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COMPARISON OF THE WIND RECORDED BY ANEMOGRAPH WITH THE GEOSTROPHIC WIND

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COMPARISON OF WIND RECORDED BY ANEMOGRAPH WITH THE GEOSTROPHIC WIND

By W. A. L. MARSHALL

Summary.—The commonly accepted forecasting rule that the surface wind speed is one third of the geostrophic wind inland and two thirds of the geostrophic wind at sea is broadly valid over the whole range of synoptic conditions met with in the British Isles. Similarly, wind direction near the surface is usually backed from the mean-sea-level isobars by about 30° inland and by about 10° at sea. But this general connexion between wind and pressure distribution is be no means invariable. The wind measured at four anemograph stations has been compared with the estimated geostrophic wind at six-hourly intervals over the year 1946. Abnormalities of wind speed and direction are discussed in relation to the existing synoptic situation, the temperature lapse rate, the exposure of the anemograph and the time of day.

Introduction.—The purpose of this investigation is to compare the wind recorded near the surface by the Meteorological Office pressure-tube anemograph at four representative types of exposure in Great Britain with the geostrophic wind estimated from medium-scale synoptic charts. The stations used were :—

Stornoway (58° 11′ N., 6° 21′ W., anemometer vane 40 ft. above ground, 120 ft. above M.S.L.).—Located on the landward side of the Isle of Lewis, off north-west Scotland (see Fig. 1). The island is 40 miles wide and rises to 1,500–2,000 ft. The mainland of Scotland lies some 30–40 miles to the east and south-east.

Bell Rock Lighthouse (56° 26′ N., 2° 24′ W., anemometer vane 130 ft. above M.S.L.).—The reef off south-east Scotland (see Fig. 2) on which the lighthouse stands becomes completely covered at high water. The anemometer is singularly free from local obstructions, though the Grampians rise to 3,000–4,000 ft. some 40 miles to the north-west of Bell Rock.

Scilly Isles (49° 56′ N., 6° 18′ W., anemometer vane 65 ft. above ground, 230 ft. above M.S.L.).—The anemometer is exposed on St. Mary's, the largest island in the Scilly group off south-west England (see Fig. 3). The nearest part of the mainland is about 25 miles east-north-east of the island. The exposure of the station is open to the Atlantic from south-west through west to north.

Kew Observatory (51° 28′ N., 0° 19′ W., anemometer vane 75 ft. above ground, 92 ft. above M.S.L.).—Typical of an inland exposure in south-east England (see Fig. 4).

Information used.—The geostrophic wind at each of the four places was estimated from synoptic charts on the scale $1 \times 10{,}000{,}000$ for each of the main synoptic hours 0000, 0600, 1200 and 1800 G.M.T. over the year 1946. Estimated speeds of less than 10 m.p.h. and cases in which the passage of surface fronts or centres of depressions or anticyclones would obviously result in substantial changes of wind within one hour were not used. The estimates for Stornoway and the Scilly Isles are probably somewhat less accurate than those for Bell Rock and Kew Observatory because of their geographical position. Allowance for latitude was made in the geostrophic wind scale used, but no correction for curvature of the trajectory of the air or of the isobars was applied.

These geostrophic winds were subsequently compared with the mean wind speed and mean wind direction recorded by anemograph during the following hour, described broadly as the " surface wind ". The geostrophic wind at 0600 G.M.T. was compared with the mean surface wind for the 60 min. centred

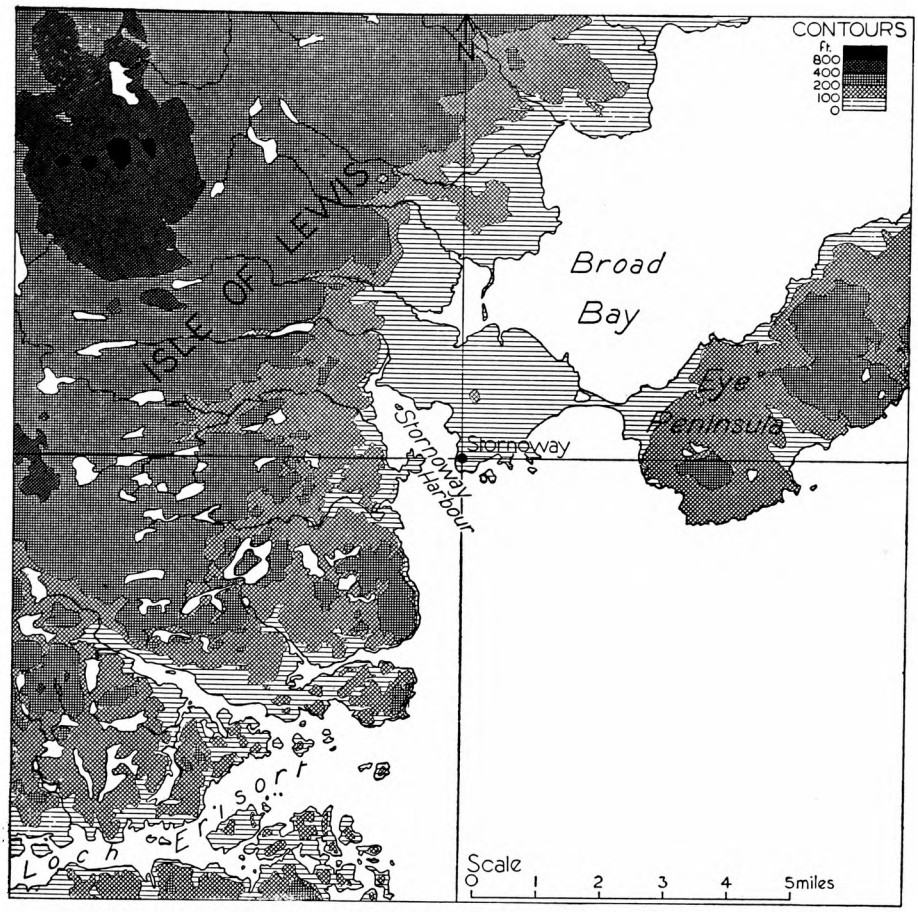


FIG. 1—SURROUNDINGS OF ANEMOGRAPH AT STORNOWAY

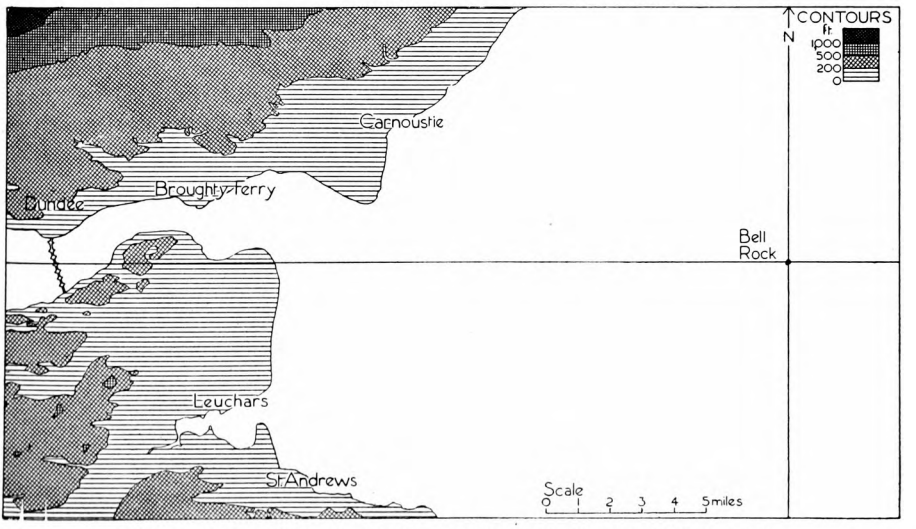


FIG. 2—SURROUNDINGS OF ANEMOGRAPH AT BELL ROCK

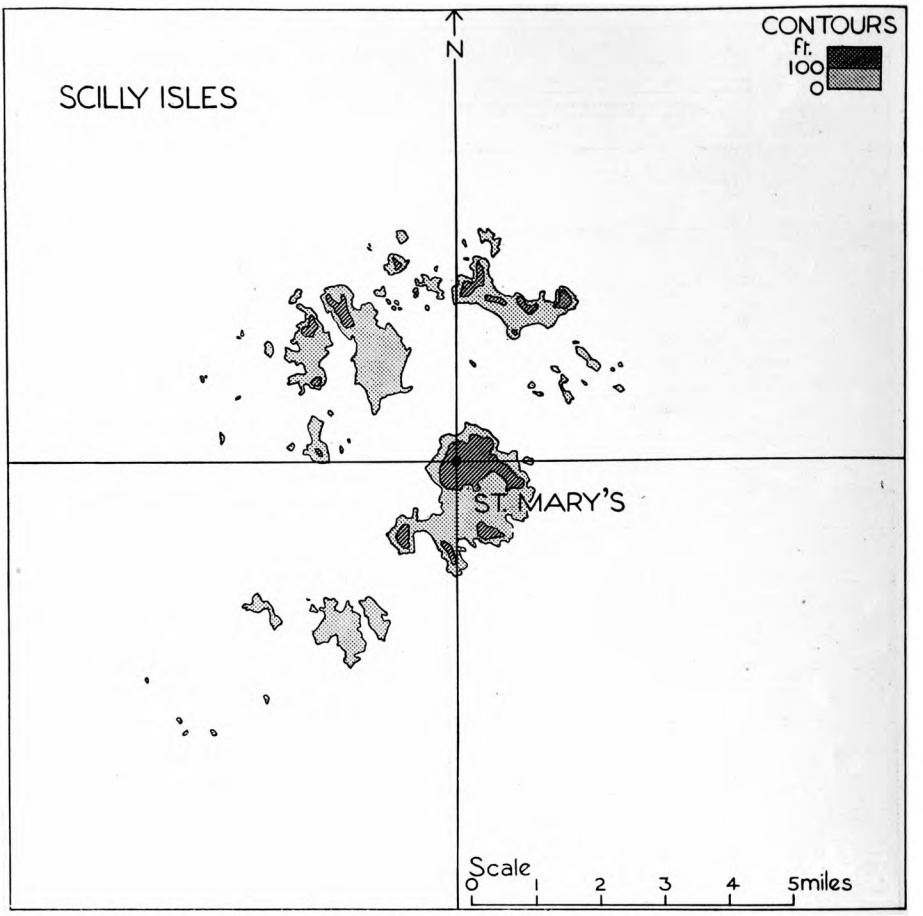


FIG. 3—SURROUNDINGS OF ANEMOGRAPH AT THE SCILLY ISLES

at 0630 G.M.T., that for 1200 G.M.T. with the surface wind from 1200 to 1300 G.M.T. and so on. Strictly, the comparisons should have been based on the mean hourly wind recorded by anemograph centred at the hour. Values, however, were already available for the 60 min. centred at the half hour, and this period was accordingly used for surface winds throughout the investigation. The pressure field would not change appreciably in half an hour.

