we should have

$$\frac{\exp(-2\pi \times 130/\lambda)}{\exp(-2\pi \times 65/\lambda)} = \frac{\cdot 30}{\cdot 47} \quad \text{for wind speeds of 20–25 m/sec.}$$

$$\& \quad = \frac{\cdot 26}{\cdot 45} \quad \text{for wind speeds of 15–20 m/sec.}$$

The values of λ required to correspond are respectively 880 feet and 780 feet, which are of the correct order for sea waves with winds of such speeds. In the cases of lower winds however we find values of λ which are too high. Thus for the groups 10–15 m/sec., 5–10 m/sec., and 0–3 m/sec. we find the values of 580, 460 and 440 feet respectively for λ. At the lower wind speeds purely convectional effects presumably contribute very largely to the gustiness and determine the magnitude of the gustiness factor.

Reference to Table I indicates that in the case of transverse gustiness, $V\theta$, the Bell Rock value, at high speeds, is only 44 per cent. of the Tiree value ; at low speeds the difference is more marked, the figure being only some 15 per cent. It would therefore appear that the transverse gustiness falls off with height to a greater extent than does the gustiness in the direction of the wind.

At Bell Rock the gustiness G is greater in winter than in summer (Figs. 18, 19), this seasonal difference reaching its maximum for SW. winds and almost vanishing in the case of NE. winds. Almost certainly the seasonal differences again are dependent on the lapse rate of temperature in the lower layers. What the lapse rates are cannot be stated from direct information, but from the following indirect information something may be gleaned. The mean air temperatures of different winds at Edinburgh, the nearest station for which an analysis is available (3) are as under :—

	NE.	SE.	SW.	NW.
Summer ..	53·7	55·1	57·9	56·1
Winter ..	34·5	36·0	41·4	36·4

The mean water temperature in the Bell Rock region is, in summer, about 55°F, and in winter about 45°F. It seems likely therefore that in summer the air is usually rather warmer than the water over which it is passing and therefore that there is considerable stability locally in the surface layer of atmosphere. In winter the case must generally be reversed. So far as the lower speeds are concerned, the reversal of conditions emerges more or less markedly in the gustiness data for SW., NW. and SE. winds ; in the case of NE. winds there is little change of behaviour with season. It may be that with NE. winds the sea water in the Bell Rock region departs considerably from its mean temperature and in such a way as to tend to a more approximate equality of sea and air temperature. In winter at both stations W winds have higher gustiness than E. winds, but in summer little difference exists.

Numerous results at land exposures and mostly with lower wind speeds have led to the assumption that the gustiness factor is constant with velocity (cf. the Dyce records already mentioned), or becomes nearly constant after a certain speed is attained. Bell Rock, however, both in winter and in summer, and Tiree in winter, show for all directions gradual and more or less consistent increase of $\frac{G}{V}$ with increase of V (Figs 18 and 19). Tiree in winter shows a definite increase after passing through a minimum factor at about 4 m/sec. The Tiree summer curve for $\frac{G}{V}$, drawn from a smaller number of readings, also shows the minimum at 4 m/sec. and thereafter the factor lies within a small range.

In the case of θ, however, all the curves seem to rise continuously with increase of V For comparative purposes the results of Scrase (4) for Salisbury Plain are reproduced in Fig. 19 (curves S.P.). The results given here are not inconsistent with the curves produced by Scrase, though the increase of $\frac{G}{V}$ and θ with V is less evident on the curves in his memoir ; this is however partly because of the scale adopted and partly because his curves are not carried beyond a mean speed of about 12 m/sec. Moreover Scrase defined gustiness as the total width of the velocity trace, and θ as the total width of the direction trace (excluding isolated extreme gusts). The question of the real relationship of $\frac{G}{V}$ to V is considerably complicated by the possibility of instrumental effects. Arising in part out of the present discussion of records, experiments have recently been conducted at the National Physical Laboratory to compare the amplitudes of applied artificial wind fluctuations with the amplitudes as recorded by a Dines anemograph. The tests were made in the four feet wind channel and the applied wind fluctuations were measured by means of a hot-wire anemometer, the indications being recorded photographically. The experiments had the somewhat unexpected result of disclosing the existence of a natural period of the order of 3 to 5 seconds, connected apparently with the working of the apparatus as a whole and depending on certain conditions such as the length of the connecting pipes and the number of bends in the pipes. For example, with 30 feet of 1-inch piping (the anemographs at Bell Rock and Tiree have pipes about 33 feet and 45 feet respectively in length) and an average wind of about 10 m.p.h. the ratio of recorded to applied gustiness rises from rather less than 0·1 at a period of 2 seconds to a maximum of 1·36 at just over 7 seconds and thereafter approaches gradually to unity. At an average speed of some 25 m.p.h. the ratio rises from 0·3 at 2 seconds to a maximum of about 1·14 just under 5 seconds and thereafter gradually approaches unity.

In the Cardington Report on *The Structure of Wind over Level Country* (5) a number of anemograms of " ultra-quick runs " are reproduced. It was thought that an examination of these might give some information (*a*) as to the more usual periods of wind fluctuations and (*b*) as to whether any resonance effects emerged in practice. These runs relate mostly to winds of moderate mean speeds and they do not cover a great range of mean speed. By counting up the fluctuations on the speed traces, however, the conclusion was reached that the mean periods recorded range from about 3½ seconds for the highest speeds to 6 seconds for some of the lowest given. Thus the periods vary roughly inversely as the speeds. Some suspicion of artificial effect might be attached to this feature, but it is not unlikely to be real, at least over a land surface. At all events, if we suppose the fluctuations to relate to real eddies in the atmosphere and not to any instrumental peculiarity, the result suggests that the dimensions of the eddies are sensibly constant—156 feet in the mean—or in more detail the sizes vary from about 136 feet for winds between 13 and 20 m.p.h. to 176 feet for winds between 26 and 40 m.p.h. On the other hand the result ought perhaps to be interpreted as indicating that the instrument was particularly responsive to an eddy of period about 5 seconds or dimensions of the order of 150 feet.

It cannot be said, however, that signs of resonance on these speed traces are frequent. There are a few cases which might be due to this cause ; in all of these the speed lies between 12 and 24 m.p.h. and the period is very closely 5 seconds. In two other, but rather less likely, cases of winds of 30 and 40 m.p.h. respectively the period is slightly over $3\frac{1}{2}$ seconds.

It will thus be seen that the evidence of the National Physical Laboratory results and the Cardington results must cause doubt meantime as to the interpretation of the recorded relationship of G/V to V. The curves ought perhaps to be steeper or perhaps less steep. On the other hand no doubt of a similar character attaches to the relation of θ to V, which is indeed rather steeper than the relation shown between G/V and V. The reality of a slight minimum in the G/V factor at about 4 m/sec. is supported by an analysis, by the present writer, of airmeter observations made in northern France a number of years ago. In these there could scarcely have been an instrumental effect. The slight hump, however, between 5 and 10 m/sec. in the Tiree curves is suggestive of an instrumental peculiarity. In the absence of further information we can for the present only discuss the results as actually given by the anemograms.

