Met O 11. Technical Note No. 28

The effect of changes of atmospheric stability and surface roughness on off-shore winds over the East Coast of Britain

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Introduction

It is an observable fact that surface winds are affected by changes in surface roughness and in atmospheric stability. In particular, winds blowing across a coastline undergo changes in direction and speed because of the change in the surface roughness characteristics and also because of the changes in the atmospheric stability of the lower layers, due to the different thermal properties of the land and sea surfaces. A knowledge of the winds over the sea is of obvious importance to shipping, sailing enthusiasts and fishermen, who have a direct interest in the wind strength and direction, and in the waves and currents that the winds induce. Not so obvious is the interest of river-boards engineers and costguards. Their concern in this respect is the generation of storm surges (abnormally high tides) by strong wind fields over the sea. Because it is relatively shallow and partially enclosed the North Sea is nearly ideally suited for the generation of wind induced surges. As a result of this interest in the structure of the wind over the sea the meteorologist is often required to supply relevant information, which in view of the lack of on the spot observations is a difficult task.

At any given time a coastal observing station on the East Coast can supply anemograph data which determine the local wind field. These local winds will differ from station to station because of the varying effects of topography and exposure. The North Sea itself is almost devoid of wind observations except for a few light ships and the occasional report from a commercial vessel. In order to gain some insight into the structure of the wind field over the main sea areas, say up to fifty miles from the coastline, the following investigation was undertaken. A long series of simultaneous wind observations taken at a coastal station and at a light-vessel stationed in adjacent waters were examined and an empirical relationship between the observed winds at the two stations was arrived at.

A description of some previous work on this subject, together with a review of other, earlier, work may be found in Richards, Dragert and McIntyre (1966) referred to in this paper as [A]. All the work referred to in [A] was carried out over the Great Lakes of North America, and the findings of that work will be compared to the results arrived at in this account. One major difference must be pointed out from the beginning; since Richards et alia found that the length of over water fetch was an important factor when considering the changes in wind when it blows off land onto water, it was decided to consider only off-shore winds in this paper so that the variations in fetch for our observations would be small.

Data

The observing stations used in this investigation were Gorleston, on the Norfolk coast, and the Smith's Knoll Light Vessel. The light vessel is positioned about twenty miles off-shore on a bearing of approximately 070° from Gorleston, this direction being nearly perpendicular to the coastline. Observations from the ten years 1957-1966 were used. Off shore winds were defined as blowing from between 210° and 290° at Gorleston, and to ensure that both observations were made in the same air-mass the criterion

$$|\text{direction at Gorleston} - \text{direction at Smith's Knoll}| \leqslant 30^\circ$$

/was applied.

was applied. Observations not satisfying this criterion were discarded and in this way the chance of there being an intervening frontal discontinuity was minimised. Under these conditions a total of 3366 simultaneous observations were retained as being suitable for analysis. The data were extracted from punched cards in the Meteorological Office records and put onto magnetic tape, each individual observation consisting of the following information:-

Year, month, day, hour, wind direction, wind speed, temperature.

For the Gorleston observations the temperature recorded was that of the air, while in the Smith's Knoll observations the sea-surface temperature was recorded. All the sea-surface temperatures, and air temperatures before 1961, were in degrees Fahrenheit, so this was chosen as the reference scale for temperature. Accordingly the air temperatures from 1961 were converted from degrees Centigrade. Wind speed measurements were recorded in knots, to the nearest whole knot, and wind directions in tens of degrees.

Method and Results

From each pair of simultaneous observations three parameters were tabulated:-

(a) $R = \frac{U_s}{U_l} = \frac{\text{wind speed over sea}}{\text{wind speed over land}}$

(b) D = wind direction over land-wind direction over sea

(c) T = air temperature over land-sea-surface temperature

The parameter T was taken as a measure of the instantaneous stability of the surface layers of atmosphere as they are convected from off the land onto the sea. Following the method in [A] it was proposed to investigate the variation of R with the wind speed over the land, U_l, and with T, and in addition to find out whether any information concerning the variation of D with the same parameters could be obtained.

To facilitate the analysis the range of U_l was divided into four arbitary sub-ranges called "wind-speed classes". These classes and the frequency of observations within them are given in Table 1. The range of value of T in the observations was from -21 to +24 Fahrenheit degrees (F^o). Once again this complete range was split up into sub-ranges, called "stability classes". As might have been expected the frequency distribution of T values was very peaked, having a maximum near 0 F^o. The total range was split up in a manner designed to give approximately equal frequencies to the five sub-ranges. Consequently the middle class was narrow while the outer classes were quite wide. Thus these stability classes have no inherent physical basis but a terminology of the form

very stable - stable - neutrally stable - unstable - very unstable

may be applied as long as it is remembered that no strict definition is being made. The divisions of the total range with their observation frequencies are shown in Table 1.