At the same time an estimate was made of the cyclonic or anticyclonic curvature of the isobars in the neighbourhood of the stations on the scale below :—

Scale figure	Isobars of radius	Scale figure	Isobars of radius
9 =	50 miles	4 =	500 miles
8 =	100 miles	3 =	700 miles
7 =	150 miles	2 =	900 miles
6 =	200 miles	1 =	1,100 miles
5 =	300 miles	0 =	1,300 miles

— = straight isobars

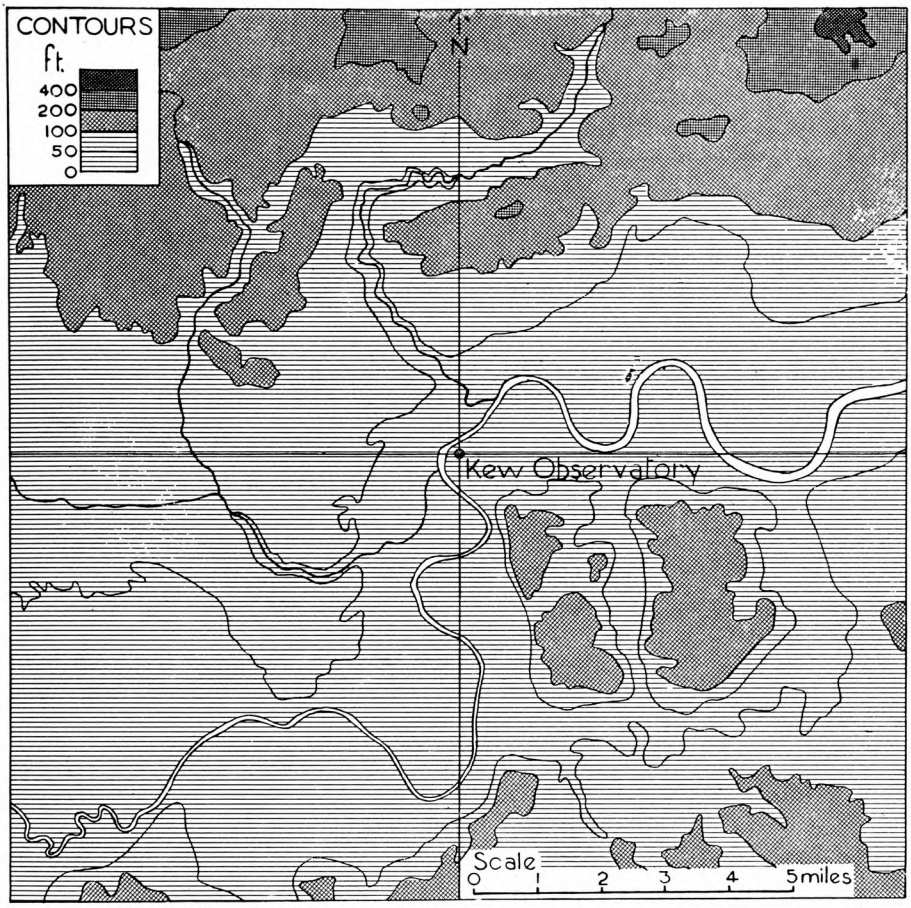


FIG. 4—SURROUNDINGS OF ANEMOGRAPH AT KEW OBSERVATORY

General comparison.—The average ratio of surface wind speed to the geostrophic wind and the deviation of the surface wind direction from the isobars over the whole range of cases examined are summarized in Tables I and II respectively.

TABLE I—AVERAGE PERCENTAGE RATIO OF SURFACE WIND SPEED TO THE GEOSTROPHIC, 1946

	No. of cases	0000	0600	1200	1800	All hours
		per cent.				
Stornoway	1,256	48	48	57	54	52
Bell Rock	1,217	68	66	67	70	68
Scilly Isles	1,236	68	66	66	67	67
Kew Observatory	1,192	30	30	45	38	36

Surface wind characteristics varied with different types of pressure distribution. In the more detailed examination which follows, the geostrophic winds from the four quadrants centred at 360°, 90°, 180° and 270° and the corresponding winds recorded by anemograph are treated separately.

TABLE II—PERCENTAGE FREQUENCY OF DIFFERENT DEVIATIONS OF SURFACE WIND FROM THE ISOBARS

	Deviation from the isobars				
	Backed		Within	Veered	
	50–70°	20–40°	10°	20–40°	50–70°
	per cent.				
Stornoway	18	58	19	1	0·4
Bell Rock	4	23	48	18	2
Scilly Isles	5	37	48	7	1
Kew Observatory ..	21	55	16	2	0·2

Average surface winds at main synoptic hours.—The wind recorded by anemograph at the Scilly Isles was consistently stronger with northerly geostrophic winds than with geostrophic winds of similar intensity from the other quadrants, but at Stornoway, sheltered by the Isle of Lewis, a northerly type resulted in relatively light winds. At Bell Rock and Kew Observatory surface winds were markedly stronger with easterly geostrophic winds than with any other type of pressure distribution. Strong easterlies were also a feature of the wind at Stornoway over the year as a whole.

Except at Stornoway, surface winds were, on the whole, lightest compared with the geostrophic winds in southerly types. Surface winds associated with geostrophic winds from a westerly point were fairly strong on the average at all four places, though not nearly so strong as with the easterlies at Stornoway, Bell Rock and Kew Observatory, or as with the northerlies at the Scilly Isles.

Surface wind speed at main synoptic hours over the whole year expressed as an average percentage of the geostrophic wind is summarized in Table III.

TABLE III—PERCENTAGE RATIO OF SURFACE WIND SPEED TO GEOSTROPHIC WIND SPEED

	Geostrophic wind direction	No. of cases	0000	0600	1200	1800	All hours
			per cent.				
Stornoway ..	Northerly	218	38	41	54	50	46
	Easterly	184	53	54	66	64	60
	Southerly	392	53	49	54	53	52
	Westerly	462	47	48	58	53	52
Bell Rock ..	Northerly	198	62	77	66	64	67
	Easterly	188	90	85	85	80	85
	Southerly	327	58	58	60	66	61
	Westerly	504	69	64	67	72	68
Scilly Isles ..	Northerly	193	80	79	72	86	79
	Easterly	269	66	63	62	58	62
	Southerly	259	56	58	61	54	57
	Westerly	515	72	68	68	71	70
Kew Observatory	Northerly	174	27	26	48	38	35
	Easterly	255	38	37	56	50	45
	Southerly	200	27	28	42	33	32
	Westerly	563	28	29	41	36	34

Diurnal variation of wind speed over the year.—The diurnal variation of wind speed over the year as a whole was greatest with northerly geostrophic winds. The least variation occurred with geostrophic winds from a southerly point at Stornoway, with southerlies and westerlies at Bell Rock and with westerlies at the Scilly Isles and Kew Observatory.

At Stornoway, sheltered to north and west by the large and mountainous Isle of Lewis, but with little high ground to the north-east, winds were lighter at night than by day with all types of pressure distribution except those for south-south-west geostrophic winds. At Kew Observatory, typical of inland conditions, winds were fairly consistently lighter at night than by day, but at both places the diurnal variation was less pronounced with pressure gradients for strong winds.

Wind speeds at the height of the Bell Rock anemograph, representing conditions in coastal waters, and at the small island of St. Mary's, the Scilly Isles, were as strong at night as by day on the average. The speed at night was often stronger than by day with geostrophic winds from the easterly and westerly quadrants at Bell Rock and from the exposed south-west to north sector at the Scillies.

Diurnal variation of wind speed in winter.—The broad diurnal variations of wind speed given in the last section are complicated somewhat by the fact that some of the 0600 and 1800 G.M.T. values relate to daylight and others to the hours of darkness. Considering only the period mid October to mid March, when the sun is below the horizon at both these times, the surface wind speed expressed as a percentage of the geostrophic wind was as shown in Table IV.

TABLE IV—DIURNAL VARIATION OF WIND SPEED IN WINTER

	Surface winds all directions			
	0000	0600	1200	1800
	percentage of geostrophic winds			
Stornoway	53	53	55	50
Bell Rock	64	63	67	67
Scilly Isles	70	70	69	69
Kew Observatory ..	30	31	41	36

Midday winds at Stornoway were a little lighter in winter compared with the geostrophic wind, and the diurnal variation was smaller in winter than over the year as a whole. This was due, in part at least, to the frequency of southerly geostrophic winds in the winter months of 1946, with which direction surface wind tended to remain fairly strong at night.

Except at midday the wind at Bell Rock was a little lighter compared with the geostrophic winds in winter than over the whole year. The prevailing winds at Bell Rock during the winter period examined were from between S. and W., which are normally associated with stable temperature lapse rates. At the Scilly Isles, however, where winds were more often unstable westerlies, the surface wind in winter was rather stronger than the average over the year, the diurnal variation being about the same in winter as in summer.

The wide scatter of the data is one of the features of Fig. 5 in which surface wind speed over the periods January 1–March 15 and October 16–December 31, 1946, is plotted against the corresponding geostrophic wind.