Whereas G/V for Bell Rock was greater in winter than summer, θ is almost independent of season or direction, and the θ, V relationship is the linear one

$$\theta = \cdot 013V \ (\theta \text{ in radians, } V \text{ in m/sec.})$$

The Tiree curves are not so nearly linear. The Tiree summer curve, although obtained only from winds of speeds less than 15 m/sec., is of the same shape as the winter one, but in summer the values of θ are about 30 per cent. higher than those for equal winter winds. The linear part has a gradient of ·016. In both summer and winter θ is noticeably small at Tiree for NE. winds. The component of eddy velocity perpendicular to the direction of wind was taken as the mean value of $\frac{1}{2}\ V\theta$. This differs from the exact expression $V \sin \frac{\theta}{2}$ by less than 1 per cent. of V, which is considerably less than the ambiguities in measurement.

Taylor (6) found from records on Pyestock Chimney the relationship $\overline{u} = \overline{v}$ at 130 feet ($\overline{u} = \frac{1}{4}G, \overline{v} = \frac{1}{2}V\theta$), while Scrase (4) found this does not hold at lower heights. The Bell Rock and Tiree records for both winter and summer show an increase of $\frac{\overline{v}}{\overline{u}}$ with V, at least up to winds of medium speed. The values of $\frac{\overline{v}}{\overline{u}}$ are :—

	At 5 m/sec. Winter	At 5 m/sec. Summer	At 10 m/sec. Winter	At 10 m/sec. Summer	At 15 m/sec. Winter	At 15 m/sec. Summer
Bell Rock ..	·29	·48	·58	·73	·72	·81
Tiree	·77	·64	1·00	1·00	1·02	1·11

The mean curve for the two places and the two seasons taken together rises from a ratio of about ·2 at 2 m/sec. to unity at about 22 m/sec. In the case of the very low speeds there may be some instrumental effect, but it is likely that a correction on this account would increase rather than diminish the longitudinal gustiness at low speeds and thus it can scarcely be doubted that there is some real rise of ratio with wind speed, the ratio tending towards unity as speed rises. At a moderate speed in the case of Tiree unity is actually reached, but in the case of Bell Rock, with the instrument at a much greater height and over water, the ratio reached even at a speed of 22 m/sec. does not exceed ·85. It therefore appears that for light and moderate winds at Tiree and for all winds up to gale force at Bell Rock the condition of equipartition of eddying energy is not fulfilled. The undernoted table gives values of $\frac{\overline{v}}{\overline{u}}$ for the different directions for the means of cases of wind speed between 5 and 15 m/sec.

TABLE II—MEAN VALUES OF $\bar{v}/\bar{u}$ AND θ

Mean Values of $\bar{v}/\bar{u}$, wind speeds 5–15 m/sec.

	Summer					Winter				
	NE.	SE.	SW.	NW.	All Directions	NE.	SE.	SW.	NW.	All Directions
Tiree ..	·89	·96	·90	1·00	·93	·83	1·08	·98	·97	·97
Bell Rock	·67	·67	·76	·69	·70	·47	·58	·57	·54	·55

Mean Values of θ

	Summer					Winter				
	NE.	SE.	SW.	NW.	All Directions	NE.	SE.	SW.	NW.	All Directions
Tiree ..	23·8	27·7	24·8	27·1	25·7	18·2	21·2	22·0	21·8	21·2
Bell Rock	7·2	6·8	7·0	7·6	7·1	5·2	6·9	7·3	6·9	6·9

One feature, most notable in winter at both stations, is that NE. winds have a low transverse gustiness as compared with other winds. There is no equally conspicuous direction of maximum gustiness. As to seasonal effect it has to be noted that whilst values of G attain their maximum in summer at Tiree and in winter at Bell Rock, the values of $\bar{v}/\bar{u}$ behave in exactly the opposite way. Values of θ at Tiree are greater in summer than in winter; at Bell Rock the variation is small.

§ 4—WIND WAVES AND SQUALLS

The remarkably low gustiness at Bell Rock, especially in the case of light and moderate winds, permits the longer period variations of wind to be seen with great clearness. Thus waves (7) of periods of the order of some minutes up to one or two hours are much more frequently evident in the Bell Rock records than in the anemograms of most other stations. For example the Bell Rock and Tiree records of April 12–13, 1931 (a W. or NW. wind) both show long period fluctuations of wind speed, but these fluctuations are much more clearly indicated in the Bell Rock record where the range of ordinary gustiness is low (Figs. 21, 22). These waves may be more or less in evidence for periods of a week or more at a time at Bell Rock and it seems worth considering whether they are peculiar to certain types of meteorological conditions.

The period April 8–17, 1931, was one during which wind was mainly between S. and W. and the records were continually " wavy " or squally (*vide* Figs. 20 to 23). The upper air was relatively warm above 10,000 feet, and there was frequently either an inversion or a considerable region of small temperature gradient somewhere between 5,000 and 10,000 feet. (A very great change came with the strong N. wind on the 17th, when, according to an observation at Duxford, temperature in the 15–20,000 feet region came down by 15°–20°F. and in fact became about 30° colder than it had been a week earlier.) The approximate mean winds (m.p.h.) each day at Bell Rock (7–18h.), at 2–4,000 feet at Leuchars, Renfrew and Aberdeen, and the nearest measurements of 6–10,000 feet winds were as under :—

	Bell Rock	2–4,000 ft.	6–10,000 ft.
8th	SSE. 25	195°—26	230°—40
9th	W—S 12	299°—12	265°—22
10th	W—S 12	255°—22	265°—22
11th	SW 22	245°—27	260°—27
12th	W 20–25	— —	— —
13th	W 25	285°—29	325°—40
14th	W. 20 changing at 16h. 30m. to ESE. 10.	305°—24	325°—25
15th	SW. 12	290°—25	330°—43
16th	W 20	285°—23	315°—28
17th	W. by N. 20 at 7h., then squally N., then NNE. 45 after 16h.	330°—29	330°—32
Means excluding 12th and 17th.	228°—18	269°—23·5	290°—31

