

DUPLICATE

F.T.B.M.2

*Re-written as Scientific Paper No 21.*

---



METEOROLOGICAL OFFICE

FORECASTING TECHNIQUES BRANCH MEMORANDUM No. 2

SURFACE AND 900 MB WIND RELATIONSHIPS

by

G. A. HOWKINS, T. N. S. HARROWER and D. S. GILL

1965



## SURFACE AND 900 mb WIND RELATIONSHIPS

### ABSTRACT

This memorandum summarises work carried out in the branch over the past three years, some of which is contained in unpublished papers by H.L. Wright and J. Findlater (p.17). Apart from the general interest in the drag of the air over differing land and sea surfaces there is need for a forecasting technique yielding surface winds from the forecast pressure field. No proved forecasting technique emerged, but the factual matter assembled is important in itself and the various comparisons of 900 mb and surface wind may prove useful when designing further work.

Five to ten years of observations of winds and temperatures at 900 mb and the surface, for the two weather ship stations "India" and "Juliett" and the two land stations, Leuchars/Shanwell and London (Heathrow) Airport/Crawley were compared objectively. The paper is in four sections:-

Section 1 - Introduction

Section 2 - Background to the analysis

Section 3 - Factors affecting the relationship

Section 4 - Possible forecasting techniques



## 1. INTRODUCTION

### 1.1. Objective.

The main objective was to devise a technique for forecasting the surface wind, given a forecast isobaric chart as a source of the forecast wind in the 'free' air. As there are no precise relationships linking the two winds this prompted a statistical comparison of actual surface and upper winds based broadly on the results of turbulence investigations and high mast data.

### 1.2. Controlling parameters.

The relationship between the two winds is believed to depend mainly on six factors:-

- a. character of the underlying surface ("roughness")
- b. anemometer exposure
- c. topography
- d. temperature lapse rate in the lowest layers
- e. strength of the wind
- f. time of day and possibly of year

### 1.3. Choice of data.

The factors a, b and c, imply that results will be highly localised in application, while the inclusion of d limits the choice to radio sonde stations or stations nearby. Geostrophic or gradient winds from actual charts should provide the best 'free air' data but neither are derived as a routine and their measurement or calculation in retrospect is laborious. Also in some areas - notably at sea - values are liable to considerable error because of the relatively sparse observational network to support the pressure pattern. For these reasons actual 900 mb radar wind observations were employed instead of calculated winds from isobaric charts.

### 1.4. Choice of location.

This finally rested on the two weather ships "India" and "Juliett", because conditions at sea hold interest in their own right and because topographical effects and directional variations of roughness would be avoided. Over land it was chosen to compare surface winds at London (Heathrow) Airport with upper winds at Crawley and surface winds at Leuchars with upper winds at Shanwell. Both Heathrow and Leuchars are busy aerodromes and any useful results would find immediate application. The anemometer exposures are generally good at both stations, although some complications occurred temporarily at Leuchars and are discussed in section 3. At Heathrow there are no major topographic features within ten miles of the site, but at Leuchars the topography is known to exert considerable influence on winds in some sectors and complications may also arise from land and sea breezes.

### 1.5. Data used.

Data were taken from upper air soundings and recorded surface winds for the hours 0200 or 2300 GMT and 1400 or 1100 GMT. Incomplete observations and those giving upper wind speeds of less than 10 knots or calms at the surface were omitted. 'Off station' data for the ships were also excluded.



The periods and numbers of observations used were as follows:-

OWS "India"	59°N.19°W.	1951-60	5,556
OWS "Juliett"	52°30'N.20°W.	1951-58	4,728
London (Heathrow) Airport/Crawley		1954-61	4,090
Leuchars/Shanwell		1957-61	2,532

#### 1.6. Data treatment

Each observation was classified according to eight 45° sectors of 900 mb wind direction (centred on the main compass points), five classes of 900 mb wind speed in the ranges 10-19, 20-29, 30-39, 40-49, ≥ 50 knots, and six classes of lapse rate. The lapse rate was defined as the temperature difference between the surface and the 900 mb level, divided by the height of the 900 mb level above the station. In the two land station analyses the surface temperatures used were those at Heathrow and Leuchars, not those at the upper air stations Crawley and Shanwell.

Much of the basic data was in °F and ft and the lapse classification was therefore determined in these units

Class	°F/1000 ft	
1	≥ 5.5	Adiabatic
2	4.0 to 5.4	
3	2.5 to 3.9	
4	1.0 to 2.4	
5	-0.5 to 0.9	Isothermal
6	≤ -0.6	Inversion

No attempt was made to reject anomalous values such as might be expected at fronts or when non-uniform lapse rates occurred between the surface and 900 mb. This and other considerations discussed later are bound to lead to irregularities.

#### 1.7. Computer Programme.

This automatically calculated the lapse rate from tapes of 900 mb and surface temperatures and heights. It resolved each observation of surface wind into two components - a 'p' component along and a 'q' component at right angles to the 900 mb wind direction and expressed these as fractions of the 900 mb wind speed. Components were automatically sorted into the various classes already mentioned and mean values and standard deviations calculated for each class. Data was also sorted by season and, for the two land stations, by day and by night. This yielded a total of 960 classes for the ships and 1920 classes for Heathrow and Leuchars.

## 2. BACKGROUND TO THE ANALYSIS..

2.1. Before presenting the results it is necessary to consider the validity of several assumptions stated or implied in the analysis.

2.2. What is the 900 mb wind?

The 900 mb wind from radio sonde data was chosen to represent the wind in the free air, largely because it is the lowest standard level appearing on punched card data. It is a mean wind over an interval of two or three minutes and hence through a layer 800 to 1200 metres deep. It is not strictly coincident in time with the surface wind and, especially at the two land stations, it is displaced in plan from the surface wind. Although



Although the mean height is around 900 metres, the height of the 900 mb level varies over a wide range from about 400 to 1200 metres and, when below about 600 metres, surface frictional effects may be incorporated into the layer. However, this occurs only rarely and a comparison of the 900 mb analysis for Leuchars with a similar analysis employing 900 metre winds revealed no significant differences in the means or standard deviations of the p and q surface wind components. High mast data (JEHN and DURIE 1, THUILLIER and LAPPE 2) indicate that, for a station with a good general exposure, the wind speed above about 300 metres is very nearly constant with height and hence the mean wind centred around 900 metres and taken over a depth of 800 to 1200 metres, should represent the friction-free wind. The latter is generally assumed to occur at or above 600 metres.