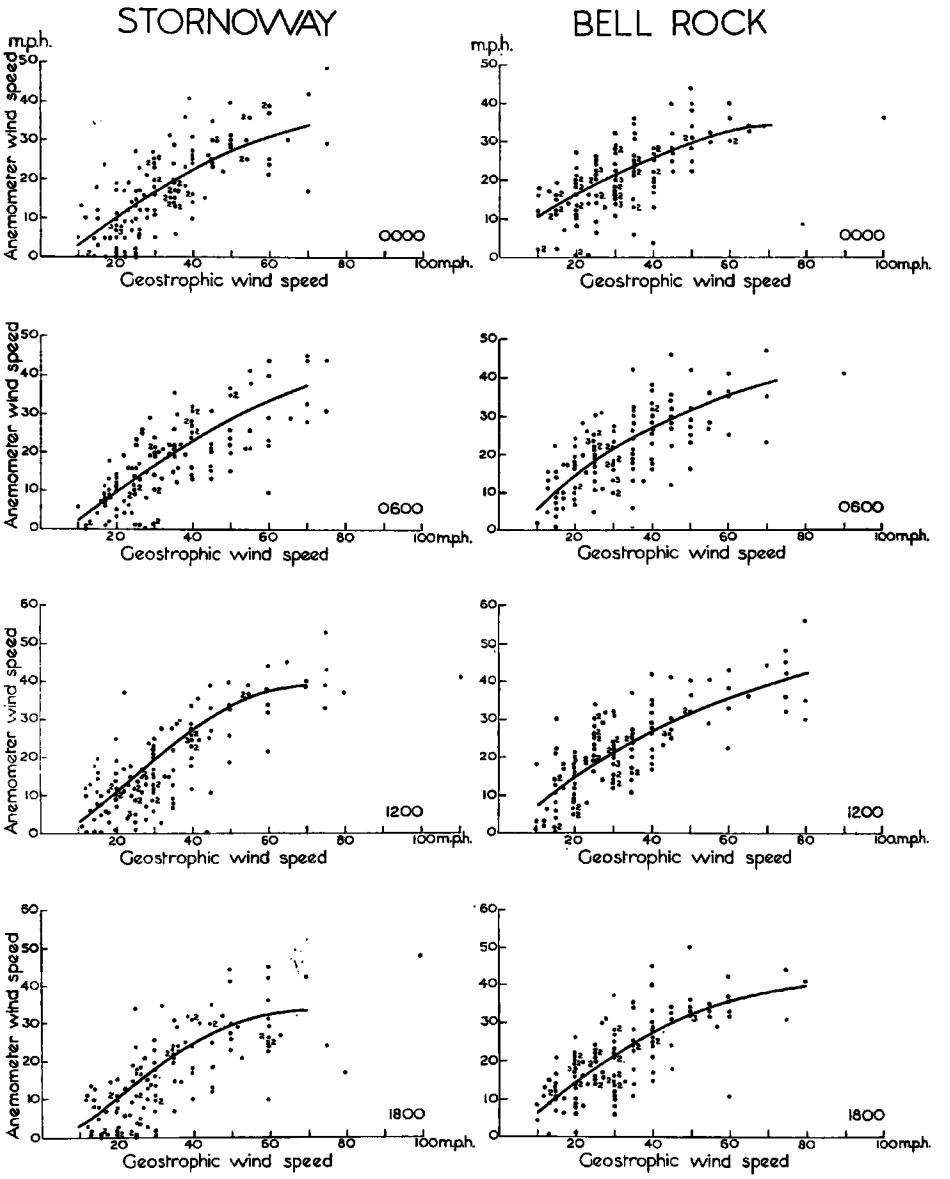
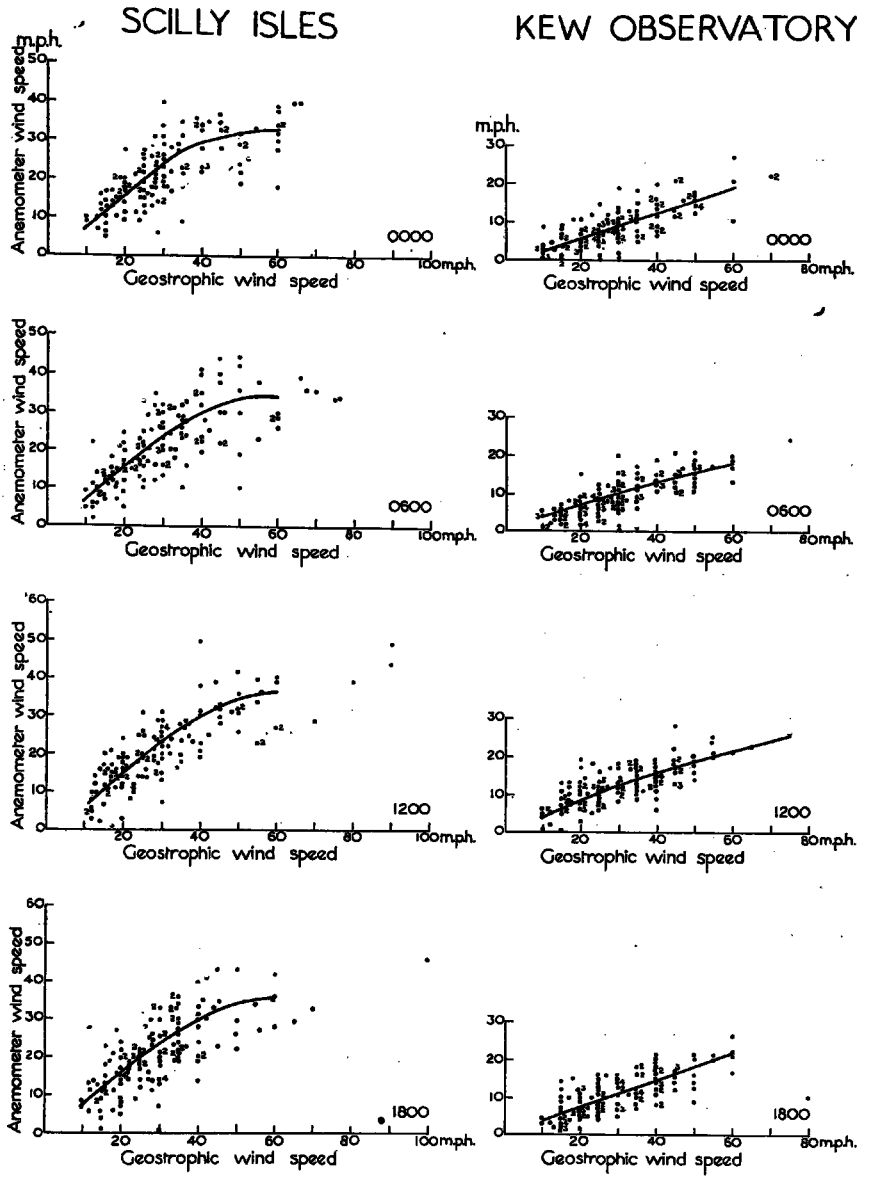


FIG. 5—COMPARISON OF MEAN HOURLY WIND SPEED RECORDED
Period : January 1–March 15,

Seasonal variation of wind speed.—The seasonal variation of surface wind speed compared with the geostrophic wind is summarized in Table V.

In winter and spring the surface wind at the Scilly Isles with northerly geostrophic winds was some 20–25 per cent. stronger than with geostrophic winds from a southerly direction. At Bell Rock the northerlies often resulted in stronger winds at the surface compared with the geostrophic winds than with the easterlies around dawn in summer and early autumn.

At Bell Rock and Kew Observatory the easterlies were not only least frequent in summer, but were also lightest compared with the geostrophic winds at that



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October 16–December 31, 1946

time of year. On summer evenings the wind at Bell Rock associated with easterly geostrophic winds was lighter than with comparable southerlies.

With southerly geostrophic winds the surface wind was relatively strongest in winter at Stornoway and the Scilly Isles, and in summer and autumn at Bell Rock.

The seasonal variation of surface wind with westerly geostrophic winds at the Scilly Isles was small, but at Stornoway and Kew Observatory the wind was relatively lighter with westerlies in winter than at other seasons.

TABLE V—SEASONAL VARIATIONS OF SURFACE WIND SPEED
all main synoptic hours

	Geostrophic wind	Jan.–Feb.	Mar.–Apr.	May–June	July–Aug.	Sept.–Oct.	Nov.–Dec.
		Average percentage of geostrophic wind speed					
Stornoway	Northerly	48 (44)	43 (17)	50 (48)	43 (52)	45 (20)	46 (37)
	Easterly	69 (5)	75 (34)	61 (49)	57 (25)	47 (41)	58 (30)
	Southerly	59 (76)	54 (60)	39 (53)	52 (54)	37 (73)	59 (76)
	Westerly	46 (94)	58 (113)	52 (51)	58 (88)	47 (60)	48 (56)
Bell Rock	Northerly	59 (46)	68 (26)	58 (32)	62 (33)	79 (24)	85 (37)
	Easterly	81 (6)	90 (49)	86 (50)	64 (17)	86 (42)	91 (24)
	Southerly	52 (54)	56 (40)	60 (48)	72 (40)	66 (73)	60 (72)
	Westerly	56 (108)	67 (107)	71 (58)	75 (101)	76 (58)	73 (72)
Scilly Isles	Northerly	80 (35)	85 (24)	71 (23)	68 (34)	68 (20)	82 (57)
	Easterly	73 (30)	60 (83)	52 (64)	81 (10)	73 (51)	71 (31)
	Southerly	61 (46)	58 (52)	45 (31)	53 (23)	58 (56)	60 (51)
	Westerly	70 (99)	70 (25)	60 (96)	72 (128)	65 (86)	79 (81)
Kew Observatory	Northerly	35 (32)	37 (31)	33 (24)	33 (27)	33 (21)	35 (39)
	Easterly	50 (25)	47 (67)	45 (73)	37 (3)	45 (53)	40 (34)
	Southerly	31 (28)	33 (19)	34 (30)	29 (23)	33 (51)	31 (49)
	Westerly	32 (113)	37 (53)	37 (84)	36 (137)	34 (86)	30 (90)

The figures in brackets are the number of observations of each geostrophic wind direction.

Abnormally strong winds.—Mean hourly surface wind speeds equal to the geostrophic wind speed occurred fairly frequently with geostrophic winds from the easterly quadrant at Stornoway, from the northerly, easterly and westerly quadrants at Bell Rock, and from the northerly and westerly quadrants at the Scilly Isles. At Kew Observatory the surface wind reached three-quarters of the geostrophic wind occasionally during the day-time with easterly geostrophic winds.