/Table 1

TABLE 1

The wind-speed and stability classes, with the frequency of observations in each class.

U_1 (kt) / T (F^o)	1-5	6-10	11-15	16	ALL WINDS $\leq$ 1
- 6	157	557	126	55	895
- 5 to - 2	119	334	140	57	650
- 1 to + 1	94	230	108	77	509
+ 2 to + 5	81	234	151	101	567
+ 6	86	270	229	160	745
ALL TEMPS	537	1625	754	450	3366

A total of twenty classifications was then possible, as the combination of four wind-speed and five stability classes. For each of the twenty classifications the mean value of R and D was calculated, also the standard deviation of R and D and the maximum and minimum values of R. The results of these calculations are tabulated as Table 2.

TABLE 2

The mean values and standard deviations of R and D for each class together with the maximum and minimum values of R

U_1 (kt)	T (F^o)	Mean D (10^o of arc)	Standard Dev.D (10^o of arc)	Mean R	Standard Dev. R	Maximum R	Minimum R
1-5	-21 to -6	-0.66	1.79	3.39	2.61	18.0	0.4
	- 5 to -2	-0.24	1.79	3.07	1.85	10.0	0.4
	- 1 to +1	-0.06	1.81	2.95	2.34	14.0	0.6
	+ 2 to +5	-0.11	1.84	2.59	2.08	12.0	0.2
	+ 6 to +24	0.41	1.79	2.53	1.79	12.0	0.4
6-10	-21 to -6	-0.84	1.64	1.90	0.68	4.3	0.2
	- 5 to -2	-0.41	1.71	1.83	0.61	4.2	0.2
	- 1 to +1	-0.08	1.72	1.57	0.54	3.5	0.3
	+ 2 to +5	0.27	1.72	1.40	0.43	2.6	0.4
	+ 6 to +24	0.34	1.73	1.31	0.50	3.0	0.2
11-15	-21 to -6	-0.64	1.53	1.78	0.45	2.7	0.7
	- 5 to -2	-0.33	1.63	1.61	0.42	3.5	0.7
	- 1 to +1	0.11	1.68	1.48	0.32	2.4	0.5
	+ 2 to +5	0.20	1.73	1.29	0.32	2.3	0.1
	+ 6 to +24	0.77	1.57	1.11	0.32	2.2	0.1
≥16	-21 to -6	-0.33	1.79	1.55	0.30	2.3	0.7
	- 5 to -2	-0.23	1.41	1.54	0.29	2.4	0.7
	- 1 to +1	0.00	1.75	1.35	0.26	2.2	0.6
	+ 2 to +5	0.08	1.68	1.23	0.27	2.2	0.5
	+ 6 to +24	0.68	1.50	1.06	0.27	1.6	0.2

(a) The influence of wind speed and stability on change of direction:

Before any use was made of the results set out in Table 2 it was necessary to justify the classifications of D, the change in direction, by wind speed U_L, and stability T. While such a classification may facilitate the analysis and presentation of results it might also introduce an unnecessary degree of complication. Accordingly an analysis of variance was performed on the mean D values of the classification in order to test whether or not there was a significant variation in the mean values between both stability and wind speed classes. The results were

$$\frac{\text{Variance due to wind speed classification } (3)}{\text{Residual variance } (12)} = 2.36$$

$$\frac{\text{Variance due to stability classification } (4)}{\text{Residual variance } (12)} = 36.88$$

the numbers in brackets being the respective degrees of freedom. At the 95% level of significance $F_{3,12} = 3.49$ while at the 99.9% level $F_{4,12} = 9.63$. It was concluded from these results that the variation of mean D values between the wind speed classes was not significant while the variation between stability classes was highly significant. In view of this conclusion there was nothing to be gained by classifying D according to wind speed, so the mean values and standard deviations for the stability classes were recalculated using data for all wind speeds. The results are shown in Table 3 together with the 95% confidence limits that were ascribed to the class means. A graphical presentation of their results is given in Figure 1.