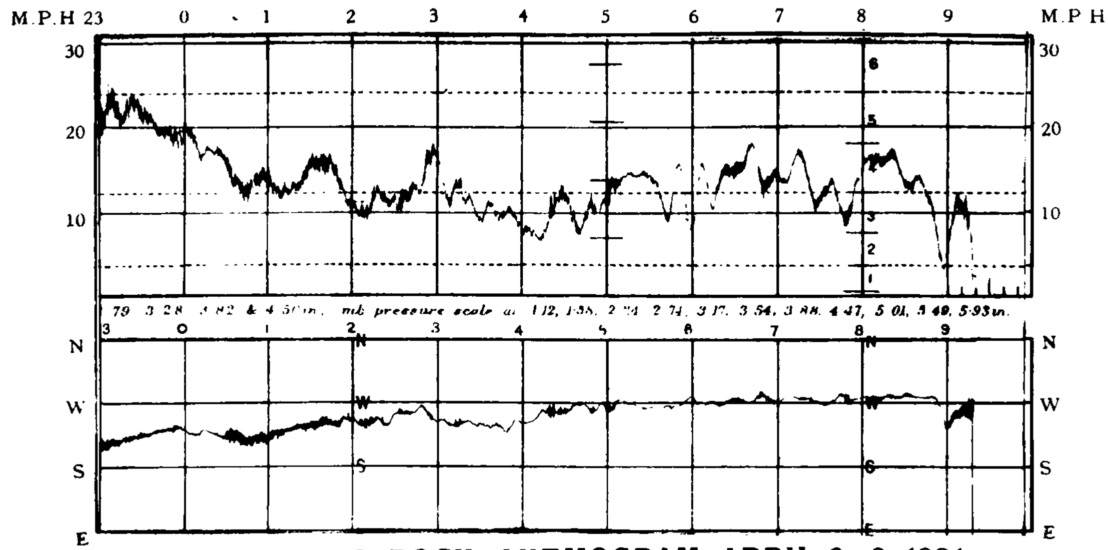

FIG. 20 BELL ROCK, ANEMOGRAM, APRIL 8 - 9, 1931

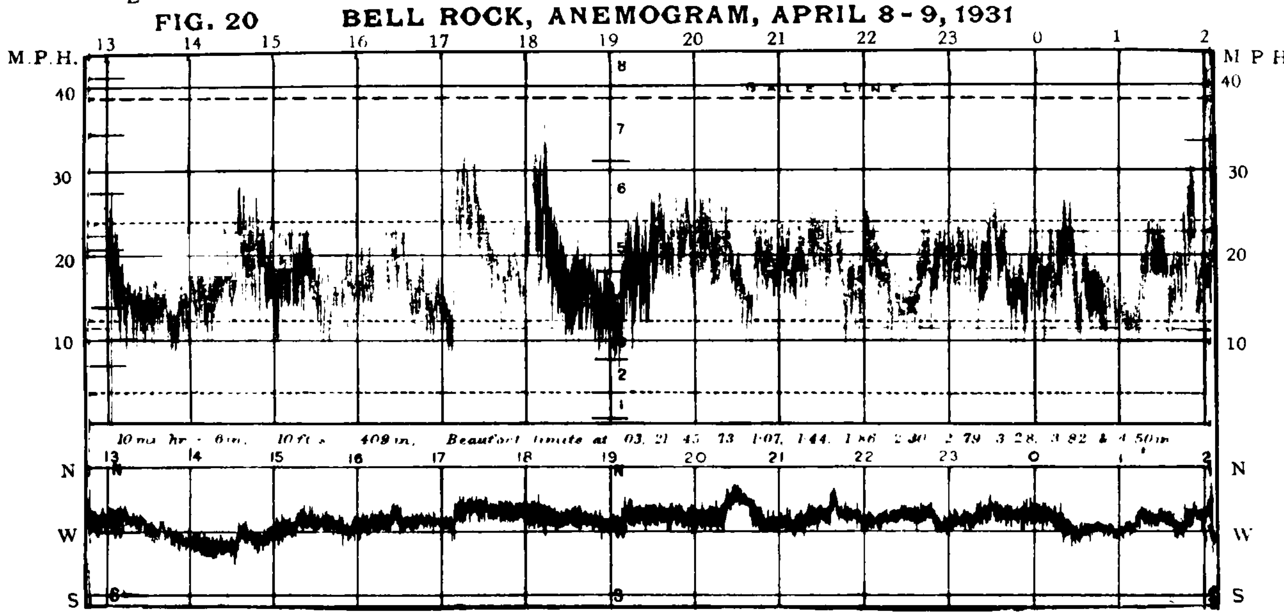

FIG. 21 TIREE, ANEMOGRAM, APRIL 12 - 13, 1931

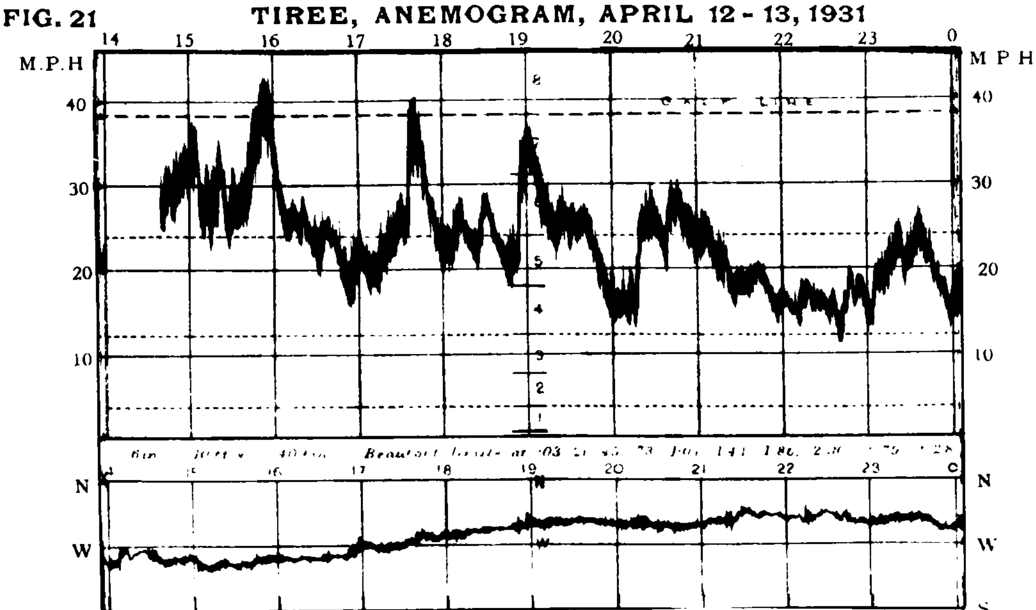

FIG. 22 BELL ROCK, ANEMOGRAM, APRIL 12, 1931

This case can thus be regarded as one where there was considerable atmospheric stability in the vertical direction, a fairly considerable variation of wind with height and probably a general tendency to stratification. It is therefore probably quite correct to regard the variations of wind indicated on the anemograms of this period as waves originating in consequence of a horizontal discontinuity or discontinuities.

The variations just considered are smooth or at least fairly symmetrical in shape and wave-like in appearance. There is however a different type of variation, more or less periodic in nature, but appearing in the speed record as a saw-toothed effect, i.e. the rise and fall of speed do not take place in a symmetrical manner, but the rise is rapid and the fall is slow. Variations of this sort have been described by Durst (5) and ascribed to instability. In the experience of the present writer they are characteristic of many northerly winds. The following is a summary of cases of these two types of variations, extracted from notes made on the examination of a year's records from Bell Rock. The remarks regarding the upper air are based on the observations contained in the *Upper Air Supplement to the Daily Weather Report*, where most of the observations refer to the south of England. They have therefore been quoted only in cases where there was reason to believe that the thermal conditions in the upper air in the Bell Rock region were not greatly different. The upper wind speeds quoted refer as far as possible to observations at Renfrew, Leuchars or Aberdeen.

The period August 21–28, 1929, was one of S. to W. wind and the trace was never long free from waves (*vide* Fig. 24). On the afternoon of the 25th there were some beautifully regular waves of an amplitude reaching 15 m.p.h. and a period of about $1\frac{1}{2}$ hours. The period and amplitude both decreased as evening advanced, but waves were still visible from midnight till 3h. of the next day, at which time the mean wind had fallen to a very light breeze and practically no gustiness remained. During all this period the upper air was stable and warm and there was an inversion mostly at about 7,000 or 8,000 feet. Above the inversion the wind, so far as could be ascertained, was of the order of 40–50 m.p.h.

The anemograms of the following dates showed waves, September 2, 7–8, 11–15, 22–27. On all of these there seemed also to be warm upper air, and either an inversion or a layer of almost isothermal conditions. On the afternoon of September 18, with a fairly steep lapse rate of temperature, there were a few oscillations of the saw-tooth type.

After September 27 and until October 10 there was much colder upper air and there were no waves; then there were fairly frequent waves until October 16 and coincidently an inversion about 6–7,000 feet with warm air above that level.

A further unsettled period with rather cold upper air and no wind waves followed. The N. wind on October 20 showed some saw-tooth variations. October 23, with an inversion about 5,000 feet, showed some waves in a wind of about gale force. Thereafter there was cold upper air and we find no waves until the 28th. On October 28 and 30 there were some waves. The warm upper air indicated at stations in south-east England on the 31st may have been already in the Bell Rock region on these dates.