TABLE VI—PERCENTAGE FREQUENCY OF OCCURRENCE OF SURFACE WINDS EQUALLING THE GEOSTROPHIC WIND

Geostrophic wind	Stornoway	Bell Rock	Scilly Isles
	per cent.		
Northerly	3	16	22
Easterly	11	39	8
Southerly	5	6	6
Westerly	5	13	12

Noteworthy examples of these abnormally strong winds are given below :—

Northerly geostrophic winds.— Abnormally strong surface winds in a northerly type were mostly isolated occurrences with geostrophic winds of 25 m.p.h. or less, unstable temperature lapse rates near the surface and anticyclonic or slight cyclonic curvature of the sea-level isobars. At the openly exposed Bell Rock they occurred with geostrophic winds from all parts of the northerly quadrant, but at the Scilly Isles they were usually associated with geostrophic winds from the exposed section between north-west and north. Exceptionally, the surface wind speed at Bell Rock on November 7 and 8, 1946, exceeded northerly geostrophic winds of 40–45 m.p.h. A well marked cold front passed southwards

across the area soon after 0000 G.M.T. on November 7, followed by deep cold air. Unstable conditions continued until relatively warm air spread south-eastwards from Iceland on the 9th. Another short burst of polar air later the same day resulted in the surface wind again reaching the geostrophic speed for a time. Details are given in Table VII.

TABLE VII—ABNORMALLY STRONG SURFACE WINDS IN A NORTHERLY TYPE

1946	Time	Geostrophic wind			Surface wind	
		Curvature	Direction	Speed	Direction	Speed
	G.M.T.		°	m.p.h.	°	m.p.h.
Bell Rock						
November 7 ..	0000	c5	280	25	280	22
	0600	—	030	22	030	28
	1200	a3	030	28	010	32
	1800	—	020	40	020	45
November 8 ..	0000	—	030	50	020	44
	0600	—	030	45	020	46
	1200	—	040	40	040	42
	1800	a0	040	30	030	37
November 9 ..	0000	a5	020	40	020	25
	0600	a4	010	25	330	17
	1200	a2	020	40	030	35
	1800	a2	040	40	030	40

c = cyclonic curvature ; a = anticyclonic curvature ; — = straight isobars.

Although the surface wind at Kew Observatory did not reach the geostrophic speed in a northerly type it attained three-quarters of the geostrophic speed twice : at 1200 and 1800 G.M.T. on April 6. Both these occasions were associated with geostrophic winds of 10–20 m.p.h., very unstable temperature lapse rate up to 900 mb., and large anticyclonic curvature of the isobars.

Easterly geostrophic winds.—Surface wind speeds at Bell Rock frequently equalled and sometimes exceeded the easterly geostrophic wind. These abnormally strong winds occurred, on the average, in 5 cases out of 10 in the first half of the year, and were practically all associated with anticyclonic or straight isobars. Of the 37 cases at Bell Rock of well marked anticyclonic curvatures (i.e. isobars of radius 300 miles or less) there was only one case in which the mean hourly anemograph wind speed was less than half the geostrophic wind speed. Two spells of abnormally strong winds coincided with consistently unstable conditions up to at least 750 mb.

The instances of surface wind speed attaining the geostrophic wind speed at Stornoway and the Scilly Isles were mostly with speeds of less than 20 m.p.h. A few occurrences at both places with speeds of 25–30 m.p.h. were associated with unstable lapse rates in the lowest layers at nearby upper air sounding stations.

The mean hourly surface wind speed at Kew Observatory reached three-quarters of the geostrophic wind speed on 1 occasion out of 21 on the average. Most of these cases occurred with anticyclonic curvature of the isobars at midday, and with one exception all occurred in the first four months of the year. The occurrences of relatively strong winds at Kew Observatory with geostrophic winds of 20 m.p.h. or more are detailed in Table VIII. Upper air soundings in southern England indicated superadiabatic temperature lapse rates near the ground in all cases.

TABLE VIII—ABNORMALLY STRONG SURFACE WINDS IN AN EASTERLY TYPE

1946	Time	Geostrophic wind			Surface wind	
		Curvature	Direction	Speed	Direction	Speed
	G.M.T.		°	m.p.h.	°	m.p.h.
Kew Observatory						
January 2 ..	0600	a2	115	20	080	15
March 31 ..	1200	a2	090	20	065	15
April 10 ..	1200	a7	055	20	035	16
May 5	1200	a4	045	25	020	20
September 28 ..	1200	a4	100	20	070	16

a = anticyclonic curvature.

Southerly geostrophic winds.—Mean hourly surface winds equalled the geostrophic wind much less frequently at Bell Rock with southerly geostrophic winds than with any other type. Most of the occurrences were at 1800 G.M.T. Abnormally strong winds were also infrequent at the Scilly Isles. At Stornoway they were unusual with geostrophic winds from between S and SE. and fairly common with geostrophic winds from between S and SW. The outstanding cases listed on Table IX were all associated with very unstable temperature lapse rates near the surface.

TABLE IX—ABNORMALLY STRONG SURFACE WINDS IN A SOUTHERLY TYPE

1946	Time	Geostrophic wind			Surface wind	
		Curvature	Direction	Speed	Direction	Speed
	G.M.T.		°	m.p.h.	°	m.p.h.
Stornoway						
January 21 ..	0600	c2	205	35	180	36
October 30 ..	1800	a0	200	32	160	35
Bell Rock						
December 15 ..	1200	a3	180	35	180	37
Scilly Isles						
October 17 ..	1800	a1	135	28	120	30

c = cyclonic curvature ; a = anticyclonic curvature.

Of the 200 occurrences of southerly geostrophic winds at Kew Observatory the surface wind speed reached three-quarters of the geostrophic wind speed on three occasions, all in spring or autumn at midday or 1800 G.M.T. with geostrophic winds of less than 20 m.p.h.

Westerly geostrophic winds.—Mean hourly winds attained the geostrophic wind speed fairly frequently with westerly geostrophic winds at Bell Rock and the Scilly Isles, mostly in deep polar air but occasionally in unstable warm air. Some of these latter cases are marked with an asterisk in Table X.

The connexion between the temperature lapse rate in the lowest layers and the surface wind speed was exemplified at Bell Rock on March 26–27. At midday on March 26 the upper air sounding in warm air at Leuchars indicated very unstable conditions up to 950 mb. with a temperature inversion above that level. At 0600 G.M.T. on the 27th, when the surface wind at Bell Rock had decreased to half the geostrophic wind speed though still in the same air mass, the air was isothermal from the surface to 850 mb.

TABLE X—ABNORMALLY STRONG SURFACE WINDS IN A WESTERLY TYPE

1946	Time	Geostrophic wind			Surface wind	
		Curvature	Direction	Speed	Direction	Speed
	G.M.T.		°	m.p.h.	°	m.p.h.
Stornoway						
December 21* ..	0000	a0	250	40	200	41
Bell Rock						
March 26*	1200	a2	280	25	270	28
	1800	a3	280	15	270	23
March 27*	0000	a4	290	15	300	24
	0600	a2	260	20	250	11
June 5 ..	1800	c8	260	50	260	50
Scilly Isles						
January 30 ..	1200	a0	300	40	290	50
February 23* ..	0600	—	285	40	270	41
December 7 ..	0600	c4	280	40	280	40
December 26 ..	1800	—	305	40	310	40

* Unstable warm air. c = cyclonic curvature; a = anticyclonic curvature; — = straight isobars.

Abnormally light winds.—Mean hourly surface wind speeds less than a quarter of the geostrophic wind speed were infrequent at the open exposures at Bell Rock and the Scilly Isles. The relatively high frequency shown for Bell Rock in Table XI with northerly geostrophic winds is dealt with in more detail below and on p. 18. Such abnormally light surface winds were common at Kew Observatory at night. At midday they were more frequent at Stornoway than at Kew Observatory, especially with geostrophic winds from SSE.

TABLE XI—PERCENTAGE FREQUENCY OF OCCURRENCE OF SURFACE WINDS LESS THAN A QUARTER OF THE GEOSTROPHIC WIND

Geostrophic wind	Stornoway†	Bell Rock*	Scilly Isles*	Kew Observatory†
	per cent.			
Northerly	13	12	3	4
Easterly	10	1	5	5
Southerly	20	6	1	2
Westerly	4	3	2	6

* All main synoptic hours. † 1200 G.M.T. only

Northerly geostrophic winds.—The rather frequent number of occasions on which the surface winds at Bell Rock were much lighter than would be expected from the pressure gradient occurred almost exclusively with geostrophic winds estimated from the charts to be from west of north. They were probably due to the presence of small lee depressions in the Bell Rock area formed by the passage of the north-westerly air stream over the mountains of Scotland. Abnormalities in wind direction were also well marked with geostrophic winds from between NW. and N. (see p. 18).

Abnormally light winds compared with the geostrophic winds were rare at the Scilly Isles. Most of the instances were with slack pressure gradients, but at 1200 G.M.T. on February 16 the surface wind was 310°, 7 m.p.h. with an

estimated geostrophic wind of 320°, 30 m.p.h. A warm anticyclone was centred near the Scilly Isles at the time. The upper air soundings at Penzance showed the air mass to be unstable up to 3,500 ft. with a well marked temperature inversion at about that level.

Surface wind speeds less than a quarter of the geostrophic wind speed were more frequent at midday at Stornoway than at Kew Observatory, practically all cases being associated with geostrophic winds of 20 m.p.h. or less.

Easterly geostrophic winds.— Surface winds less than a quarter of the geostrophic wind speed were infrequent with easterly geostrophic winds at Stornoway and Kew Observatory during the day-time, and at Bell Rock throughout the 24 hr. The few cases at these places were mostly associated with cyclonic curvature of the isobars, but they had no common temperature lapse rate. The surface wind at Kew Observatory at 0000 G.M.T. on December 9, 1946, was 15°, 11 m.p.h., compared with a geostrophic wind of 70°, 60 m.p.h. Cyclonic curvature of the isobars on that occasion was very pronounced.