TABLE 3

The classification of D into stability classes for all values of U_L

T (F^o)	-21 to -6	-5 to -2	-1 to +1	+2 to +5	+6 to +24
Mean D (10^o of arc)	-0.75 ± 0.11	-0.35±0.13	-0.03±0.15	0.16±0.14	0.55±0.12
S.D. D (10^o of arc)	1.67	1.69	1.73	1.74	1.65

The change in direction, D, was measured in units of 10^o of arc. It can be seen in Table 3 that the mean D values for each class were all less than unity, and that the standard deviations (and hence confidence limits) were relatively large. In view of this only a qualitative interpretation of the results is possible since the actual numerical values can hardly be significant. It is perhaps possible to state that off-shore winds tend to back if initial conditions over the sea are very stable, and tend to veer if initial conditions are very unstable. This change in direction is thought to be independent of the wind speed over the land.

(b) The influence of wind-speed and stability on the ratio R:

It became apparent from the results set out in Table 2 that more variation in R values existed in the 1-5 kt wind-speed class than in any of the other wind-

/speed

speed classes. For the whole class, irrespective of any stability classification, the range in R values was 0.2 to 18.0, the standard deviation of the R values was 2.23 and the mean R value was 2.98. These results being very different from the corresponding statistics of the other wind-speed classes. The 95% confidence limits placed on this mean were ± 0.19 and it was concluded that no significant result could be deduced from the data for this class. One could perhaps point to the inaccuracies of an anemometer when measuring winds in the 1-5kt range as being the main source of the observed peculiarity of the class results, but it is interesting to note that a similar result was recorded in [A] where it was apparently taken at its face value. Because of this suspicion of the results in the 1-5kt class it was ignored for the remainder of the analysis.

An analysis of variance was carried out on the class mean R values and the resulting F values indicated that there were significant variations between both wind-speed and stability classes. It was of interest to note that the percentage of the total variance accounted for by the wind-speed classification fell from 86.7% to 19.4% when the 1-5 kt class was omitted, thus confirming the suspicion that the class as a whole was unrepresentative. Table 4 is a numerical statement of the results for all winds ≥ 6 kts over land, and a graphical interpretation is presented in Figure 2.

TABLE 4

The mean values of R, classified by wind speed and stability

U_L (kt) / T (F^o)	6-10	11-15	≥ 16	All Winds ≥ 6
-21 to -6	1.90±0.06	1.78±0.08	1.55±0.08	1.86±0.05
-5 -2	1.83±0.07	1.61±0.07	1.54±0.07	1.74±0.05
-1 +1	1.57±0.07	1.48±0.06	1.35±0.06	1.50±0.04
+2 +5	1.40±0.06	1.29±0.05	1.23±0.05	1.33±0.03
+6 +24	1.31±0.06	1.11±0.04	1.06±0.04	1.18±0.03
ALL TEMPS	1.67±0.03	1.40±0.03	1.27±0.03	1.53±0.02

An inspection of the results chows in Table 4 revealed several general trends in the R mean values. Firstly however it was noticed that the 95% confidence limits on all the mean values were small, amounting to a maximum of 5% of the actual values, thus a high significance could be attached to the numerical values obtained for the means. Within each wind speed class the mean R values decreased as the stability index (T) increased, this being clearly shown in Figure 2. Thus more unstable conditions over the sea caused a greater increase in wind speed. Another general observation was that for all stability classes the stronger land winds were less affected by changes in stability e.g. even in the most unstable regime the ≥ 16 kt wind speed class was increased by only 55% while in neutrally stable conditions the 6-10 kt class was increased by 57%. These trends were reflected in the overall results for all winds and all temperature differences,

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also shown in Table 4. The mean R value, for all winds ≥ 6 kt, and for all stability indices, was 1.53 ± 0.02.

(c) Comparison of results.

The general variations of R with wind-speed and stability, noted in the previous paragraph, were also observed in [A]. Since the Great Lakes region experiences greater extremes of temperature than the North Sea area, the stability classification in [A] includes a larger total range i.e. -47 to +42F°. However the central stability classes are comparable to those in this paper if we amalgamate our central three classes. The R mean values for the extreme stability classes in [A] confirm the relationships observed for the central classes. On comparison of results the general impression is that for the corresponding stability classes the R mean values for the North Sea region are higher than those for the Great Lakes. These results are tabulated for easy comparison in Tables 5(a) and 5(b). The results in Table 5(a) are for an over-water fetch of 16-25 n. miles roughly the same as for the North Sea data. The differences between the two sets of mean R values were tested and found to be significant at the 95% level. The mean R value over the Great Lakes for 16-25 n. miles of fetch, ≥ 6 kts, and for $-22 \leq T \leq +22F^{o}$ was 1.38, significantly different from the value of 1.53 for the North Sea.