### 2.3. Geostrophic or Gradient Wind?

When making a forecast of surface wind, the starting point is usually the forecast geostrophic wind taken from a forecast isobaric chart. But the free wind is not necessarily geostrophic. Geostrophic winds for Crawley were available from another project covering 24 winter months over four years. These were obtained by a computer programme which used as basic data pressure values from a number of stations in the vicinity of Crawley and were compared with the corresponding 900 mb winds from Crawley radar soundings. Table 1a. shows the differences in direction and Table 1b. the differences in speed. Twenty-nine of the  $10^{\circ}$  sectors show differences of  $10^{\circ}$  or less, but there is some hint of a small systematic difference in the sectors  $020-050^{\circ}$  and  $130-160^{\circ}$ . The correspondence between geostrophic and 900 mb wind speeds (Table 1b.) is good in the low speed ranges, but the mean 900 mb winds fall short of geostrophic in the higher ranges. The difference amounts to about 10% at 30 knots, increasing to 30% at 65 knots. A discrepancy in this sense is to be expected because the strongest winds are probably associated with cyclonic curvature, causing the 'free' wind to fall short of geostrophic by an amount which increases as the geostrophic wind speed increases. It follows that, in arriving at the 'free' wind, cyclostrophic effects must be taken into account whenever geostrophic gradients exceed about 40 knots and they may well be important at lower speeds if the contours are strongly curved.

### 2.4. Effect of different location of the surface and upper winds.

In the analysis for Heathrow the surface winds are compared with 900 mb winds measured at Crawley, 25 miles away. To test the effect of this, comparisons were made of geostrophic winds at Crawley and geostrophic winds at Heathrow with 900 mb winds at Crawley. The results are not produced in full but standard errors and correlation coefficients (Table 1c.) suggest that the effect of using upper winds at Crawley for comparison with the surface winds at Heathrow is negligible. However, the change of location may involve important lapse rate changes in the lowest layers near the ground. These changes are discussed in the following paragraph.

### 2.5. Cross-correlation between the classifying parameters.

High mast data (JEHN and DURIE 1, THUILLIER and LAPPE 2) suggest that the lapse rate affecting the surface/upper wind relationship is that in the lowest layers within 300 metres of the surface and it is likely that conditions in a very shallow layer near the ground exert the greatest influence. Hence, it is doubtful whether the mean lapse rate based on the surface and 900 mb temperatures adequately represents the vertical temperature distribution. Special points are included in synoptic messages when significant lapse rate changes occur below 900 mb and the forecaster therefore has more data than that appearing on punched cards. It is difficult to make a simple but conclusive test of the effectiveness of the lapse classification. The effect of using 'special point' data was tested in a short run of data for a particular wind speed and lapse class for ship "India".



Of the 138 observations examined, 41 were reclassified but only 4 were altered by more than one lapse class. The test was repeated using all observations in a 3-month period, when 51 of a total of 116 observations were reclassified but only 5 were altered by more than one class.

An examination of Tephigrams for Shanwell showed that the classification may be much less satisfactory over land. Low level inversions occur frequently at night and the mean lapse rate based on the temperatures at the surface and 900 mb is not typical of conditions near the ground. A brief inspection of Crawley Tephigrams suggested that night-time inversions are less frequent than at Shanwell - possibly because Crawley is 145 metres above mean sea level and cold air would tend to drain away from the site. However, the behaviour at Crawley is almost certainly not typical of Heathrow, where night-time inversions are more frequent than at Shanwell. Nocturnal cooling is closely connected with cloud cover (BEST et. al. 3; SHAW, 4) and, since night-time low cloud cover is rather less at Heathrow than at Leuchars - especially during summer nights -, there will be a greater tendency towards night-time stability at Heathrow. Consequently there will be more cases when the lapse classification does not represent the lapse rate near the ground at night; and, although the lapse classification may be adequate at sea, this is not so over the land.

#### 2.6. Omission of surface calms.

The basic analysis (para. 1.5) rejected occasions when calms at the surface were associated with upper winds exceeding 9 kts. Inspection of the data revealed only a small number of such cases at the two weather ships and these analyses are largely unaffected. At Leuchars 10% of all night-time observations and 3% of daytime observations fell in this category. Most were associated with the 10-19 kt upper wind speed class and represented 20% of night-time observations in this class. Although the effect on the mean values of p and q is small in most classes, it will be large in speed class 10-19 at night and probably exceeds 20% in the stable lapse classes when associated with this upper wind speed range. However, the mean value of  $V_0$  for upper wind speed class 10-19 rarely exceeds 5 kts so that the effect on  $V_0$  is still quite small. The angle  $\alpha$ , between the surface and upper winds will be unaffected. At Heathrow 7% of night-time and 1% of day-time observations were associated with surface calms. The night-time observations in the 10-19 kt upper wind speed class represent 15% of the class and hence the overall effect on mean p and q values is less than at Leuchars.

#### 2.7. Layout of data.

The computer analysis produced mean values of p and q in 1920 classes for the land stations and 960 classes for the ships. The number of observations varied from 2532 at Leuchars to 5556 at ship "India" and it is apparent that classes must be combined in order to ensure reliable mean values of the p and q ratios. The first approach was to employ each classifying parameter in turn, temporarily discarding the other four. This limited the classes to a maximum of eight at any one time and yielded representative means values of p and q but it involved the risk that the full effect of the parameter may not be discernible because of cross-correlation with those discarded. It is well known that mechanical turbulence affects the lapse rate in the lower layers and it must lead to correlation of wind speed with lapse rate. Both wind speed and lapse rate may be correlated with wind direction although, at a land station, the wind direction is more likely to reflect directional changes of surface roughness, orography or anemometer exposure. With these considerations in mind all four stations were analysed employing the six lapse classes and five wind speed classes simultaneously and, in the case of the two land stations, observations were also separated by day and by night.



Classification by wind direction and lapse class was also made, but classification by all three parameters simultaneously was not attempted and it was necessary to test for cross-correlation wherever there were prior grounds for expecting it, or the results themselves suggested it.

## 2.8. Presentation of results.

2.8.1. Where possible these are presented (Section 3) as diagrams, tables being reserved mainly for displaying correlation between parameters. Two types of diagram are used; the first when one classifying parameter is employed at a time, the second when two parameters are used simultaneously. In the first diagram, unit length along the p-axis represents the 900 mb wind ( $V_{900}$ ) q components are measured along the other axis, so that any line drawn through the origin to a point in the diagram with coordinates p and q represents the surface wind, expressed as a fraction of the upper wind ( $V_o/V_{900}$ ). It follows that the angle ( $\alpha$ ) between any such line and the p axis is the angle between the surface and 900 mb winds. In the second diagram, where two classifying parameters are used, the p and q components are plotted independently. The standard deviations of the mean p and q components are large in most classes. They are not shown in either tables or diagrams but the numbers of observations are given in brackets beside each plotted point in the diagrams and several significance tests on typical lapse, wind speed and wind direction classes are included in section 4, where forecasting techniques are discussed.