November 4–5 showed some waves and on that day there was also an inversion.

The next period calling for mention is the afternoon of November 20 when a long saw-tooth type of variation was in evidence, with shorter smoother waves superposed on the latter part of each tooth, i.e. the part in which mean speed is gradually falling (Fig. 25). At this time there was an inversion near the ground, then fairly warm air above that and then a steep lapse rate. The direction record showed a slight veer with each rise of wind. Assuming the effects to be explained on Durst's theory, the "cells" require to be enormous, 25 to 30 Km. long, and perhaps 4 Km. deep. Pilot balloon ascents at this time indicated a slight veering and a considerable increase of speed with height, the wind being SW. by S. of the order of 50 m.p.h. at 3 Km. Fig. 25 indicates backings of a few points when the speed rose sharply from 6 or 8 to 17 or 18 m.p.h. It is also notable that the saw-tooth variation is in evidence only between about 10h. 35m. and 16h. 35m., between which times the mean speed (over these six hours) was reduced to about 14 m.p.h. Before and after the times mentioned the speed was fairly constantly around 22 m.p.h. A retardation applied (by convection) in the surface levels to an unstable current was therefore perhaps an essential feature of the phenomenon.

After this time there were rather steep lapse rates, continual depressions and an absence of waves until about December 13 when some waves, an inversion and warmer upper air again appeared. The upper air became very cold on the 16th, in front of a " high," then gradually much warmer with an inversion about 5,000 feet and more waves on the 18th. Conditions were again unsettled and unstable until the end of the year.

On January 2, 6–7, 17–19 (of 1930) in SW. or W. winds there were some waves and there were also inversions between 2,000 and 4,000 feet. On January 23–24 there were waves in a S. wind, but the upper air information does not suffice for an estimation of the probable upper air conditions in the Bell Rock region.

On February 22–26, March 4, 6–8, 22, 25–29, 31, April 1–3, 15–16, 21, 22, May 16–17, 19–20, there were waves and also inversions. On March 17, with cold upper air and a fairly steep lapse rate, the saw-tooth type of variation appeared in a NE. wind.

These results seem to leave no doubt that what we have here called waves are associated with marked stratification and the existence of discontinuities in the upper air; whilst wind variations of the saw-tooth type are associated with steep lapse rates of temperature.

§ 5—WIND SPEED—DIURNAL AND ANNUAL VARIATION

The data of the three years October 1929–September 1932 have been summarized to indicate the nature of the diurnal variation of wind speed at Bell Rock, whilst the data of the same period for Tiree and Butt of Lewis have been similarly treated for purposes of comparison. The data for the three stations and the four seasons are set out in Table IV whilst the nature of the diurnal variation at Bell Rock is given in Fig. 26. Spring is taken as comprising the months March, April, May; Summer as June, July, August; Autumn as September, October, November; and Winter as December, January, February. In Table IV, the data are grouped also into " summer six months " and " winter six months," these comprising respectively the months April to September inclusive and October to March inclusive.

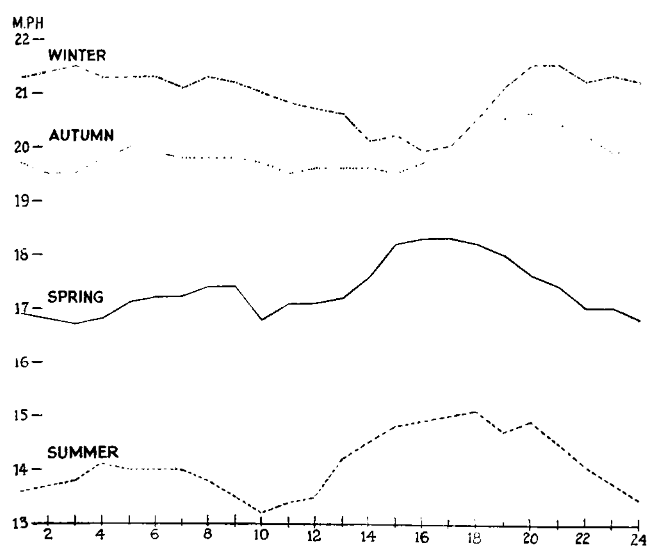

Fig. 26.—Bell Rock, diurnal variation of wind speed.

Looking first at the summer and spring data we note very appreciable diurnal variations of wind speed at Tiree, rather similar to those at a land station. At Butt of Lewis in summer there is also a slight variation rather like that of a land station, but very much flattened and of small range; in spring the variation is still there but barely appreciable. At Bell Rock the type of variation differs entirely from these and from the usual land variation. Spring and summer have the same features, the latter in more marked degree, so that they must be presumed to be real. The type is quite definitely semi-diurnal and it is therefore interesting to recall that Buchan in the " Report on the Scientific Results of the Voyage of H.M.S. *Challenger* during the years 1873–76," found some evidence of a semi-diurnal variation over the open oceans, the range however being slight and the variations not consistent in different oceans. At the Bell Rock the variation has minima about **10**h. and near midnight, and maxima in the late afternoon and in the early morning hours. Very roughly it is similar to the diurnal variation of pressure reversed, at least qualitatively. At Bell Rock autumn still shows some semi-diurnal effect, but it is slight and appreciably displaced in phase as compared with spring or summer. In winter there is a marked minimum about **16–17**h, a sharp rise to a maximum about **20–21**h. and then a gradual fall to the **16–17**h. minimum.

Tiree in winter and Butt of Lewis in autumn also show indications of the semi-diurnal variation. In autumn and winter we still find at Tiree evidence of the land type of diurnal variation though the maximum of wind speed gets progressively later (**13**h. and **14**h.). Also the minimum of wind, which all through the seasons at Tiree is in the late evening and not in the early morning hours, becomes particularly marked in autumn and winter. At Butt of Lewis it is rather remarkable that the autumn and winter diurnal variations exceed in range those of spring and summer. In autumn and winter the maximum occurs about **15–16**h., the minimum in autumn being about **7–9**h. and in winter about **4**h.

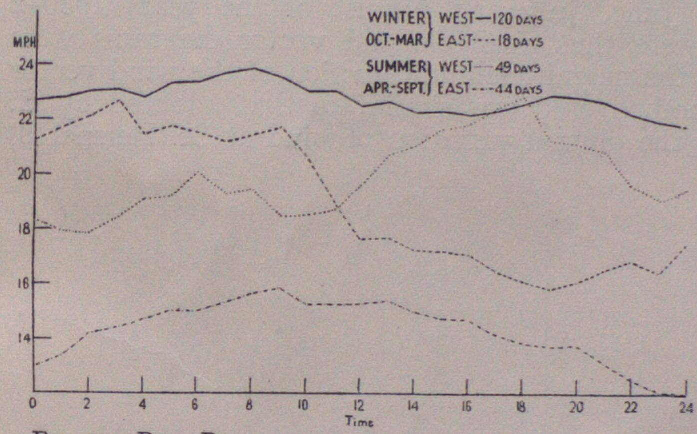

FIG. 27.—BELL ROCK, DIURNAL VARIATION OF SPEED IN WEST AND EAST WINDS.