TABLE 5(a)

Mean values of R for stability and wind-speed classifications
Richards, Dragert and M.Intyre (1966)

$T(F^{o})$ \ U_L(kt)	6-10	11-15	≥16
-22 to - 8	1.82	1.40	1.30
- 7 to + 7	1.49	1.31	1.02
+ 8 to +22	1.15	0.90	0.94

TABLE 5(b)

Mean values of R for stability and wind-speed classifications
Francis (1969)

$T(F^{o})$ \ U_L(kt)	6-10	11-15	≥16
-22 to - 6	1.90	1.78	1.55
- 5 to + 5	1.63	1.45	1.34
+ 6 to +22	1.31	1.11	1.06

As already mentioned the R mean values in the 1-5 kt range recorded in [A] are also very different from the means for other wind speed classes. Accordingly they are not included in the comparison.

/Interpretation

Interpretation of results

The changes in the wind field as the wind blows off the land onto the sea arise from two different physical sources. One is the result of the abrupt change in the roughness characteristics of the terrain over which the wind is blowing. Some accounts of theoretical and experimental work on this problem are to be found in Panofsky and Townsend (1964), Bradley (1968) and Taylor (1969 a, b, c). The other physical process is effected by the different thermal structure of the atmosphere over the sea. The effect of stability on the velocity profile in lower layers has been investigated at great length by Deacon (1953) and also by Swinbank (1964) and by Lettau and Zabransky (1968). Other references to associated works may be found in the papers cited, and a general account in Priestly (1959).

The work on changes of terrain roughness introduces the concept of an internal boundary layer, arising at the region of discontinuity. From all the accounts, we may suppose that the over-water fetch in this investigation is of a more than sufficient length to allow the profile of surface wind to attain an equilibrium form again, after passing through the transition zone of this internal boundary layer. We therefore make the assumption that the wind speed profiles at the observing stations are functions of the atmospheric stability at those stations, and also of the roughness characteristics of the terrain surrounding those stations.

For conditions of neutral stability the wind speed profile follows the well known logarithmic law,

$$U = \frac{U_*}{k} \log \left(\frac{Z}{Z_o} \right)$$

where U_* is the so-called friction velocity, Z_o the roughness length and k is Von Karman's constant $\sim$ 0.4. For non-neutral stability conditions this form is deviated from considerably and many empirical formulations have been made, to fit observational findings. Deacon (1953) suggests

$$U = \frac{U_*}{k(1-\beta)} \left\{ \left(\frac{Z}{Z_o} \right)^{1-\beta} - 1 \right\}$$

where $\beta > 1$ for unstable conditions and $\beta < 1$ for stable conditions. This formulation reduces to the logarithmic law as $\beta \to 1$ and as $(\frac{Z}{Z_o}) \to 1$ i.e. for small heights.

A different formulation was suggested by Swinbank (1964)

$$U = \frac{U_*}{k} \log \left\{ \frac{\exp\left(\frac{Z}{L}\right) - 1}{\exp\left(\frac{Z_o}{L}\right) - 1} \right\}$$

where $L = - \frac{U_*^3 C_p T \rho}{kgH}$ and where in addition to the symbols already defined ρ is the air density, C_p the specific heat at constant pressure, T the air temperature and H the heat flux, defined as positive when directed upwards. Hence negative values of L indicate unstable conditions and positive values indicate stable conditions. For neutral stability L becomes infinite and Swinbank's formulation reduces to the ordinary logarithmic profile.

/It

It is difficult to make use of the theoretical models described above when attempting to interpret and explain the results of this paper. The main reason being that the parameter T is only a measure of the intial stability over the sea, after an interval of time the temperature profile of the air is modified into a state more in equilibrium with the sea-surface temperature. However we can make general statements about the physical processes involved which do explain some of the observed features.

The first observation to explain is that the R' mean values recorded in this paper are all greater than unity. This phenomenon becomes obvious when it is realised that the value of z_o is at least ten times less for the sea surface than for the land. As T becomes more positive i.e. conditions become more stable over the sea, then $\beta_s < \beta_L$ and $L_s > L_L$, where the subscripts denote sea and land values. This effect induces a process in opposition to that brought about by the decrease in value of z_o, so much so that for the extreme conditions of stability recorded in [A] the value of R was observed to be less than unity. In this manner we can explain why the increase of wind speeds is less in stable over-sea conditions. Finally there is the fact that for strong winds the velocity profile is dominated by the effect of mechanical turbulence and hence the effect of changes in stability is very small. This fact explains why stronger land winds are less affected by the changes in stability.