2.8.2. The following symbols are used:-

$V_o$	=	wind at anemometer level
$V_{900}$	=	radar wind ascribed to the 900 mb level
$V_g$	=	geostrophic wind
$\alpha$	=	angle between $V_o$ and $V_{900}$ (positive when $V_o$ is backed with respect to $V_{900}$ )
p	=	component of $V_o$ along $V_{900}$ , expressed as a fraction of $V_{900}$ and reckoned positive in the direction of $V_{900}$
q	=	component of $V_o$ at right angles to $V_{900}$ , expressed as a fraction of $V_{900}$ and reckoned positive in the direction of low pressure.

The p and q components are sometimes referred to in the text as 'component ratios'.

'Winter'	=	December-February
'Spring'	=	March-May
'Summer'	=	June-August
'Autumn'	=	September-November

## 3. FACTORS AFFECTING THE RELATIONSHIP

### 3.1. Overall mean values

Fig. 1 shows that the  $V_o/V_{900}$  ratio is much larger at sea than over the land, indicating that the surface drag is least at sea. The larger ratio at sea is accompanied by a smaller angle  $\alpha$  between the surface and upper winds.

### 3.2. Effect of 900 mb height

Fig. 1 shows a small difference in the  $V_o/V_{900}$  ratio between the two ships and Figs. 2-4 show that this difference persists even when data are



classified by lapse rate, wind speed and wind direction. The mean height at ship "India" is 50 metres lower than at ship "Juliett"; consequently there are more occasions when the 900 mb level is low enough for the 900 mb wind layer to include surface friction effects (para. 2.2.). This reduces the 900 mb mean wind speed and causes an apparent increase in the mean speed at the surface because this is expressed as a fraction of the upper wind. Thus the larger  $V_0/V_{900}$  ratio arises from the manner in which the data is treated and has no physical significance. The mean height at Leuchars is less than the mean at Heathrow, but the  $V_0/V_{900}$  ratios are generally higher because the terrain is rougher at Leuchars.

### 3.3. Effect of Lapse Rate

3.3.1. Except in lapse class 6 which is poorly populated, the  $V_0/V_{900}$  ratios vary systematically at all four stations (Fig. 2). The highest values occur with unstable lapse class 1, when the vertical exchange of momentum should be greatest, and the lowest values occur with stable lapse classes 5 and 6, there being little variation between classes 4, 5 and 6.

3.3.2. Inspection of Figs. 5a and 5b for the weather ships, confirms that the variation by lapse class takes the same form in all wind speed classes. This is not so for the two land stations. Figs. 5c-f show that there is less variation by lapse class in the higher wind speeds, especially at Heathrow. This restriction probably occurs because mechanical turbulence in the higher wind speeds will tend to establish neutral (class 3) lapse rates in the lower layers, whatever the mean lapse rate from the surface to 900 mb.

3.3.3. Figs. 5c-f show that the effects of lapse rate are markedly different by day and by night, especially at Heathrow. The variation by lapse class in the lowest windspeed class is large by day, but small by night and  $V_0/V_{900}$  ratios are reduced in all lapse and speed classes at night. This suggests that the relationship between the surface and 900 mb wind depends mainly on the lapse rate in the lowest layers. By day this lapse is well represented by the mean lapse used in the analysis, although it may be modified by mechanical turbulence at high wind speeds, but by night the lowest layers are much more stable than the mean lapse would suggest. Consequently all night-time  $V_0/V_{900}$  ratios are smaller. At Heathrow this effect is so marked that the ratio is apparently quite insensitive to lapse class at night. The effect is less marked at Leuchars - possibly because the mean cloudiness is greater at night, especially during summer, and this restricts the nocturnal cooling. Consequently the lapse rate in the lowest layers, although more stable than by day, is still reflected in the lapse class based on the surface and 900 mb temperatures.

### 3.4. Wind speed and surface roughness at sea.

Wind energy must be depleted in the production of sea waves, the heights of which are related to wind speed (5). This accounts for the systematic decrease in the  $V_0/V_{900}$  ratio as the wind speed increases (Figs. 3a. b.). It is observed that in very strong winds, sea waves tend to be disrupted and the sea surface is flattened. This could lead to some reduction in roughness.  $p$  and  $q$  ratios for several cases of exceptionally strong winds are listed in the insets of Figs. 5a. and b. and show this tendency.

### 3.5. Wind speed over land.

Wind energy is depleted when roughness elements such as grass or trees are set in motion but the proportion of energy absorbed should not increase with increasing wind speed, as it does at sea. At Heathrow, where the



exposure is good and roughness elements are small, the cross wind components  $q$  show some tendency to decrease with increasing wind speed, except in the unstable classes. At night there is an accompanying tendency for the  $p$  component to increase, but this is barely perceptible at Leuchars. These changes are thought to be due to the effect of mechanical turbulence on lapse rate.

### 3.6. Cross correlation of lapse rate and wind speed.

Data for ship "India" and Heathrow were tested for correlation by extracting, for the well populated southwesterly direction class, frequencies of each lapse class within each speed class. These frequencies were expressed as percentages for each lapse class and weighted to eliminate the bias due to varying frequency of occurrence in each speed class. The weighted frequencies (Table 2a) show no established correlation at ship "India" but at Heathrow there is a distinct bimodal tendency towards stable and unstable lapse classes at low windspeeds and a tendency towards the neutral class 3 at high wind speeds. This is consistent with the behaviour of the  $V_0/V_{900}$  ratios in Fig. 5c.

### 3.7. Wind direction at sea.

3.7.1. The ratios and their associated angles  $\alpha$  vary in a similar manner with upper wind direction at both ship stations (Figs. 4a, b), although the magnitudes differ (para. 3.2). The variation is such as to cause a roughly elliptical rotation in the diagrams, which could be caused by a component of the 900 mb wind which is independent of the 900 mb direction. This suggests the possibility of a thermal wind, as indicated by Sheppard et al (6), from observations near the Scilly Isles. However, unstable lapse classes, with accompanying high  $V_0/V_{900}$  ratios, must be correlated with Northerly winds; while stable lapse classes, with low ratios, must occur with Southerly winds (Table 2b). Also, wind speed classes may be correlated with wind direction. These correlations must be avoided before conclusions may be drawn about a thermal wind. To do this separate direction analyses were made for the two weather ships, for the most populated lapse/speed classes. These are shown in Figs. 6a-d and Fig. 4 is reproduced on the same page to facilitate comparison. The spread of the  $V_0/V_{900}$  ratio by direction is reduced in Figs. 6a-d, which suggests that some of the 'rotation' in Fig. 4 may be due to correlation of lapse rate and/or wind speed with wind direction. The 'rotations' in Figs. 6a-d are much less systematic than in Fig. 4 - presumably because the thermal wind component of the 900 mb wind has a large standard deviation from the mean in Fig. 4. The apparent correlation of lapse rate and/or wind speed with wind direction prompted a search for further correlation with direction.