In order to see how far land and sea breezes might enter into the diurnal variation at Bell Rock, the winds of the period September **1929**–February **1931** were divided into W. and E. and the variations for these directions in summer and winter separately computed. The results are shown in Fig. **27**. Taking summer it will be seen that W. winds show a variation closely resembling the mean of all winds in Fig. **26**, but of about twice the amplitude, the semi-diurnal character of the variation being evident. E. winds show a simple diurnal variation with maximum rather before midday. We are naturally led to the conclusion that the period **9–12**h. contains the sea-breeze maximum of easterly component and the period around **18**h. has the land breeze maximum of westerly component, but it is possible that general as well as local effects contribute to the complete variation. The point is examined in greater detail later in this section. The W. wind curve in winter shows similar features again with semi-diurnal variation, but rather later in phase and of smaller amplitude. Again, in order to see whether the semi-diurnal variation of wind at Bell Rock was connected with a similar variation of turbulence, an attempt was made to ascertain the diurnal variation of gustiness. For this purpose the data of the three summer months June to August **1930** and the three winter months December **1929** to February **1930** were taken, all days being included for which it

TABLE III—DIURNAL VARIATION OF GUSTINESS (G) AT BELL ROCK.

Hour	Midt.	1	2	3	4	5	6	7	8	9	10	11
Summer ..	1·28	1·28	1·29	1·37	1·42	1·43	1·42	1·35	1·33	1·27	1·29	1·24
Winter ..	2·66	2·67	2·79	2·92	2·88	2·98	2·98	2·95	2·84	2·72	2·73	2·67
Hour	**Noon**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**
Summer ..	1·30	1·38	1·43	1·39	1·40	1·38	1·38	1·37	1·39	1·40	1·39	1·34
Winter ..	2·61	2·48	2·48	2·47	2·55	2·67	2·66	2·81	2·84	2·81	2·82	2·70