At the Scilly Isles, however, abnormally light winds at the surface were more frequent with easterly geostrophic winds than with any other type. At 1800 G.M.T. on May 18 and at 0000 G.M.T. on May 19 the wind at the Scilly Isles was calm with geostrophic wind 70–105°, 40 m.p.h. and very pronounced cyclonic curvature of the isobars. The Scilly Isles were then near the centre of an almost stationary depression. The upper air sounding at Penzance at 1800 G.M.T. May 18 indicated an unstable temperature lapse rate, but the slightly lower surface temperature at the Scilly Isles may have resulted in a shallow temperature inversion near the ground.

Southerly geostrophic winds.— Southerly geostrophic winds were favourable for abnormally light surface winds at Bell Rock, but at the Scilly Isles mean hourly wind speeds less than a quarter of the geostrophic wind speed were uncommon. Most of the instances at midday at Stornoway occurred with geostrophic winds from east of south. The abnormally light winds detailed in Table XII were mostly associated with inversion or isothermal conditions near the surface, though at Stornoway on December 14 there was a 2–3° F. temperature fall in the first 1,500 ft. with an inversion at 3,000 ft.

TABLE XII—ABNORMALLY LIGHT WINDS IN A SOUTHERLY TYPE

1946	Time	Geostrophic wind			Surface wind	
		Curvature	Direction	Speed	Direction	Speed
	G.M.T.		°	m.p.h.	°	m.p.h.
Stornoway						
May 29	1200	c0	140	45	090	6
December 14 ..	1800	—	160	80	140	17
Bell Rock						
January 21 ..	0600	a0	205	35	240	1
November 4 ..	0000	—	210	30	220	4
Scilly Isles						
August 9 ..	1200	a6	190	23	..	1
Kew Observatory						
December 8 .	1800	c8	140	80	075	10
December 11 .	0600	c1	170	60	140	13

c = cyclonic curvature ; a = anticyclonic curvature ; — = straight isobars.

Westerly geostrophic winds.—Surface winds less than a quarter of the geostrophic were infrequent with westerly geostrophic winds. The few such occurrences at Bell Rock and the Scilly Isles were mostly associated with old or slow-moving depressions.

Gales.—The geostrophic winds on the occasions of mean hourly wind speeds of 39 m.p.h. or more (Beaufort force 8 or more) are shown in Table XIII. Winds of force 7, although described as " moderate gale " in the Beaufort scale, are not counted as gales in official summaries.

TABLE XIII—GALES AT MAIN SYNOPTIC HOURS 1946

Geostrophic winds (all directions)	Stornoway	Bell Rock	Scilly Isles
m.p.h.		*Number of gales*	
30–39	..	1	1
40–49	2	7	9
50–59	7	10	8
60–69	8	5	7
70–79	11	7	1
⩾80	2	3	5
Total	30	33	31

Gales occurred most frequently with geostrophic winds from SSW. at Stornoway, from westerly and north-easterly directions at Bell Rock and from WSW. to NW. at the Scilly Isles. While southerly geostrophic winds of 60 m.p.h. resulted in gales frequently at Stornoway and occasionally at Bell Rock there were no gales at the Scilly Isles in a southerly type with geostrophic winds of less than 80 m.p.h.

Comparison of gales at Leuchars and Bell Rock.—Strong NNE. gales blew at Bell Rock during the abnormally rough period of November 7–8, while the wind at Leuchars (56° 23′ N., 2° 53′ W.) was only moderate in strength. Strictly comparable wind data for the two places are not available; but wind speed was measured hourly at Leuchars by cup anemometer for synoptic reporting purposes, and these values have been taken as representative of the wind along the coast for comparison with the mean hourly wind speeds recorded at Bell Rock, more than 20 miles out at sea. The local surroundings at Leuchars are shown in Fig. 6.

The midnight and midday differences between the surface wind speed at Bell Rock and at Leuchars are plotted against the geostrophic wind in Fig. 7. Wind speed at the two places showed a fairly consistent relationship with easterly geostrophic winds, but in general the wind became progressively stronger at Bell Rock compared with that at Leuchars as the pressure gradient increased, especially with northerly and southerly geostrophic winds at night.

The amount by which the mean hourly wind speed at Bell Rock differed from the Leuchars wind speed during the 244 hr. of gale at Bell Rock during 1946 is given in Table XIV.

Gales were more frequent at Bell Rock in day-time than at night. The diurnal difference between the Bell Rock and Leuchars wind speeds during gales was noticeable though not large.

TABLE XIV—DIFFERENCE IN WIND SPEED (BELL ROCK MINUS LEUCHARS) DURING GALES

Direction of gale	Bell Rock – Leuchars wind speed					Hours with gale
	−5 to −1 m.p.h.	0 to 9 m.p.h.	10 to 19 m.p.h.	20 to 29 m.p.h.	30 to 39 m.p.h.	
°	*Number of hours*					
10– 40	..	..	5	28	12	45
50– 80	..	..	1	3	..	4
90–120	..	1	18	6	..	25
130–160	..	..	4	4	..	8
170–200	..	..	6	29	3	38
210–240	1	3	8	7	..	19
250–280	..	12	41	34	..	87
290–320	..	1	8	5	..	14
330–360	..	..	3	1	..	4
Hours with gale	1	17	94	117	15	244

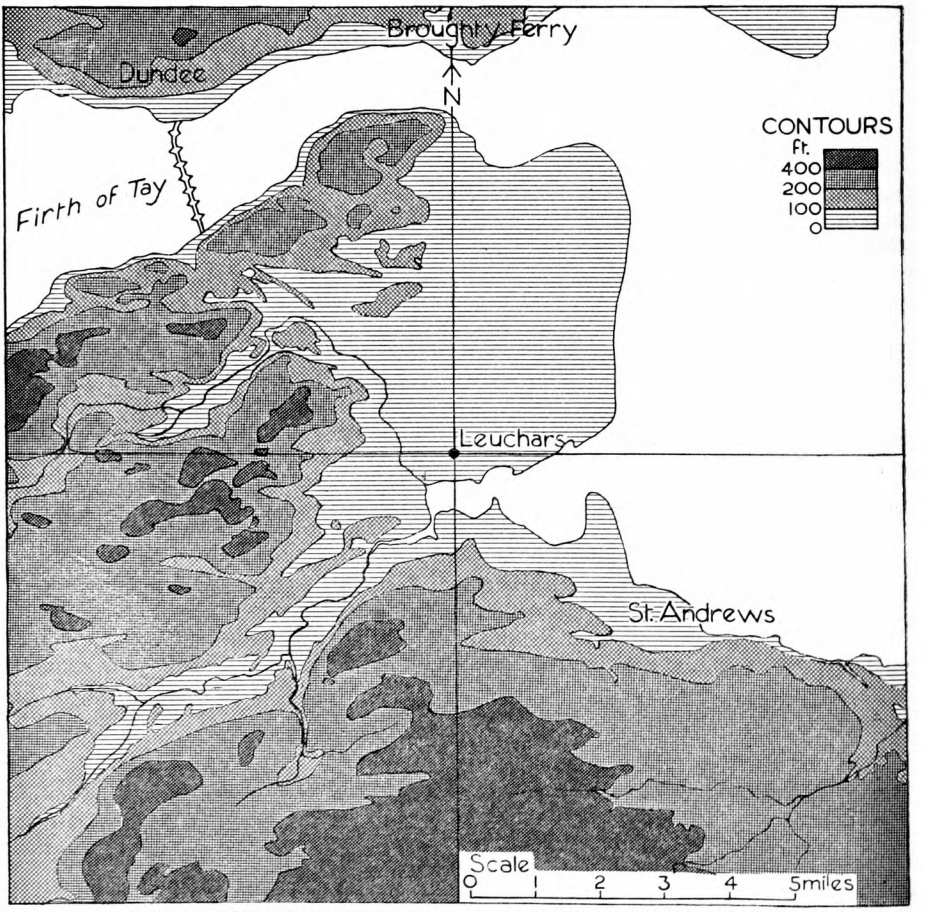


FIG. 6—SURROUNDINGS OF ANEMOMETER AT LEUCHARS

TABLE XV—INCIDENCE OF GALES AT BELL ROCK AND ASSOCIATED WIND-SPEED DIFFERENCES (BELL ROCK MINUS LEUCHARS)

Time of gale	Hours with gale	-5 to -1 m.p.h.	0 to 9 m.p.h.	10 to 19 m.p.h.	20 to 29 m.p.h.	30 to 39 m.p.h.	Average
G.M.T.		*Number of occasions*					
0100–0300	19	..	1	7	9	2	21
0400–0600	20	..	1	7	10	2	20
0700–0900	31	..	..	14	14	3	21
1000–1200	41	..	3	14	24	..	19
1300–1500	50	1	6	23	19	1	16
1600–1800	32	..	3	15	12	2	19
1900–2100	29	..	2	8	17	2	21
2200–0000	22	..	1	6	12	3	22

Surface wind speed and curvature of the isobars.—Surface winds were markedly stronger with anticyclonic curvature of the isobars than with cyclonic curvature at Bell Rock, with its unobstructed exposure for the anemograph, and to a less extent at the Scilly Isles, especially with geostrophic winds of up to 30 m.p.h. At 1200 G.M.T. this feature was also noticeable at Kew Observatory, but it was scarcely perceptible at Stornoway.

TABLE XVI—SURFACE WIND SPEED AND ISOBARIC CURVATURE

Sea-level curvature of the isobars	Surface wind speed			
	Stornoway†	Bell Rock*	Scilly Isles*	Kew Observatory†
	Average percentage of geostrophic wind			
All pressure gradients				
Cyclonic	56	63	62	43
Anticyclonic	58	74	70	49
Geostrophic winds of 10–29 m.p.h.				
Large cyclonic	59	61	64	35
Moderate cyclonic	65	63	72	46
Small cyclonic	57	74	74	53
Small anticyclonic	61	76	77	53
Moderate anticyclonic ..	56	79	70	60
Large anticyclonic	70	91	73	49

* All main synoptic hours † 1200 G.M.T. only

Large curvature = isobars of radius 50– 150 miles
Moderate curvature = isobars of radius 200– 500 miles
Small curvature = isobars of radius 700–1,100 miles.