3.7.2. The sea temperature distribution in the vicinity of the weather ships must lead to heating of the lowest layers in air masses from the North and cooling in air masses from the South. This could create a tendency for Southerly direction classes to be more stable in the lowest layers than would be indicated by the mean lapse rate from the surface to 900 mb, and similarly, for Northerly winds to be less stable. To test for this the data mentioned in para. 2.5 was split into two halves to represent winds from the North and winds from the South, but both sectors showed similar tendencies for lapse reclassification.

3.7.3. The mean thermal wind for the area was extracted as follows. Mean thicknesses of the 1000 to 900 mb layer were calculated for the four stations from upper air observations over one year and the mean



Westerly and Northerly thermal wind components derived from differences between pairs of stations. This yields a mean thermal wind of  $248^{\circ}/1.7$  kts which compared well with unpublished figures obtained by J. Findlater from seven years of Weather Ship data for ships "Juliett" and "India". Findlater also constructed maps of annual and seasonal mean surface air isotherms, treating eight wind sectors based on the main compass points separately. From this he demonstrated that the mean thermal wind at both "India" and "Juliett" was very nearly constant in direction regardless of the surface wind direction. If a thermal wind of  $248^{\circ}/1.7$  kts is applied to a diagram such as Fig. 1, assuming a mean 900 mb wind speed of 30 kts, in all eight direction classes, then the point p, q, would sweep out an area roughly equal to those in Figs. 6a-d.

3.7.4. If the thermal wind is constant in speed and direction then the rotation by direction class (Fig. 4) should depend on the mean upper wind speed. The area bounded by the curve should increase if the mean speed is low and decrease if it is high. This is demonstrated (Fig. 7) by splitting the data for ship "India" into two parts - speeds in class 10-19 kts, and all other speeds combined. Thus there is good evidence for the existence of a thermal wind component in the 900 mb wind but its magnitude and direction are probably subject to large deviations from the mean.

### 3.8. Wind direction at Heathrow.

The distribution in wind direction classes (Fig. 4c) is somewhat like that for the two ships, where the rotation is thought to be caused by a thermal wind plus some correlation of lapse rate and possibly wind speed with wind direction. The same factors could influence the pattern at Heathrow but there must also be effects due to variation of the topography and roughness in different directions. The latter have practical importance but there is no method of isolating them from the other effects in a directional analysis. Conditions at night tend to be predominantly stable (Fig. 5d) and a night-time analysis was attempted for the four seasons separately in the hope that the pattern would show some persistent features which could be ascribed to topography. However, the patterns proved very variable - the only persistent feature being a tendency for high values of q in Southeasterly winds - and it is possible that there is a large variable thermal wind component in the 900 mb wind.

### 3.9. Wind direction at Leuchars.

3.9.1. The distribution (Fig. 4d) is even more complex than at Heathrow and the pattern varies seasonally and diurnally. The only constant features are in the West and Southwest sectors. The complexity prompted an attempt at a more detailed analysis into classes of lapse rate, wind speed, wind direction and season simultaneously. This calls for a much larger series of observations than the 2,532 available and only very tentative conclusions may be drawn. Topographical effects may be very critically related to wind direction and smaller or overlapping sectors are desirable. The conclusions drawn are listed in the following paragraphs 3.9.2-3.9.5 but supporting data is not presented. There are also complications caused by site and instrument changes between 31st July 1960 and 17th February 1961, and possible instrumental defects prior to August 1960. These are discussed in para. 3.12.

3.9.2. The generally high values of the ratios in the East sector (Fig. 4 d) reflect the good exposure to seawards. A test was made in the Southeast and East sectors for variation of the ratio with wind speed but no established trend could be seen with the small number of observations available.



3.9.3. The Southwest sector shows a very small angle $\alpha$  of the surface wind to the 900 mb wind, regardless of the lapse rate class. This is probably a valley effect.

3.9.4. Upper winds from North and Northeast are frequently associated with veered surface winds. This may be partly a topographic effect but sea breeze effects may also be involved.

3.9.5. Excepting the stable lapse classes in winter, almost all cases in the South sector show surface winds sharply backed from the 900 mb direction. This is probably caused by the high ground to the South of the station.

3.9.6. All eight directional analyses for the stable lapse classes 4 and 5 in winter suggest a mean westerly component of the 900 mb wind which persists regardless of the 900 mb direction. This amounts to a mean westerly vector of about  $0.2V_{900}$  occurring in each of the eight winter direction classes, and is possibly a net winter-time land breeze. This is not to say that the stable lapse class is the cause - only that a correlation exists between stable conditions and winds from landwards in winter. Correlation of lapse classes with land and sea breezes must occur because both show strongly diurnal trends. This is illustrated in Table 3, which shows the distribution of different lapse classes at 1200 and 0001 GMT for the whole year at Leuchars. The markedly higher incidence of stable lapse classes in daytime during Winter, compared to the other three seasons (Table 6) also lends support to the idea of a net land breeze when both day and night observations are combined.

### 3.10. Annual and diurnal variations at sea.

3.10.1. Table 4 contains mean values of the p, q component ratios for ship "Juliett", treating each of the four seasons by day and by night separately. The values were obtained in an earlier analysis which included 900 mb winds between 4 and 9 kts (excluded in this analysis). They show only small seasonal and diurnal changes.

3.10.2. Figs. 8 (a) (b) show the mean values of the component ratios at ships "India" and "Juliett" for the different lapse classes, separated according to season. There is some tendency for high values in summer and low values in winter, which is consistent with the lower mean surface wind speeds in summer and hence lower surface roughness due to smaller waves. (Table 5).

### 3.11. Annual and diurnal variations over land

3.11.1. Table 4 shows the marked variation of component ratios, diurnally and, to a less extent, seasonally at the two land stations. This is primarily due to the differing distribution of lapse rates with time of day and year, and can be demonstrated for Leuchars as follows. The percentage frequencies (f) of the different lapse rate classes are given in the first six columns of Table 6. These may be multiplied by the mean annual values  $\bar{p}$  and  $\bar{q}$  for each class, at the foot of Table 6, to yield the weighted means appearing in the last two columns of Table 6. These values should amount to seasonal means and are plotted in Fig. 9 against the seasonal means from Table 4. The cluster of points near the origin refer to the q components and the remainder are p components. All the points lie close to the straight line through the origin which bisects the diagram, thus demonstrating the equality of the seasonal means from Table 4 and the weighted means from Table 6.