PLATE VIII

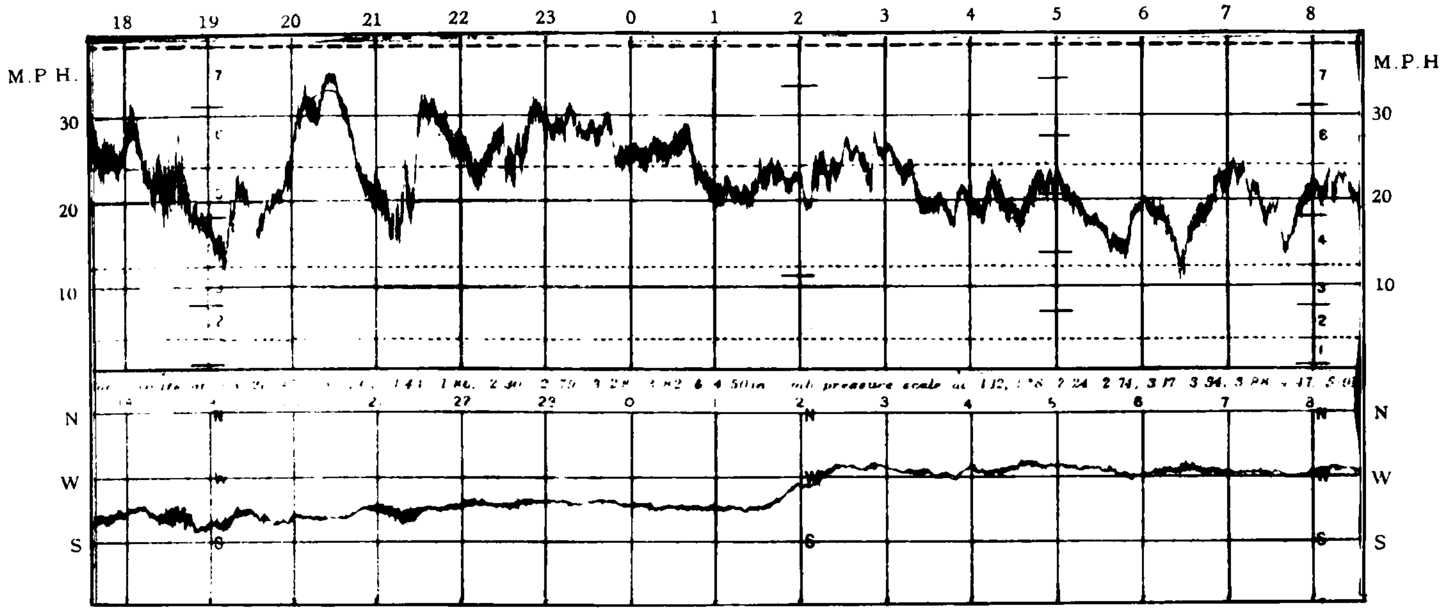

FIG. 23 **BELL ROCK, ANEMOGRAM, APRIL 11-12, 1931**

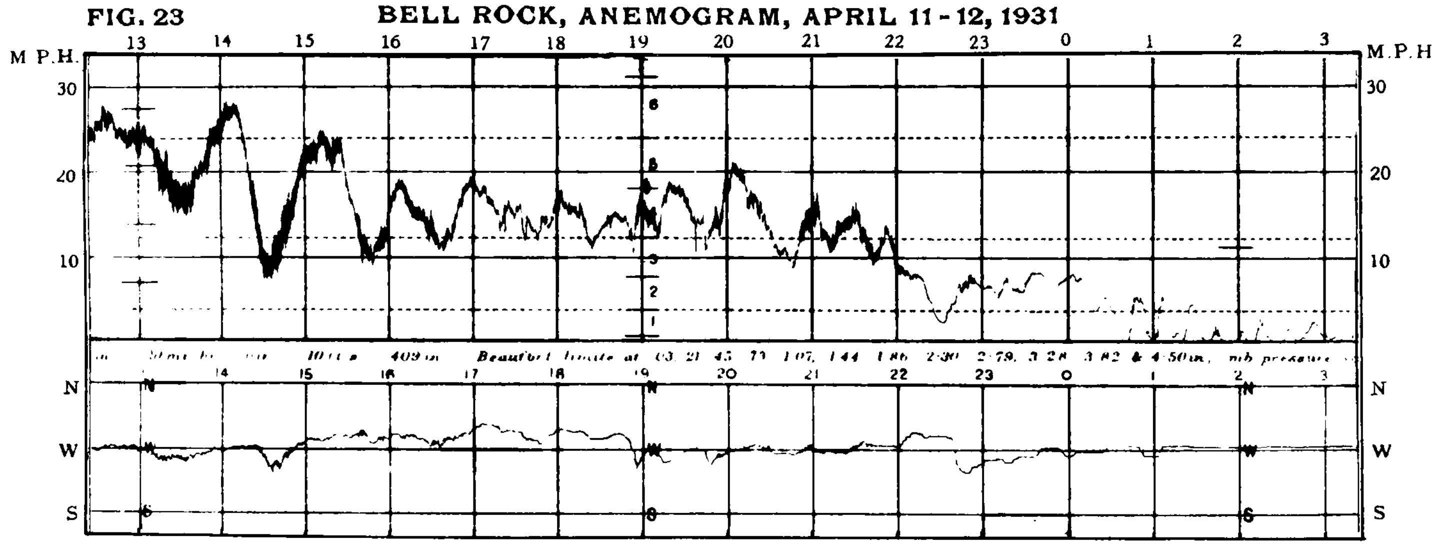

FIG. 24 **BELL ROCK, ANEMOGRAM, AUGUST 25-26, 1929**

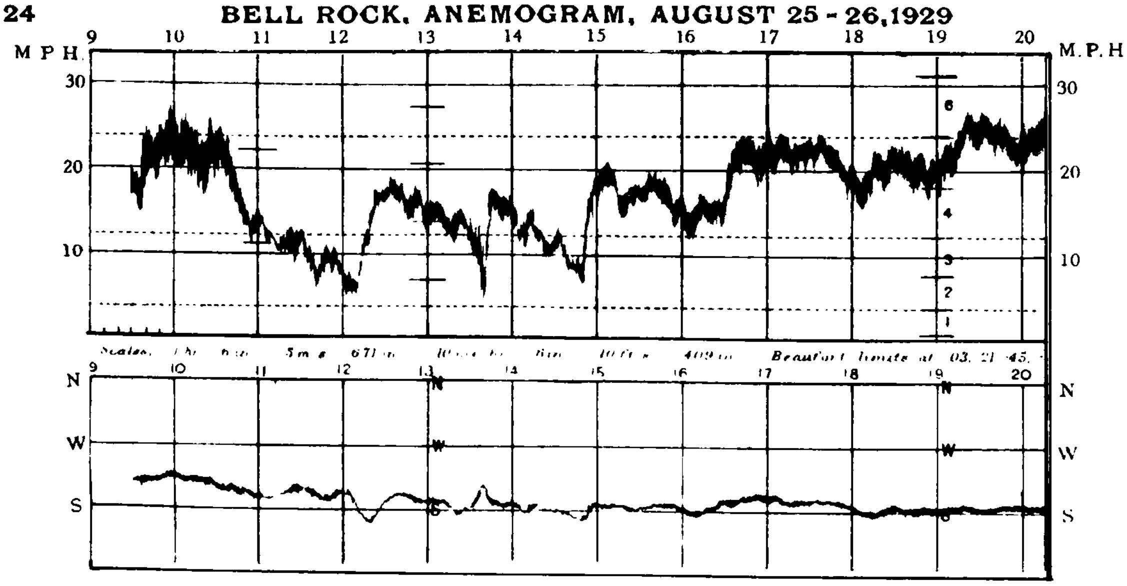

FIG. 25 **BELL ROCK, ANEMOGRAM, NOVEMBER 20, 1929**

was possible to measure the range of gustiness at each hour throughout the day, or, failing that, at 18 or more hours, the gaps in the last-mentioned cases being filled by interpolation. The mean ranges of gustiness so obtained are given in Table III. It will be seen that both summer and winter show variations of semi-diurnal nature. The winter values are all roughly twice the summer ones, corresponding as they do to higher mean speeds, whilst the range of the semi-diurnal variation is also almost exactly doubled. Summer and winter agree in having their first maximum centred about 5h. In winter the second maximum is about 20h. whilst in summer there is a sustained high level of range of gusts from 14h. to about 22h.

When the range of diurnal variation of gustiness is compared with the range of the diurnal variation of mean speed, it is seen that the gustiness factor G/V possesses a similar diurnal variation. Thus we conclude that fairly approximately when turbulence attains its maximum values, the surface wind speed also attains its maximum values.

Finally, however, a clearer idea of the nature of the diurnal variations of wind speed was obtained from an analysis of the hourly values into components, W.–E. and S.–N. Both the Tiree and the Bell Rock data were treated in this way, the period covered being the months June, July and August of the years 1930–2 inclusive. Nine summer months were thus available and vector diagrams were worked out for each place to show the magnitude and direction of the wind vector for each hour of the day. The method used was similar to that adopted by E. Gold and J. S. Dines in discussing the diurnal variation of wind at St. Helena (8)

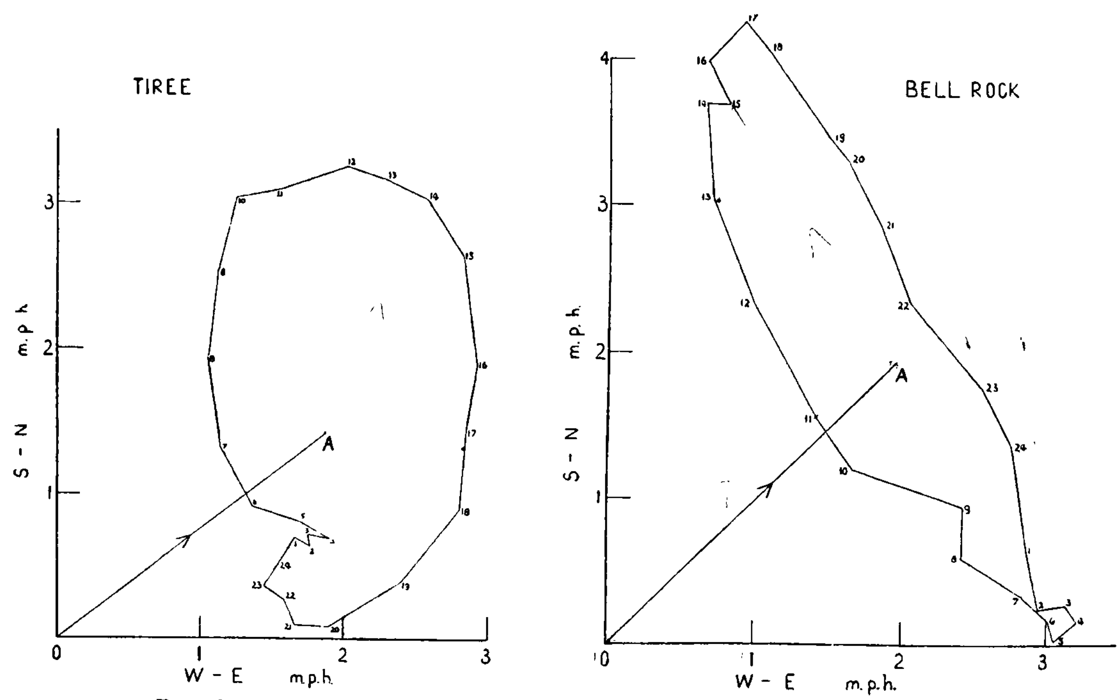

FIG. 28.—VECTOR DIAGRAMS SHOWING THE DIURNAL VARIATION OF WIND IN SUMMER (JUNE, JULY, AUGUST, 1930–2.)

and the analysis was added on the suggestion of Col. Gold. The results for Tiree and Bell Rock are set out in Table VI and in Fig. 28. The mean wind for the day in each case is represented by the line OA, the mean winds at individual hours by the lines joining the origin O to the points 1, 2, 3, etc., on the diagrams. In each case the mean wind is from a point slightly to W. of SW., the greater strength at Bell Rock being due to the greater height of the anemometer head above the surface. The diagrams have also in common with one another (as well as with the corresponding St. Helena diagrams and with the well-known diagrams illustrating diurnal variation of magnetic force) the feature that by far the greater part of the area is swept out by the diurnal vector during daylight hours.