Average deviation of surface wind from the isobars.—The percentage frequency of occasions when the surface wind direction was backed or veered from the isobars in steps of 10° is shown diagrammatically in Figs. 8–12, in which the radius of each 10° segment depends on the frequency with which the wind was backed or veered from the sea-level isobars by the amounts given. The figures enclosed in the circles refer to those occasions when the wind was more than 90° different from the isobars. In general, these cases were associated with slack pressure gradients.

Northerly geostrophic winds.—On the whole, surface winds at Stornoway and Kew Observatory were backed some 10–30° with northerly geostrophic winds; rather more at Kew Observatory than at Stornoway. Surface winds at the

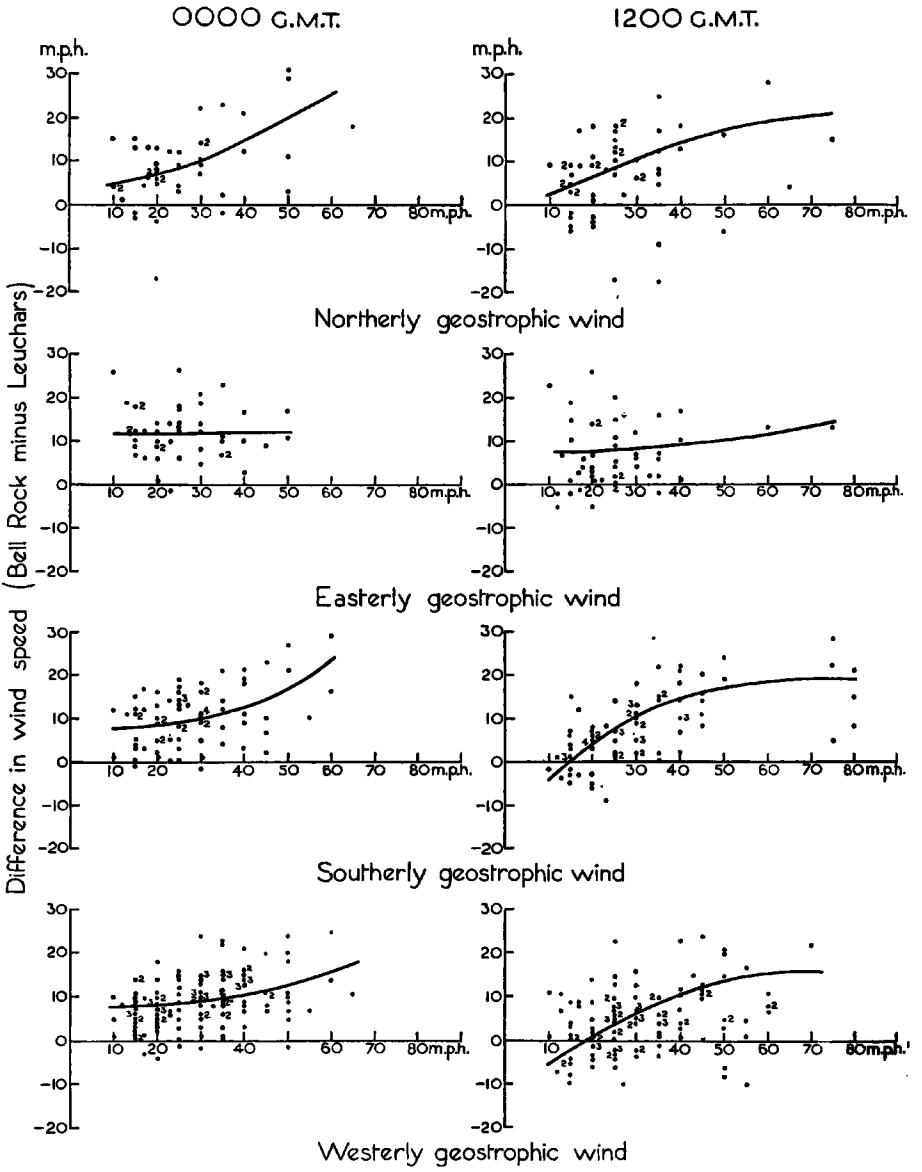


FIG. 7—DIFFERENCE BETWEEN WIND SPEEDS MEASURED AT BELL ROCK AND LEUCHARS AT MIDNIGHT AND MIDDAY

Scilly Isles were within 10° of the isobars on 51 per cent. of occasions ; they were backed less from the open exposure to west of north than from east of north, where the small amount of ground on the island rising to 100 ft. seemed to cause some additional backing.

At Bell Rock differences between the surface wind direction and the isobars were very irregular over the quadrant as a whole. The diagram relating to northerly geostrophic winds at Bell Rock in Fig. 8 has been subdivided into the sectors 320–360° and 10–40° of which the northerly quadrant diagram is compounded (see Fig. 9). With geostrophic winds from east of north surface

winds bore a fairly consistent relationship to the isobars. The continued large differences in the 320–360° octant, combined with the surface-wind-speed abnormalities referred to on p. 13, emphasize the need for caution in estimating surface wind over the sea to the lee of mountains. Lee troughs or depressions in the Bell Rock area with NNW. air streams that have travelled over the mountains are often not shown on medium-scale synoptic charts on which smoothed isobars are necessarily drawn at 2 mb. or even larger intervals.

Easterly geostrophic winds.—Surface winds at all four places were backed appreciably more with easterly geostrophic winds than with any other type. The backing often amounted to 30–50° at Kew Observatory and Stornoway, and to 10–30° at the Scilly Isles. The subdivision at Fig. 10 of the easterly quadrant diagram for Bell Rock indicates that the irregular surface wind direction was associated more with geostrophic winds from north of east than from south of east.

Southerly geostrophic winds.—Winds at the level of the Bell Rock anemograph were close to the general run of the sea-level isobars with southerly geostrophic winds. Surface wind was backed rather less on the average at the Scilly Isles than at Stornoway or Kew Observatory.

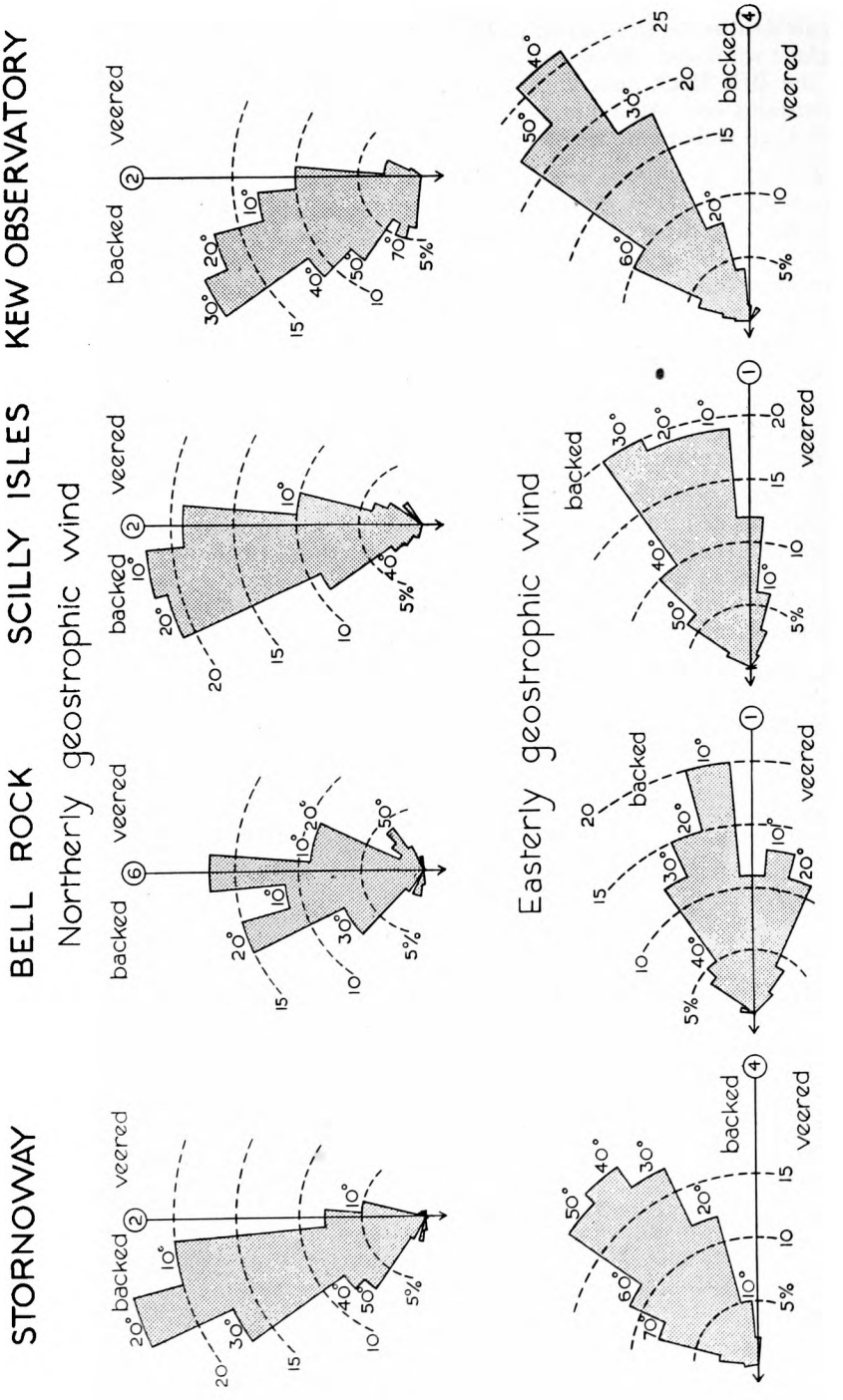
Westerly geostrophic winds.—Winds at Stornoway and Kew Observatory were mostly backed 20–40° from the sea-level isobars in a westerly type. At Bell Rock and the Scilly Isles the wind was within 10° of the isobars on more than half the cases examined, and within 20° of the isobars on about 8 cases out of 10. The wind at the Scilly Isles, from the open 230–360° sector shown diagrammatically in Fig. 11, exhibits the same general features.