3.11.2. Figs. 8 c, d, show the mean values of the component ratios for different lapse rates by season and Fig. 10 shows the diurnal variation. The variations by season are generally small. The largest variations are in lapse classes 1 and 2 and may be due to an increased tendency for shallow inversions, which are not typical of the mean lapse, to persist through the day in winter. Fig. 10 shows that the  $V_0/V_{900}$  ratio is systematically smaller by night than by day in all lapse classes. This diurnal tendency and the bimodal distribution of lapse rate frequencies in the low speed class 10-19, which also has diurnal significance, were discussed in paras. 3.3.3. and 3.6. The frequency distribution of lapse classes in different speed classes by day and by night are plotted in Figs. 5c-f. At Heathrow (Figs. 5c, d) the maximum by day appears in speed class 10-19 kt/lapse class 2, but is transferred to speed class 20-29 kt/lapse class 4 by night. This is probably a reflection of the general change in vertical wind profile from day to night when, as the stability increases in the lowest layers and the coupling between the upper and lower layers decreases, the upper flow accelerates. This diurnal change in frequency distribution by lapse and speed class is consistent with the diurnal changes in component ratios in Table 4 for Heathrow. The effect is not so well established at Leuchars (Figs. 5e, f) although there is a distinct increase in the frequencies of lapse classes 3, 4 and 5 in the 900 mb speed range 20-39 kt.

### 3.12. Effects of Anemometer site and instrument changes at Leuchars.

A remote recording Dines pressure tube anemometer was in use until the end of July 1960. It had a good exposure in all directions with an effective height of 40 ft. It was replaced from 1st August 1960 until 17th February 1961 by an electric cup anemometer on a different but generally well exposed site. This was transferred to the old Dines site on 17th February. Although the effective height of the anemometer was unchanged throughout the entire period 1957-1961 the wind speeds in a sector from  $070^\circ$  to  $160^\circ$  recorded by the electric cup anemometer from August 1960 to February 1961 were considered by the staff at Leuchars to be about 30% less than speeds recorded at the Dines site. This was due to an increased roughness effect from a belt of trees which did not affect the Dines site. Station records do not indicate discrepancies in other sectors but a comparison of monthly mean wind speeds for Leuchars with Auchterhouse (about 12 miles to the Northwest) for 1960 and 1961 suggests that the instrument change on 1st August 1960 and probably the site changes on 1st August 1960 and 17th February 1961 affected the recorded speeds. The comparisons, shown in Table 7 indicate changes which coincide with the site and instrument changes at Leuchars. Assuming no change in instrument performance at Auchterhouse, then the differences in the monthly means appear to indicate that, after February 1961, the cup anemometer at Leuchars was reading in the mean about 2.8 kts. higher than the Dines instrument in use before August 1960. Although this probably has little effect on the relationships between  $V_0$  and  $V_{900}$  over the whole 5 year period, it does emphasise the highly localised nature of relationships obtained from such comparisons.

### 3.13. The general effects of topography.

Wind roses showing frequencies of surface winds in twelve  $30^\circ$  sectors have been compiled for thirtyseven stations, to accompany aerodrome weather diagrams. A selection of these are plotted on a topographical map of the British Isles in Fig. 11 and provide clear evidence of topographical effects at most stations. The mean pressure distribution yields a maximum of Southwesterly winds but the maximum at individual stations may vary through a wide range of directions. For example its occurrence from  $270^\circ$  at Rhoose,  $240^\circ$  at Filton,  $210^\circ$  at Pershore and  $180^\circ$  with a secondary maximum from  $300-330^\circ$  at Liverpool, is very suggestive of airflow round the Welsh Mountains. The maxima from  $120-150^\circ$ ,  $000-030^\circ$  at Dishforth, in the Vale of York and  $150-180^\circ$ ,  $300-330^\circ$  at Dyce, all of which sectors normally display minima, are especially striking.



### 3.14. Inter-relation of $V_0/V_{900}$ , $\alpha$ , p and q.

3.14.1. Figs. 1-4 show that, whenever the ratio of surface wind to 900 mb wind ( $V_0/V_{900}$ ) decreases, then the angle  $\alpha$  between the two winds almost always increases. This is not true of lapse class 6 which is poorly populated and behaves erratically from station to station, nor of wind direction classes at Heathrow and Leuchars, where the relationship is complicated by topography.

3.14.2. The  $V_0/V_{900}$  ratio depends both on lapse rate and surface roughness (see paras. 3.3, 3.4) and the same ratio may arise with different combinations of lapse rate and roughness. Identical ratios do not necessarily yield identical values of  $\alpha$ .

3.14.3. Figs. 5a, b show the p and q components for the two ships for each lapse and wind speed class. Both increasing stability and increasing wind speed (surface roughness) reduce the p ratio; but the q ratio, which increases with increasing stability is insensitive to roughness changes as the wind speed increases. Although this effect is apparent in all lapse classes, it is especially striking in the unstable class 1 because the q component remains effectively zero while the p component changes from 0.97 in speed class 10-19 kts to 0.8 in speed class 40-49 kts. A similar tendency is shown in unstable lapse class 1 speed class 10-19 kt at Heathrow where a small negative q component occurs with a p component of 0.75. However, this may be possibly due to a thermal wind component in the 900 mb wind. The frictional layer model with no directional shear does not provide an explanation because the friction layer is generally assumed to be from 20 to 100 metres thick and to be surmounted by a 'spiral' layer in which the upper wind veers towards the geostrophic wind direction. Thus, the surface wind should lie within the frictional layer and the 900 mb wind within or above the spiral layer. The directional shear is a maximum between the frictional layer and the free wind level and the angle between the surface and 900 mb wind may only become zero if either the surface is frictionless (in which case p approaches unity) or the friction layer includes the 900 mb wind.

3.14.4. It is possible that some reduction in the p component may occur in strong winds at sea due to tilting of the anemometer out of the horizontal, in the direction of the wind. Weather ships head into wind to maintain position and wave heights can approach one eighth of the wave length in very strong winds. In these circumstances the anemometer may be inclined to the horizontal for a considerable proportion of the time and may consistently underestimate the mean horizontal wind.