Apart from these features, however, there are important differences and at no hour are the inequality vectors at Tiree and Bell Rock parallel to one another. The relative orientation of the vectors suggests at once that here the wind variations are controlled in the main not so much by any general cause as by something related to geographical position—most probably diurnal convection over the mainland and in particular over the great mountain massif. At Bell Rock from 12–18h. the superposed vector represents a wind of not inconsiderable speed towards the mountain massif ; at Tiree the effect is rather less, probably because of the westerly position of the station, but from about 14–18h. the superposed vector is also a wind towards the mountain massif. At both places, from the late evening up to perhaps 9h., the superposed effect is a wind away from the land. We might therefore apparently regard the central mountains as a region of convectional up-draught during the warm part of the day and as a region of down-draught during the night and early morning. If the effects arise from mainland convection they should appear in other ways. The setting in of active convection in the forenoon from about 9–11h. causes an important check to the general air drift across the mainland. Since the mean drift is from about SW. the result of the check at Tiree is most probably to diminish the westerly component and increase the southerly ; this at all events agrees with the indications of the vector diagram. At Bell Rock at the same hours the drift from SW. is diminished. Though topographical and in a sense local, this diurnal circulation seems to be on a large scale in summer and the superposed wind components at both Tiree and Bell Rock in this season are of the same order of magnitude as the mean drifts experienced in the same season at these two stations. The inward and outward circulations at the surface levels must of course be associated with outward and inward circulations at higher levels—probably about the level of the tops of cumulus clouds*. The effect, incidentally of the diurnal cloud formation over the land area concerned, is illustrated by the experience that whilst Dalwhinnie for example has an average of about 4·7 hrs. per day of bright sunshine in summer months and Onich (near Fort William) an average of only 3·8 hrs., places like Arbroath and Tiree have averages of about 5·7 hrs, i.e. the sunshine at the inland stations amongst the mountains is reduced by the order of 25 per cent. as compared with the coastal or island stations.

It is possible that in topographically induced diurnal circulations of the sort described above are to be found the explanations of some of the semi-diurnal variations of wind noted at various times at sea and of the differences in one place as compared with another. If the main effect of the topographical circulation is transverse to the mean wind (as is nearly the case at Bell Rock) the semi-diurnal variation in resultant wind speed will be fairly prominent ; the two maxima will come about 4–5h. and 16–17h. respectively and the minima about 10–11h. and 22–23h. respectively. The question of possible relations with the semi-diurnal pressure wave is referred to in a later note under Table VI.

The nature of the annual variation in wind speed is indicated in Table V to which, for purposes of comparison, have been added the annual mean variations at Lerwick (9 years) and Valentia, Aberdeen and Kew (35 years). It will be noted that whilst the range of the annual variation at Kew is only 38 per cent. of the mean speed, that at the four stations, Bell Rock, Tiree, Butt of Lewis and Lerwick, averages very nearly 60 per cent. At these four stations and at Valentia and Aberdeen the mean speed has its minimum about July or August and its maximum in December or January. This variation corresponds closely to that of cyclonic activity. At Kew by contrast the speed has a minimum in autumn and a maximum in spring suggesting that the surface wind in that region is controlled to such an extent by the degree of slip or mixing between surface and upper air, that the annual variation is both suppressed and altered in phase. The enormous effect of land friction and land shelter in reducing speed is indicated by the relative lowness of the mean speeds at Kew and Aberdeen, as compared with the other stations.

In this connexion it has to be remarked that the mean speeds shown for Lerwick are probably all a little lower than the correct values. In 1929 a leak was discovered in one of the pipes of the anemograph and it was decided to discard entirely the records of one year previous to the discovery. Later on, however, the conclusion

* See note on p. 22.

TABLE IV—DIURNAL VARIATION
MONTHLY MEANS OF V FOR PERIOD

	Hour G.M.T.	1	2	3	4	5	6	7	8	9	10
Bell Rock	Spring (Mar.–May) ..	16·9	16·8	16·7	16·8	17·1	17·2	17·2	17·4	17·4	16·8
	Summer (June–Aug.) ..	13·6	13·7	13·8	14·1	14·0	14·0	14·0	13·8	13·5	13·2
	Autumn (Sept.–Nov.) ..	19·7	19·5	19·5	19·8	20·0	19·9	19·8	19·8	19·8	19·7
	Winter (Dec.–Feb.) ..	21·3	21·4	21·5	21·3	21·3	21·3	21·1	21·3	21·2	21·0
	Summer Six Months (Apr. to Sept.) ..	15·1	15·1	15·1	15·3	15·3	15·4	15·3	15·2	15·0	14·7
	Winter Six Months (Oct.–Mar.) ..	20·7	20·7	20·7	20·7	20·9	20·8	20·8	21·0	21·0	20·7
Tiree ..	Spring (Mar.–May) ..	14·2	14·2	14·4	14·6	14·6	14·7	15·1	15·6	16·0	16·2
	Summer (June–Aug.) ..	10·5	10·8	10·7	10·9	11·0	11·1	11·6	12·2	12·8	12·9
	Autumn (Sept.–Nov.) ..	16·3	16·2	16·4	16·4	16·2	16·4	16·7	16·7	16·8	17·1
	Winter (Dec.–Feb.) ..	18·8	19·1	19·0	19·3	19·1	19·1	19·0	18·6	18·6	18·8
	Summer Six Months (Apr. to Sept.) ..	11·7	11·9	12·0	12·1	12·2	12·4	12·8	13·3	13·9	14·1
	Winter Six Months (Oct. to Mar.) ..	18·2	18·2	18·3	18·5	18·3	18·3	18·4	18·2	18·2	18·5
Butt of Lewis	Spring (Mar.–May) ..	17·9	17·9	17·9	17·7	17·6	17·7	18·0	18·2	18·1	18·1
	Summer (June–Aug.) ..	14·1	14·2	14·2	14·1	14·1	14·2	14·6	14·9	15·0	15·0
	Autumn (Sept.–Nov.) ..	20·7	20·9	20·8	20·6	20·9	20·6	20·2	20·3	20·2	20·7
	Winter (Dec.–Feb.) ..	22·9	22·7	22·7	22·6	22·8	22·7	22·9	23·1	22·9	22·9
	Summer Six Months (Apr. to Sept.) ..	15·7	15·9	15·9	15·8	15·9	16·0	16·2	16·5	16·5	16·5
	Winter Six Months (Oct. to Mar.) ..	22·1	21·9	21·9	21·7	21·9	21·7	21·7	21·8	21·7	21·8

TABLE V—ANNUAL VARIATION OF WIND SPEED (MONTHLY MEANS IN M.P.H.)

		Jan.	Feb.	Mar.	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
Bell Rock	(3 years)	22·6	17·5	17·8	18·7	15·5	14·6	14·1	13·6	16·6	21·2	21·9	22·9	18·1
Tiree ..	(3 years)	20·6	14·9	15·7	15·8	13·0	11·7	12·2	10·9	12·6	18·9	18·0	20·9	15·4
Butt of Lewis	(3 years)	24·8	20·3	17·9	19·4	16·7	16·2	13·7	13·8	17·8	23·1	22·1	24·6	19·2
Lerwick..	(9 years)	22·2	21·0	16·5	16·5	14·8	14·5	11·4	11·8	15·0	16·8	19·2	21·0	16·6
Valentia	(35 years)	14·5	13·9	13·1	12·0	11·0	10·1	10·0	10·2	10·5	12·0	13·2	14·5	12·1
Aberdeen	(35 years)	10·2	10·0	10·1	9·2	8·1	7·4	7·1	7·1	7·5	9·1	9·5	9·9	8·9
Kew ..	(35 years)	8·1	8·8	9·0	8·7	7·7	7·1	6·6	6·8	6·1	6·8	7·5	8·3	7·6

TABLE VI—DIURNAL VARIATION OF THE W.–E. AND S.–N. COMPONENTS OF WIND

	Hour ..	1	2	3	4	5	6	7	8	9	10
Tiree ..	W.–E.	1·66	1·77	1·75	1·92	1·68	1·36	1·14	1·05	1·12	1·25
	S.–N.	0·69	0·63	0·72	0·69	0·81	0·92	1·32	1·95	2·53	3·04
Bell Rock	W.–E.	2·85	2·93	3·13	3·21	3·05	3·01	2·83	2·40	2·41	1·67
	S.–N.	0·67	0·23	0·26	0·15	0·02	0·16	0·32	0·58	0·94	1·20

OF WIND SPEED (M.P.H.)
SEPTEMBER 1929—AUGUST 1933.