Diurnal variation of wind directions.—Taking the periods January 1–March 15 and October 16–December 31, when the sun was below the horizon at 0600 and 1800 G.M.T., the deviation of the surface wind from the isobars at each of the main synoptic hours is summarized in Table XVII.

TABLE XVII—DEVIATION OF SURFACE WIND FROM ISOBARS WITH TIME OF DAY IN WINTER

Period: January 1–March 15, 1946. October 16–December 31, 1946

	Time	Deviation from isobars				
		Backed		Within	Veered	
		50–70°	20–40°	10°	20–40°	50–70°
	G.M.T.	*percentage number of occasions*				
Stornoway ..	0000	18	61	19	2	..
	0600	14	63	21	1	..
	1200	14	58	23	4	1
	1800	14	57	21	..	..
Bell Rock ..	0000	2	20	51	24	2
	0600	1	22	55	20	1
	1200	1	17	52	23	4
	1800	3	16	59	17	3
Scilly Isles ..	0000	4	22	64	7	..
	0600	6	23	62	5	2
	1200	3	35	51	8	3
	1800	2	36	50	8	1
Kew Observatory	0000	32	48	14	..	..
	0600	31	52	5	5	..
	1200	10	59	26	2	..
	1800	18	64	12	4	..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SCILLY ISLES
KEW OBSERVATORY
Northerly geostrophic wind
Easterly geostrophic wind
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veered
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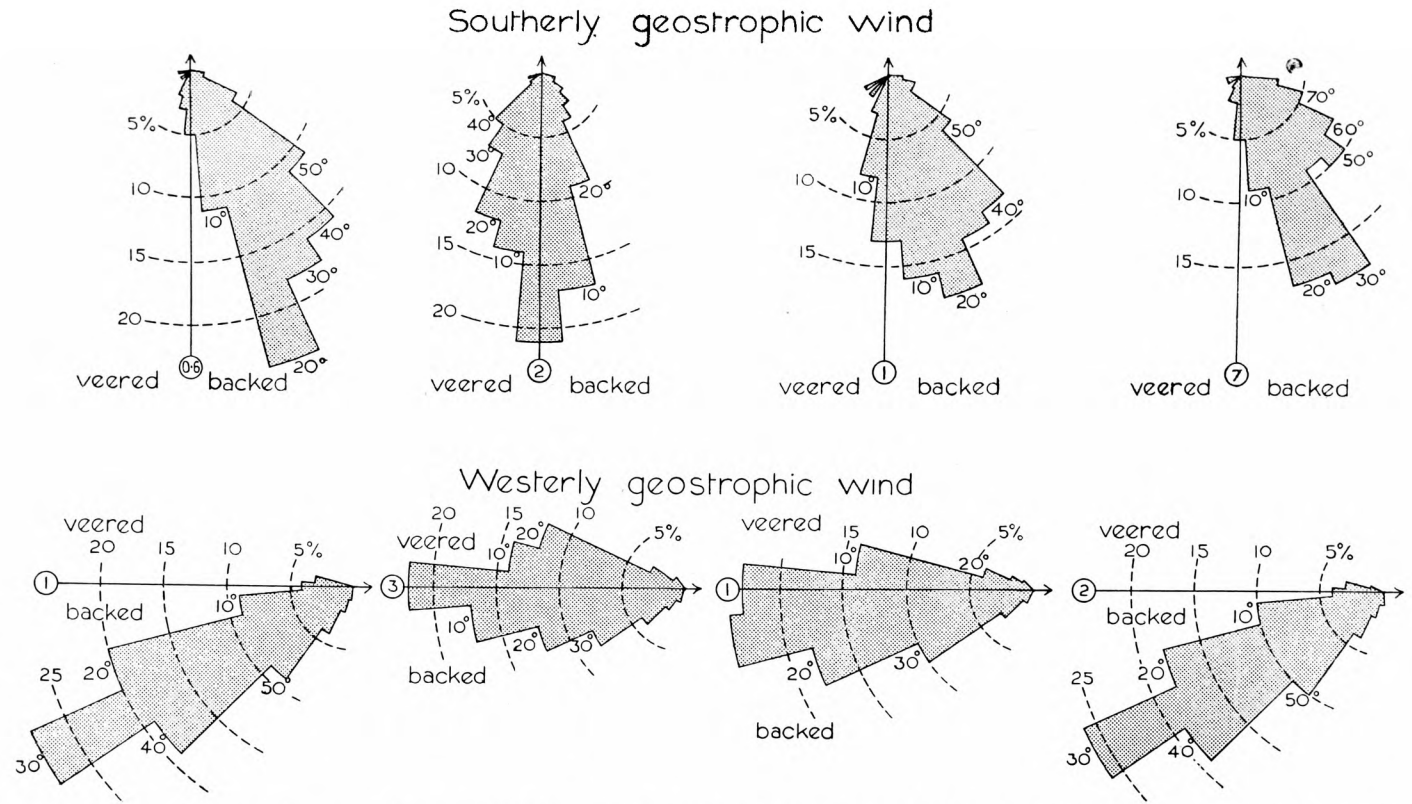
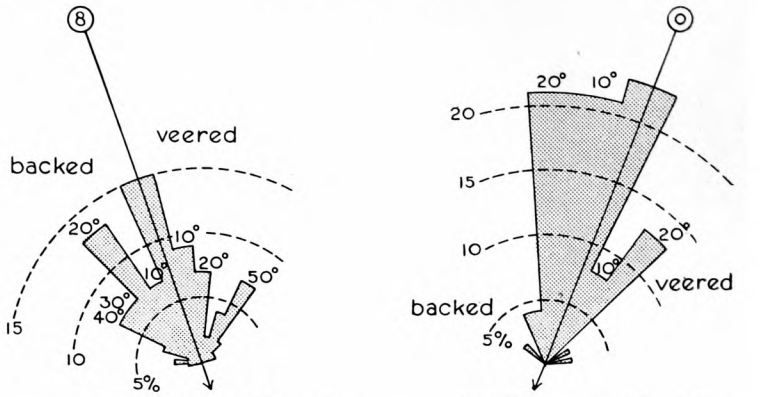


FIG. 8—DEVIATION OF SURFACE WIND FROM ISOBARS AT STORNOWAY, BELL ROCK, SCILLY ISLES AND KEW OBSERVATORY

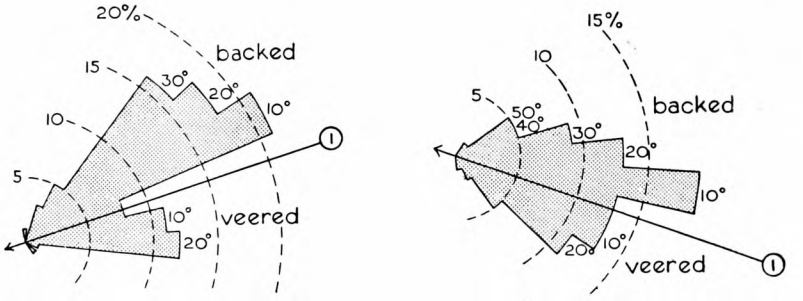
The length of each 10° segment represents the percentage frequency with which winds recorded by anemograph were backed or veered from the isobars at mean sea level by the amounts given.

The figures in the circles give the percentage frequency of directions more than 90° from the direction of the isobars.



(*a*) NNW. geostrophic wind (*b*) NNE. geostrophic wind

FIG. 9—DEVIATION OF SURFACE WIND FROM ISOBARS AT BELL ROCK WITH NNW. AND NNE. GEOSTROPHIC WINDS



(*a*) ENE. geostrophic wind (*b*) ESE. geostrophic wind

FIG. 10—DEVIATION OF SURFACE WIND FROM ISOBARS AT BELL ROCK WITH ENE. AND ESE. GEOSTROPHIC WINDS

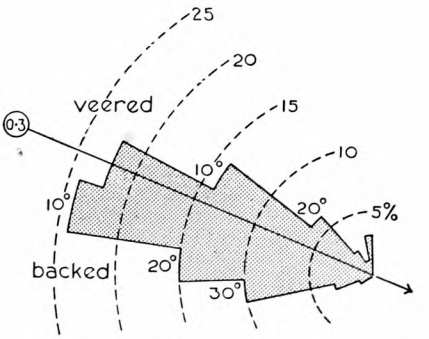


FIG. 11—DEVIATION OF SURFACE WIND FROM THE ISOBARS AT SCILLY ISLES WITH GEOSTROPHIC WINDS BETWEEN SW. AND N. THROUGH W.

The greater detail contained in Fig. 12 indicates that winds were backed about 10° more at night than by day at Stornoway and Kew Observatory on the average. At Bell Rock winds were backed rather more at 1800 G.M.T. than at the other main synoptic hours but were close to the isobars at both 0600 G.M.T. and 1800 G.M.T., and seemed often to be veered a little from the geostrophic wind direction at midday and midnight. At the Scilly Isles the wind deviated little from the general run of the isobars at night and was backed 10–20° by day.

Conclusions.—Wind speed near the surface depended not only on the intensity of the pressure gradient but also on the temperature lapse rate. Diurnal variation of wind strength was well marked inland, and on the coast with off-shore winds. Over the open sea wind speed seemed also to be related to the curvature of the isobars.