### 3.15 Summary of results

1. In the mean  $V_0 < V_{900}$  and is normally backed with respect to  $V_{900}$ .
2. The lapse rate in a shallow layer near the ground exerts a controlling influence on the  $V_0/V_{900}$  ratio both at sea and over the land. At sea and over the land in daytime this lapse is adequately represented by the mean lapse from the surface to 900 mb, but this is not so at night over land, when the surface layers become generally stable. If low cloud amounts are small then night-time conditions become generally typical of stability and the mean lapse from the surface to 900 mb is largely irrelevant. If cloud amounts are high then the night-time tendency to stability is restricted and the low level lapse conditions, although more stable than by day, still reflect conditions in the deeper layer from the surface to 900 mb.



3. Surface roughness over land is greater than at sea and shows very little variation with wind speed. The main effect of increasing wind speed over land is to modify the lapse rate and conditions in strong winds become typical of lapse class 3.
4. At sea the roughness increases with increasing wind speed, until very high wind speeds are reached, when the sea wave structure is disrupted and the surface roughness tends to decrease.
5. At sea, for any given lapse rate, the cross wind component  $q$  takes up some fixed value while the  $p$  component varies with the wind speed (surface roughness). The  $q$  value is zero in highly unstable conditions, while  $p$  varies from 0.97 in light winds to 0.80 in strong winds; but  $q$  increases to about 0.25 in very stable conditions, while  $p$  varies from 0.6 in light winds to 0.4 in strong winds.
6. The effects of topography are complex and may be critically related to wind direction. They vary from the effects of large scale topography over a whole area (para. 3.13) to those of small scale features such as a belt of trees (para. 3.12) in the immediate vicinity of the anemometer. These effects cannot be investigated properly without a very long series of observations and the use of a directional analysis in narrow or overlapping sectors.
7. Cyclostrophic effects make a significant contribution to the mean flow in the free air, when geostrophic gradients exceed 30 kts. The contribution varies from about 10% in 30 kt gradients to 30% in 60 kt gradients

#### 4. POSSIBLE FORECASTING TECHNIQUES.

4.1. The relationships discussed in section 3 go only a short way towards a forecasting technique. Some of the relationships are so specifically related to the anemometer site as to have little or no general application. Others being more fundamental, hold out some hope of a technique.

4.2. At sea there are systematic variations of the  $p$  and  $q$  ratios by lapse class, wind speed and wind direction. There are no physical grounds for supposing that wind direction will have any fundamental effect on the ratios and it has been shown that the changes which occur by wind direction are probably accountable as correlations of the lapse rate or wind speed with direction and by a thermal wind component in the 900 mb wind. Hence, it should be possible to base a forecast technique on lapse class and wind speed.

4.3. Over the land, there should still be a high correlation with lapse rate but it is with the lapse in the lowest layers and this is not adequately represented by the mean lapse for the deeper layer used in this analysis. The low level lapse is readily modified by mechanical turbulence in strong winds and it also tends to become stable in night radiation conditions whatever the mean lapse rate in the deeper layer up to 900 mb. However, if these effects can be forecast, it may still form the basis of a forecasting technique.

4.4. Wind speed has little influence on the  $p$  and  $q$  ratios apart from that which follows from a modification of the lapse rate in strong winds. Wind direction is of major importance when there are significant variations of topography or roughness in different directions. There is probably a thermal wind component in the 900 mb wind and also cross correlations of lapse rate with wind direction. There is no way of separating such effects from those of topography in a directional analysis and they could lead to forecast errors. Thus, the rotation in the Heathrow analysis (Fig. 4c) involves a variation of about 0.15 in the  $V_0/V_{900}$  ratio and  $20^\circ$  in the angle  $\chi$  and, if it was



caused by an undetected thermal wind vector, then it would introduce an error of about 0.07 in the forecast surface wind speed ratio and  $10^{\circ}$  in the forecast surface wind direction. Another complication is the discrepancy between the 900 mb and geostrophic wind directions in the Crawley data (para. 2.3). This could be a local effect at Crawley and have no bearing on the relationship of the free wind to the surface wind at Heathrow, but it may introduce an error of up to  $20^{\circ}$  in the forecast surface wind direction for the sectors  $020-050^{\circ}$  and  $130-160^{\circ}$ .

4.5. It is apparent that an analysis designed to produce a technique for forecasting surface winds from the free wind obtained from an isobaric chart, should be based on calculated gradient winds and the lapse rates in the lowest layers. Findlater (unpublished) made an analysis of Heathrow data for winter months only, using 0600 and 2100 GMT surface observations and geostrophic winds estimated from synoptic charts. The results are very similar to those for the stable lapse classes in the 900 mb analysis and, in view of this, it is reasonable to test a forecast technique at both Heathrow and Leuchars, based on the 900 mb analysis in lapse rate and wind direction classes.

4.6. The mean values for the lapse, speed and direction classes used in the analysis are subject to large standard deviations. The following 'Students t' tests of 'p' ratios were made on several classes to test whether it was justifiable to rely on lapse and wind speed classes (disregarding direction) at sea and lapse and wind direction classes (disregarding speed) over land.

4.6.1. Effect of lapse class at sea.

Ship "Juliett", Westerly wind class, 30-39 kt speed class in lapse classes 2 and 3. Probability = 0.03, indicating a significant difference between the two lapse classes.

4.6.2. Effect of speed class at sea.

Ship "Juliett" lapse class 3

Speed classes 10-19, 20-29	Probability =	0.10
Speed classes 20-29, 30-39	Probability =	0.10
Speed classes 10-19, 30-39	Probability =	0.02

Hence, although the differences between adjacent speed classes could arise by chance, this is not so between classes which are more than one class apart.

4.6.3. Effect of direction class at sea.

Ship "Juliett" lapse class 3

Classes North and Southwest Probability = 0.10

These two classes were chosen because they showed the greatest difference in 'p' ratios and it therefore appears unlikely that significant differences could arise between any wind direction class at sea.

4.6.4. Effect of direction class over land.

Leuchars lapse class 3

Direction classes West and Northwest Probability = 0.005  
which represents a significant difference.



#### 4.6.5. Effect of speed class over land.

Leuchars lapse class 3

Speed classes 10-19 and 40-49 kts Probability = 0.08  
and the differences are unlikely to have significance.

#### 4.7. Application of the techniques.

The gradient wind is obtained from the forecast isobaric chart. The lapse rate is forecast, employing techniques currently used in forecasting convective cloud, stratus or fog, night minimum and day maximum temperatures. The first step is to determine the air mass expected at the forecast time and to choose a representative ascent. This is then modified for diurnal changes by adding or subtracting heat according to the season and distributing this with height according to the lapse rate and the expected wind speed. The lapse rate required is that in a shallow layer near the surface. Having obtained the lapse rate and the free wind, the surface wind is obtained from tables or diagrams relating surface wind to lapse rate and upper wind speed, for a sea exposure; lapse rate and upper wind direction for a land station.