	11	12	13	14	15	16	17	18	19	20	21	22	23	24	Mean Speed.
	17·1	17·1	17·2	17·6	18·2	18·3	18·3	18·2	18·0	17·6	17·4	17·0	17·0	16·8	17·3
	13·4	13·5	14·2	14·5	14·8	14·9	15·0	15·1	14·7	14·9	14·5	14·1	13·8	13·5	14·1
	19·5	19·6	19·6	19·6	19·5	19·7	20·3	20·6	20·5	20·6	20·4	20·2	19·9	19·9	19·9
	20·8	20·7	20·6	20·1	20·2	19·9	20·0	20·5	21·1	21·5	21·5	21·2	21·3	21·2	21·0
	14·8	15·1	15·5	15·9	16·3	16·5	16·6	16·7	16·3	16·3	15·8	15·4	15·3	15·1	15·5
	20·6	20·4	20·3	20·1	20·1	20·0	20·2	20·5	20·9	21·1	21·1	20·8	20·8	20·7	20·7
	16·3	16·1	16·0	15·8	15·5	15·1	14·6	14·1	13·9	14·1	13·8	13·7	14·0	14·0	14·8
	12·9	13·0	12·9	12·9	12·7	12·4	11·9	11·6	11·0	10·7	10·5	10·4	10·4	10·4	11·6
	17·5	17·6	17·6	17·2	17·1	16·3	16·0	16·0	16·0	15·7	15·6	15·7	16·2	16·3	16·5
	19·1	19·3	19·6	19·6	19·5	19·3	18·5	18·4	18·2	18·1	17·9	17·9	18·0	18·2	18·8
	14·1	14·2	14·0	14·0	13·8	13·4	12·9	12·4	12·0	11·8	11·6	11·5	11·6	11·6	12·7
	18·8	18·9	19·0	18·8	18·6	18·1	17·6	17·7	17·5	17·5	17·3	17·4	17·7	17·8	18·1
	18·1	18·3	18·4	18·1	18·1	18·0	18·2	18·1	18·1	18·1	17·9	17·7	17·8	17·8	18·0
	15·1	15·1	15·0	15·0	15·0	15·0	14·9	14·9	14·6	14·2	14·0	14·0	13·8	13·9	14·5
	21·0	21·1	21·4	21·5	21·7	21·7	21·3	21·5	21·3	21·5	21·1	21·1	21·0	20·9	21·0
	23·2	23·5	23·5	23·5	23·9	23·9	23·6	23·4	23·3	23·5	23·6	23·3	23·3	23·1	23·2
	16·6	16·8	16·8	16·7	16·7	16·7	16·6	16·5	16·4	16·1	15·8	15·8	15·7	15·7	16·2
	22·1	22·3	22·3	22·3	22·6	22·6	22·4	22·4	22·2	22·5	22·5	22·3	22·2	22·1	22·1

was reached that the records of probably at least two more years and possibly two other years to a less extent had been affected by the leak. The general reduction in mean speed cannot affect the nature of the annual variation appreciably, but it probably reduces the nine-year mean speed by about one mile per hour.

Col. Gold has added the following note regarding the data of Table VI. :—

These inequalities when analysed lead to the following equations for the variation in the W.–E. and S.–N. components. The time t is measured in hours from midnight G.M.T. and the amplitudes are in m.p.h.

Tiree
$$\begin{cases} \text{W.–E.} = 1{\cdot}87 + {\cdot}61 \sin(15t + 210^\circ) + {\cdot}49 \sin(30t + 27^\circ) \\ \text{S.–N.} = 1{\cdot}43 + 1{\cdot}44 \sin(15t + 290^\circ) + {\cdot}53 \sin(30t + 117^\circ) \end{cases}$$

Bell Rock
$$\begin{cases} \text{W.–E.} = 1{\cdot}96 + 1{\cdot}23 \sin(15t + 55^\circ) + {\cdot}14 \sin(30t + 281^\circ) \\ \text{S.–N.} = 1{\cdot}92 + 2{\cdot}03 \sin(15t + 212^\circ) + {\cdot}17 \sin(30t + 351^\circ) \end{cases}$$

(M.P.H.) AT TIREE AND BELL ROCK IN SUMMER (JUNE, JULY, AUGUST 1930–2)

	11	12	13	14	15	16	17	18	19	20	21	22	23	24	Mean.
	1·54	2·01	2·30	2·57	2·71	2·91	2·84	2·80	2·39	1·88	1·66	1·59	1·45	1·54	1·87
	3·09	3·24	3·15	3·02	2·62	1·92	1·43	0·90	0·38	0·07	0·09	0·27	0·36	0·51	1·43
	1·43	0·99	0·71	0·66	0·83	0·67	0·92	1·09	1·51	1·64	1·85	2·03	2·54	2·74	1·96
	1·55	2·33	3·05	3·70	3·68	3·97	4·25	4·04	3·44	3·28	2·85	2·32	1·75	1·36	1·92

In cm./sec. the amplitudes for the two semi-diurnal waves are 22 and 24 at Tiree and 6 and 8 at Bell Rock. It will be seen that the difference of phase in the semi-diurnal variation is in both cases approximately 90°. This suggests that the semi-diurnal variation is associated with a semi-diurnal wave of pressure. The semi-diurnal wave of pressure at Aberdeen for the three months June, July, August, is approximately $\cdot 22 \sin (30t + 143^\circ)$, the amplitude being in millibars (*Observatories Year Book*, 1931, p. 89). The phases of the semi-diurnal waves in the W.–E. and S.–N. components of wind arising from a pressure wave with this phase 143° and with an amplitude varying as $\sin^3\phi$ where ϕ is co-latitude, are approximately, (1) for the case of no friction W.–E. = 323°, S.–N. = 53° (2) for friction proportional to velocity, approximately W.–E. = 30°, S.–N. = 120° (see *Phil. Mag.*, Jan. 1909, pp. 31 and 34). The amplitudes of the semi-diurnal variations of wind arising from a pressure wave such as that at Aberdeen for the case of no friction are about 50 cm./sec. and for considerable friction about 15 cm./sec.

Thus the Tiree variation appears to fit the pressure wave, and friction proportional to velocity: but the Bell Rock variation has substantially different phases from what would be expected, though the amplitudes are of the right order.

NOTE (see p. 19)—It may be recalled that "The diurnal variation in the direction of the summer winds on Ben Nevis" was investigated by R. T. Omond (*Edinburgh Proc. R. Soc.* **13**, p. 839 and *Edinburgh Trans. R. Soc.* **44**, pp. 706–14), the results leading to a vector diagram of long and narrow shape set transversely to the mean drift, which in this case was 1¼ m.p.h. from about WSW. The superposed vectors were,—from 3 to 8 a.m. a N. or NNW. wind of about 2½ m.p.h., and from 11 a.m. to 2 p.m. a S. or SSE. wind of about 3 m.p.h.; at other hours the departures from the mean were small and irregular except about midnight when there was a distinct increase in the velocity. The ridge that forms the summit of Ben Nevis lies east and west, with a steep slope to south and an almost vertical cliff to northward. It is therefore uncertain how much of this diurnal variation should be attributed to purely local topography or how nearly it might approximate to the actual mean circulation over W. Scotland at the intermediate height of 4400 feet.

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