Conclusions

From a series of simultaneous wind measurements made at Gorleston and the Smith's Knoll Light Vessel we may deduce that:-

(a) The ratio between wind speed over the sea and over land, for off-shore winds, increases as the intial instability over the sea increases.

(b) This increase is most marked for light land winds.

(c) Under initially stable over-sea conditions the wind backs, under initially unstable conditions the wind veers.

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FIGURE 1

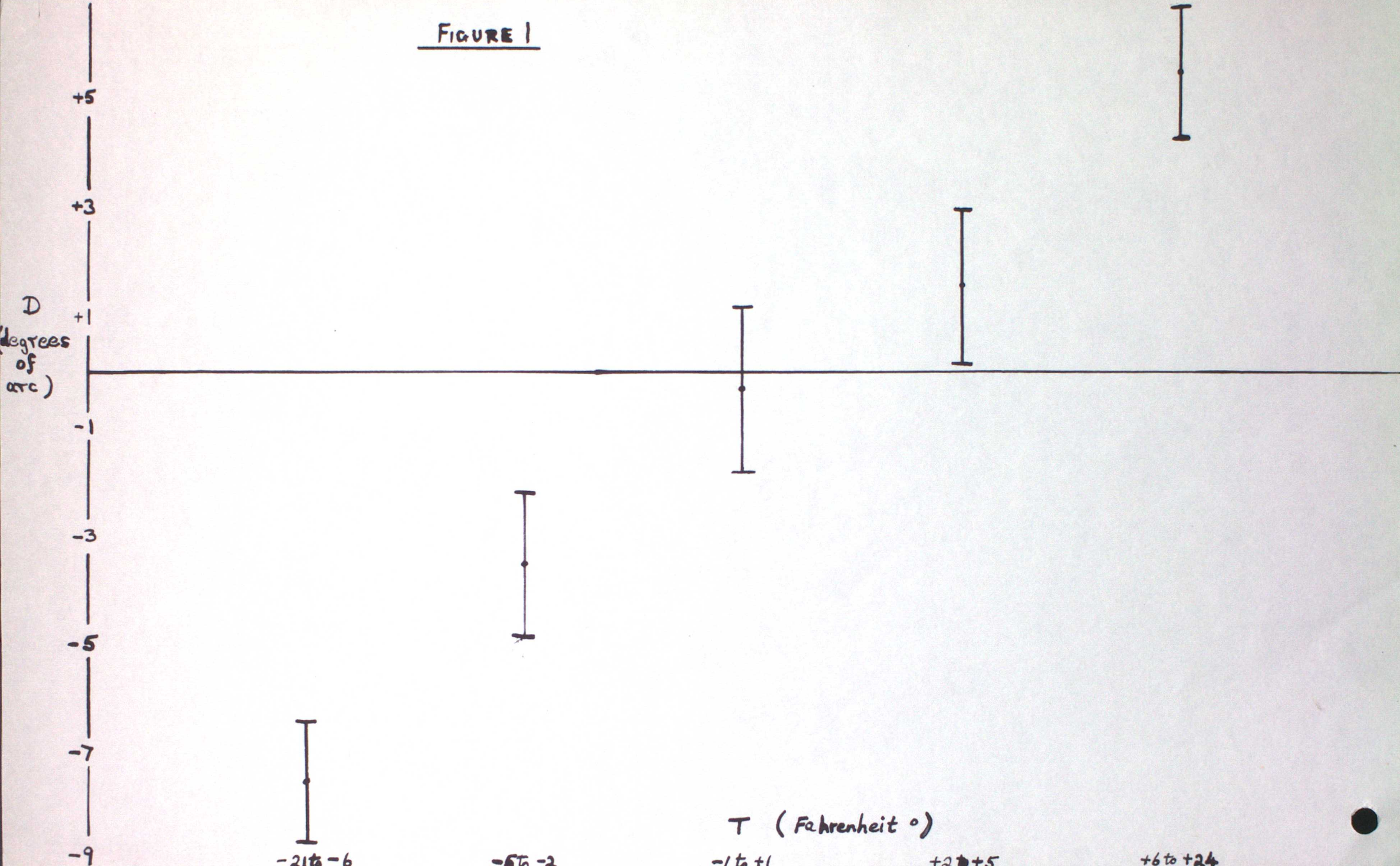
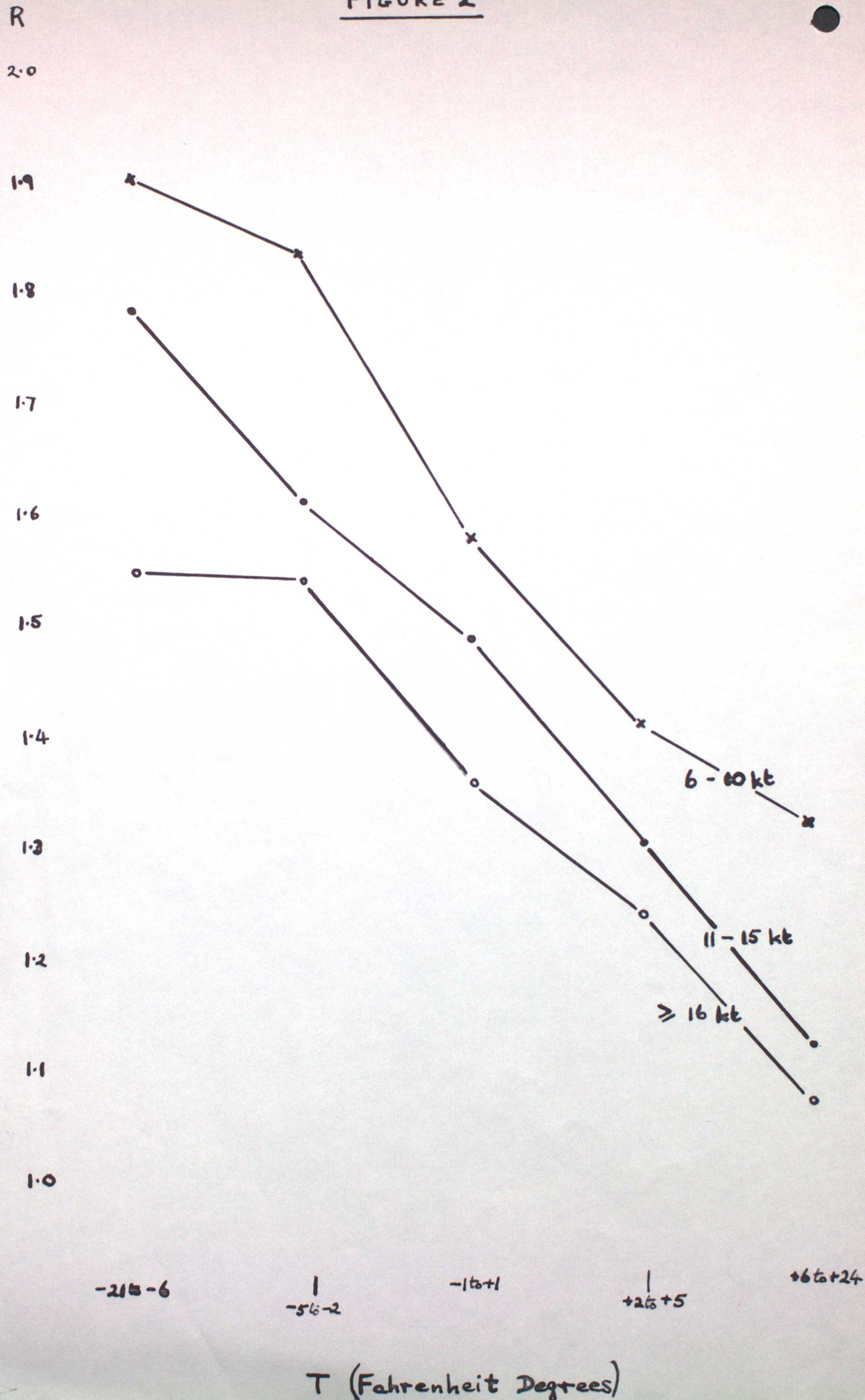

D
(degrees
of
arc)
+5
+3
+1
-1
-3
-5
-7
-9
T (Fahrenheit °)
-21 to -6
-5 to -2
-1 to +1
+2 to +5
+6 to +24

FIGURE 2


R
2.0
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1.0
6 - 10 kt
11 - 15 kt
≥ 16 kt
-21 to -6
-5 to -2
-1 to +1
+2 to +5
+6 to +24
T (Fahrenheit Degrees)