#### 4.8. At sea.

4.8.1. Figs. 12 a, b, show the variation of surface wind speed  $V_0$  and angle  $\alpha$  for various classes of upper wind speed and lapse rate. (Strictly, the strongest upper wind speed class is  $\geq 50$  kts, not 50-59 kts). Frequencies in each class are shown in brackets. In light upper winds the variation of  $V_0$  by lapse class is about 4 kts and in strong upper winds about 12 kts. Hence, the forecast lapse rate assumes greater importance as the wind speed increases.

4.8.2. Figs. 12 a, b, also show the overall mean values of  $V_0$  and  $\alpha$ , disregarding lapse rate and upper wind speed. In the upper wind speed classes 10-19 kts and 20-29 kts, the values of  $V_0$  by lapse class are evenly distributed about the overall mean but for the strongest upper winds, the overall mean values exceed all the lapse class values. This has an obvious bearing on gale warnings. The geostrophic departure of the free wind (paras. 2.3., Table 1b) is also important in this connection. Thus, if the cyclostrophic correction is ignored, a geostrophic wind of 50 kts (Fig. 12) would yield a forecast surface wind of 40 kts, using the overall mean relationship. If the cyclostrophic correction is applied,  $V_{900}$  becomes 40 kts and the forecast surface wind is 34 kts for unstable lapse class 1, 25 kts for stable lapse class 5.

4.8.3. The angle of backing ( $\alpha$ ) varies from zero in very unstable conditions to about  $15^\circ$  in stable air with light winds and  $25^\circ$  in strong winds. The distribution of  $V_0$  and  $\alpha$  is very similar for both ships and smoothed values for the various lapse and upper wind speed classes are given in Table 8, from which a smoothed diagram may be plotted for general forecasting purposes at sea. The behaviour of lapse class 6 at both ships is probably random and has been ignored.

#### 4.9. Heathrow.

4.9.1. Fig. 13 shows the variation of the  $V_0/V_{900}$  ratio and angle  $\alpha$  for classes of upper wind direction and lapse rate. The overall mean values, disregarding lapse rate and wind directions are also shown. The ratio  $V_0/V_{900}$  replaces  $V_0$  in the ordinate of Fig. 13 so that one scale may be used for all five upper wind speed classes. The inadequacy



of the mean lapse rate from 900 mb to the surface was discussed in paras. 2.5, 3.3. The probable effect of this on the mean values of the  $V_0/V_{900}$  ratio is to reduce the means in unstable classes at night (because of a bias towards stability in the lowest layer near the ground) and to increase them in stable classes during the day (when the lowest layers will tend to be less stable than the mean lapse indicates). More representative mean values might have been obtained by using only the unstable cases by day and stable cases by night, but the low frequencies of stable cases does not justify further subdivision and the small numbers of unstable cases in classes 1 and 2 at night are unlikely to affect the mean values seriously. The variation in  $V_0/V_{900}$  ratio by lapse class is generally similar in each speed class and the variation by direction is similar in each lapse class. Maxima occur in the East and West direction classes with a minimum in the North and a secondary minimum in the South. Findlater found a generally similar distribution.

4.9.2. The corresponding changes in  $\alpha$  are less systematic but there is a pronounced maximum in the South to Southeast, with a secondary maximum in the North. Minima occur in the Northeast and possibly the West. Findlater's findings confirm this distribution.

4.9.3. Findlater suggested that the large angle of backing in the North and Southsoutheast sectors may be an effect of the Chilterns and the North Downs. These hills are generally below 250 metres and 12 miles from Heathrow and it seems unlikely that they would exert such a pronounced effect. However, there is synoptic evidence that the surface flow in South to Southeast contour gradients is backed through a large angle over much of Southeastern England and East Anglia and the effect may be due to the general topography in the whole area including land and sea distribution, as well as the distribution of high ground.

4.9.4. In the absence of a convincing explanation of the large variations of  $\alpha$  with upper wind direction, there must be some doubt about a forecasting technique based on the data from Fig. 13. The smoothed values in Table 9 are tentatively suggested. As in para. 2.3, the forecast gradient wind should be used whenever there is appreciable curvature of the airflow.

#### 4.10. Leuchars.

Fig. 14 shows the variation of the  $V_0/V_{900}$  ratio and angle  $\alpha$  for upper wind direction and lapse rate classes. The overall mean values of  $V_0/V_{900}$  and  $\alpha$  are also plotted in Fig. 14. The ratios show a very marked pattern by wind direction which is roughly similar in each lapse class. Pronounced maxima occur between Northeast and Southeast where there is a good exposure seawards and secondary maxima occur in the West. There are well marked maxima in the South and North sectors. The behaviour of  $\alpha$  is very variable in different upper wind directions. In the sectors North, Northeast, East and Southeast it varies from a veer of up to  $20^\circ$  with very unstable lapse classes to a backing of  $90^\circ$  in the very stable lapse classes. There is much less variation in the South, Southwest and West direction classes - especially in the Southwest where, for all lapse classes except class 6, the surface wind is backed by  $10^\circ$  or less. The general behaviour of both  $V_0/V_{900}$  ratio and  $\alpha$  is consistent with the topography but there is an unexplained veer of wind in lapse class 6 and upper wind classes South and Southwest. It is not connected with a sea breeze because 6 of the 11 cases from South occurred in winter. The smoothed values of  $V_0/V_{900}$  ratio and  $\alpha$  in Table 10 are tentative.



#### 4.11. Future Work.

A logical extension would be to test the relationships derived in section 3 with independent data series. However, the following unresolved difficulties in the preceding analysis discourage further effort on the existing data.

- a. Over the land there is an obvious need for a refined lapse rate classification and also a more detailed directional analysis using a long series of data for stations with complicated topography.
- b. It must be demonstrated that the lapse rate finally chosen not only has a high correlation with the surface wind behaviour, but can itself be forecast with sufficient accuracy.
- c. Although it has been demonstrated that there are significant departures of the actual 900 mb wind from geostrophic, it has not been established that these are primarily due to cyclostrophic effects.

In view of this no further work on the existing data is contemplated, but a new and longer series of data is being examined at Leuchars in an attempt to find a satisfactory lapse classification and a refined directional analysis.