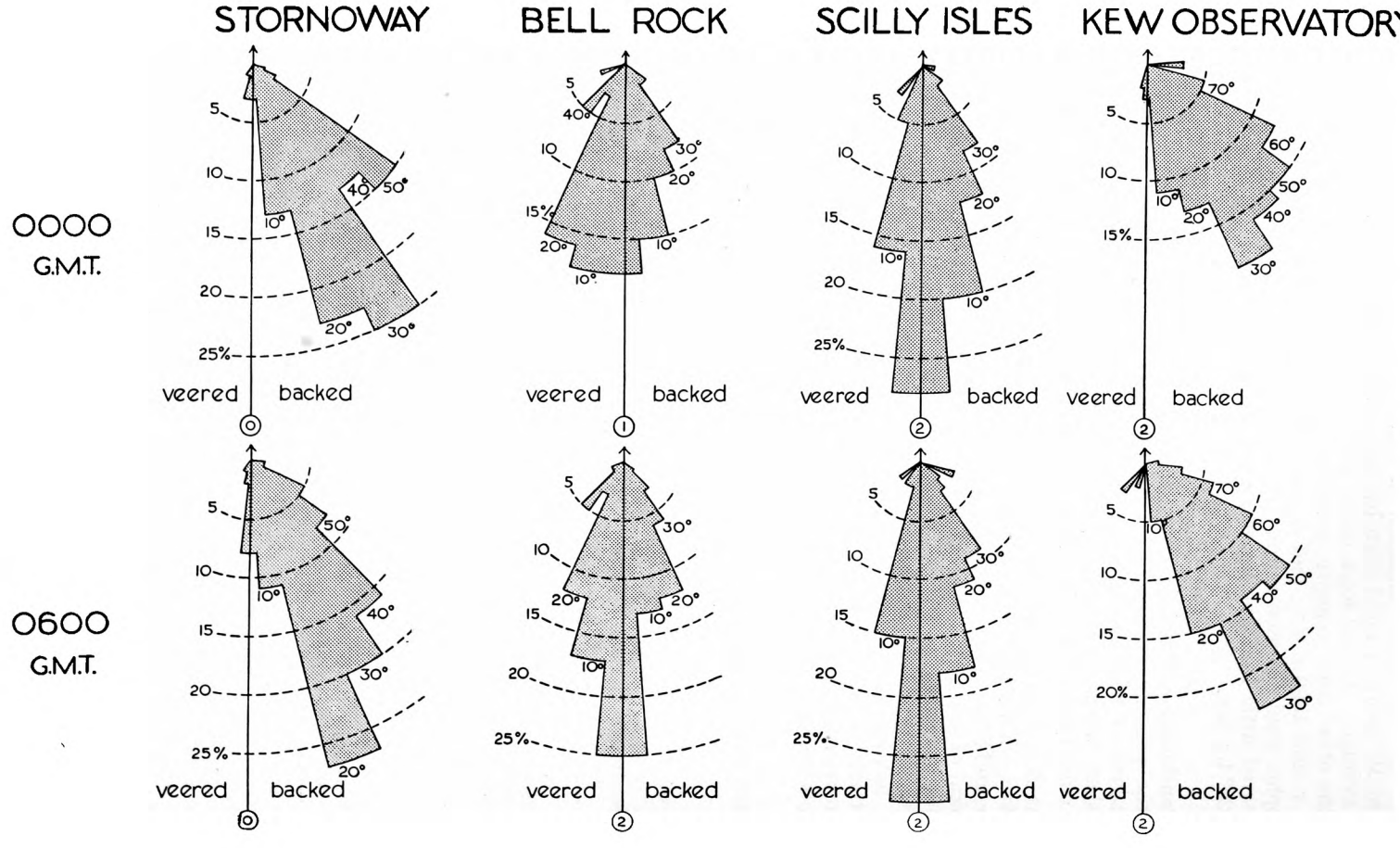
At Bell Rock and Kew Observatory, on the eastern side of the British Isles, surface wind was strongest compared with the geostrophic wind in an easterly type and lightest in a southerly type. Relatively light surface winds were also typical of southerly geostrophic winds at the Scilly Isles, though the strongest winds in relation to the geostrophic winds at the Scilly Isles occurred with a northerly type. At Stornoway, presumably because of its sheltered position, the lightest surface winds were associated with geostrophic winds from a northerly or westerly point, while southerly geostrophic winds of 50 m.p.h. or more resulted in stronger winds at the surface than with comparable geostrophic winds from any other direction.

TABLE XVIII—AVERAGE RATIO OF SURFACE WIND SPEED TO THE GEOSTROPHIC WIND SPEED

Geostrophic wind	Stornoway				Bell Rock			
	10–49 m.p.h.		⩾ 50 m.p.h.		10–49 m.p.h.		⩾ 50 m.p.h.	
	Mid-night	Mid-day	Mid-night	Mid-day	Mid-night	Mid-day	Mid-night	Mid-day
	average percentage of geostrophic wind							
Northerly ..	36	47	43	51	62	69	66	53
Easterly ..	54	66	46	..	92	88	69	64
Southerly ..	51	51	59	58	60	62	57	54
Westerly ..	47	61	46	52	71	68	59	61

Geostrophic wind	Scilly Isles				Kew Observatory			
	10–49 m.p.h.		⩾ 50 m.p.h.		10–49 m.p.h.		⩾ 50 m.p.h.	
	Mid-night	Mid-day	Mid-night	Mid-day	Mid-night	Mid-day	Mid-night	Mid-day
	average percentage of geostrophic wind							
Northerly ..	82	77	61	55	27	47	28	54
Easterly ..	66	64	..	41	39	56	24	..
Southerly ..	60	65	47	48	27	43	26	35
Westerly ..	76	71	54	58	28	42	33	37

Abnormally strong winds compared with the geostrophic winds were usually associated with unstable temperature lapse rates near the surface, and abnormally light winds with temperature inversions, but winds to the lee of mountains much lighter than would be expected from the pressure gradient were often due to the presence of small local troughs of low pressure.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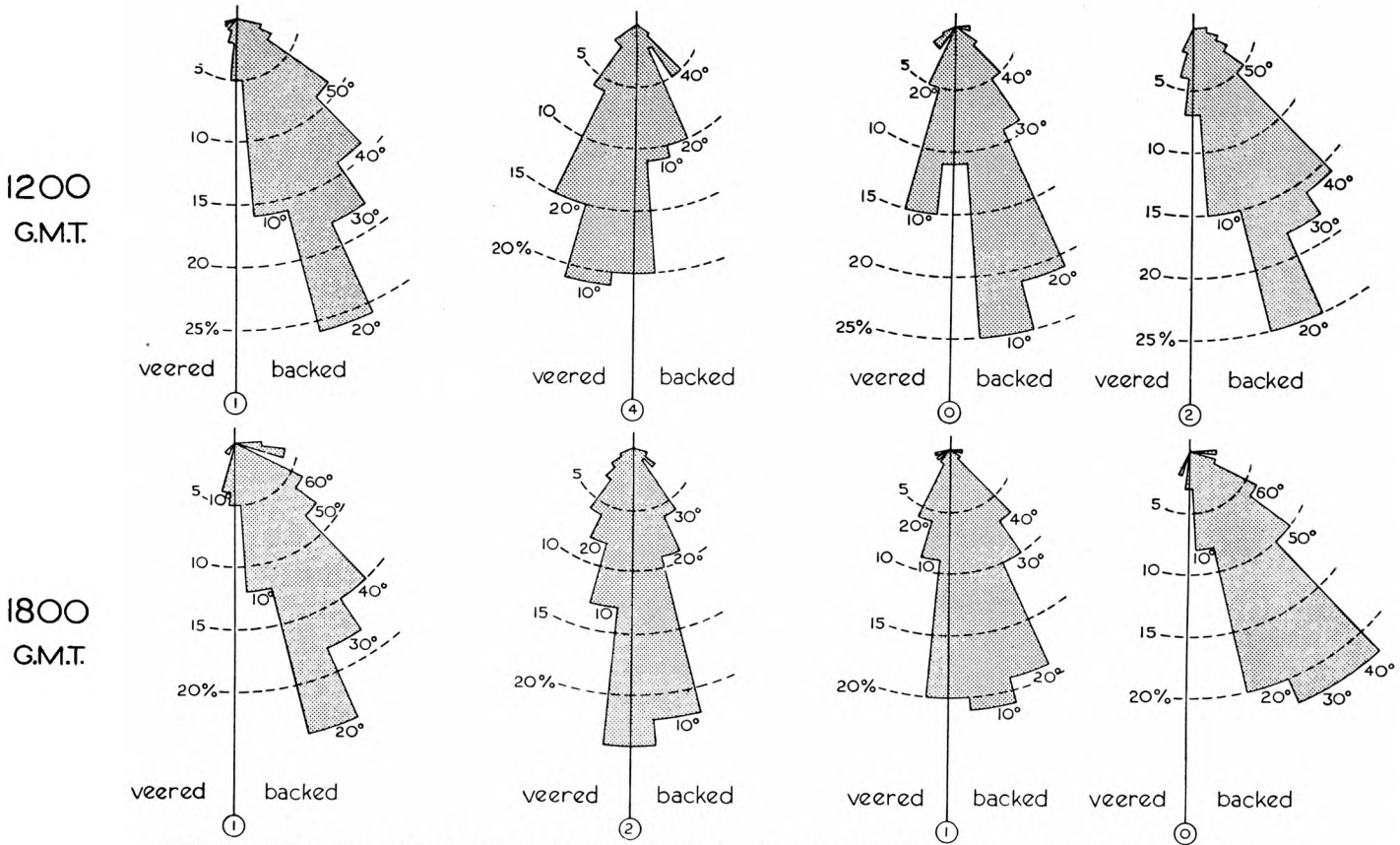

FIG. 12—DEVIATION OF SURFACE WINDS OF ALL DIRECTIONS FROM ISOBARS WITH TIME OF DAY
The figures in the circles give the percentage frequency of directions more than 90° from the direction of the isobars.

There were no instances of mean hourly wind speeds of gale force at Kew Observatory. When gales were blowing at Bell Rock Lighthouse the wind at Leuchars, on the coast, was four to five points lighter on the Beaufort wind scale on 27 per cent. of occasions and two to three points lighter on 61 per cent. of occasions. Exceptionally, mean hourly winds of 47–48 m.p.h. occurred at Bell Rock while the wind averaged only 12 m.p.h. at Leuchars.

Surface winds were stronger compared with the geostrophic wind with anticyclonic curvature of the isobars than with cyclonic curvature, especially at sea.

On the average, wind direction at the height of the Bell Rock anemograph was little different from the mean-sea-level isobars with winds from SE. through S. to NW. Similarly, wind direction at the Scilly Isles, where the anemograph is openly exposed to the sea, was in close agreement with the isobars with SW. through W. to NW. winds. Surface winds generally were backed most with geostrophic winds from an easterly direction, and inland were backed some 10° more at night than by day.

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