REFERENCES

1. JEHN, K.H. and DURIE, S.J. Boundary-layer-wind maxima and associated temperature distribution as observed on the 1400 ft television tower near Dallas, Texas 1961-1962. Austin, Texas, University of Texas, Elec. Eng. Research Lab. Report 4-09.
2. THUILLIER, R.H. and LAPPE, U.O. Wind and temperature profile characteristics from observations on a 1400 ft tower. J. Applied Met., Lancaster Pa. 3, 1964, p.299.
3. BEST, A.C., KNIGHTING E., PEDLOW, R.H. and STORMOUTH, K. Temperature and Humidity Gradients in the first 100 m. over South East England. Geophysical Memoir No. 89.
4. SHAW, J.B. Vertical Temperature Gradient in the first 2,000 ft Meteorological Magazine 1955, p.233.
5. DARBYSHIRE, M. and DRAPER, L. Forecasting Wind-Generated Sea Waves. Engineering Vol. 195, 1963, p.482-484.
6. SHEPPARD P.A., CHARNOCK H., and FRANCIS, J.R.D. Observations of the westerlies over the sea. Quart. J.R. Met. Soc., London 78, 1952, p.563.

Unpublished Papers available in Met.O.8.

- WRIGHT, H.L. Some relationships between the surface wind and the wind at 900 mb.
- FINDLATER, J. Surface and Geostrophic Winds.



# TABLES

TABLE 1	-	COMPARISON OF 900 MB AND GEOSTROPHIC WINDS (NOV-MAR 1957-1961)
1a	-	Wind Direction in 10° sectors - Crawley.
1b	-	Wind Speeds in knots - Crawley.
1c	-	Standard errors and correlation coefficients.
TABLE 2	-	FREQUENCIES OF LAPSE CLASSES
2a	-	In 900 mb speed classes for direction class Southwest - weighted.
2b	-	In 900 mb direction classes for speed class 20-29 - weighted.
TABLE 3	-	DISTRIBUTION OF LAPSE CLASSES AT 1200 AND 0001 GMT AT LEUCHARS.
TABLE 4	-	ANNUAL AND DIURNAL VARIATION OF COMPONENT RATIOS.
TABLE 5	-	MONTHLY MEAN WIND SPEEDS (KNOTS) AT "INDIA" AND "JULIETT" (1948-1952).
TABLE 6	-	PERCENTAGE FREQUENCIES (f) OF LAPSE RATE CLASSES AT LEUCHARS AND DERIVED SEASONAL AND DIURNAL VALUES OF COMPONENT RATIOS.
TABLE 7	-	COMPARISON OF MONTHLY MEAN WIND SPEEDS (KNOTS) AT AUCHTERHOUSE AND LEUCHARS.
TABLE 8	-	SMOOTHED VALUES OF $V_0$ (KNOTS) AND ANGLE $\alpha$ (DEGREES) FOR CLASSES OF 900 MB WIND SPEED AND LAPSE RATE - SHIPS "INDIA" AND "JULIETT".
TABLE 9	-	SMOOTHED VALUES OF $V_0/V_{900}$ AND ANGLE $\alpha$ (DEGREES) FOR CLASSES OF 900 MB WIND DIRECTION AND LAPSE RATE - HEATHROW.
TABLE 10	-	SMOOTHED VALUES OF $V_0/V_{900}$ AND ANGLED $\alpha$ (DEGREES) FOR CLASSES OF 900 MB WIND DIRECTION AND LAPSE RATE - LEUCHARS.



TABLE 1 - COMPARISON OF 900 MB AND GEOSTROPHIC WINDS (NOV-MAR 1957-1961)

TABLE 1a - Wind Directions in 10° sectors - Crawley

Geostrophic	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35
900 mb	35	0	0	2	3	3	6	5	9	9	10	11	13	16	16	17	17	17	19	18	20	22	21	23	22	24	27	28	29	30	32	32	32	32	33	34
No. of obs.	8	19	11	12	21	23	17	25	13	12	10	10	15	5	7	4	10	9	7	20	17	26	33	36	32	37	35	18	16	22	22	15	21	18	12	18
Difference	-1	-1	-2	-1	-1	-2	0	-2	+1	0	0	0	+1	+3	+2	+2	+1	0	+1	-1	0	+1	-1	0	-2	-1	+1	+1	0	0	+1	0	-1	-1	-1	

TABLE 1b - Wind speeds in knots - Crawley

Geostrophic	10-14	15-19	20-24	25-29	30-34	35-39	40-44	45-49	50-54	55-59	60-64	65-69
Mean 900 mb	13	16	21	25	29	31	34	38	42	41	44	45
No of obs.	102	111	107	90	74	48	40	30	21	9	6	6
Mean Difference	+1	-1	-1	-2	-3	-6	-8	-9	-10	-15	-17	-22

TABLE 1c - Standard errors and correlation coefficients

	Geostrophic Crawley/900 mb Crawley		Geostrophic Heathrow/Geostrophic Crawley		Geostrophic Heathrow/900 mb Crawley	
	Direction	Speed	Direction	Speed	Direction	Speed
Standard error	4.32	9.28	2.85	6.57	4.36	8.59
Corr. Coeff.	0.94	0.75	0.97	0.91	0.94	0.79



TABLE 2 FREQUENCIES OF LAPSE CLASSES

Table 2a - In 900 mb speed classes for direction class Southwest - weighted

Lapse Speed	SHIP INDIA						LONDON (HEATHROW) AIRPORT					
	1	2	3	4	5	6	1	2	3	4	5	6
10-19	5.4	8.1	8.1	6.7	3.0	6.7	5.8	4.6	1.3	2.5	3.9	4.9
20-29	6.3	8.3	7.1	6.0	6.8	5.0	3.1	2.9	2.6	3.3	3.3	1.8
30-39	9.8	7.0	6.7	7.9	11.5	16.9	0.7	1.8	4.1	2.8	1.3	2.8
40-49	8.5	7.4	6.4	8.5	8.5	0	0	0.9	4.1	2.9	2.9	1.5
≥50	8.5	3.9	11.6	11.4	6.8	0	0	1.6	5.5	2.3	0	0

Table 2b - In 900 mb direction classes for speed class 20-29 - weighted

Lapse Dirn.	SHIP INDIA						LONDON (HEATHROW) AIRPORT					
	1	2	3	4	5	6	1	2	3	4	5	6
N	9.3	7.9	4.3	0.7	1.4	0	3.3	3.7	5.0	3.3	1.3	2.1
NE	9.2	7.0	4.2	4.9	0	0	8.5	5.4	3.8	3.1	3.8	1.9
E	6.9	6.9	5.2	6.9	7.8	10.4	4.4	2.8	3.3	2.8	7.2	10.6
SE	2.1	5.7	7.8	15.0	6.4	8.6	5.6	2.6	3.7	3.2	5.6	8.6
S	4.0	4.8	10.6	7.9	7.9	11.0	5.0	2.4	3.9	3.6	5.0	7.5
SW	4.9	6.2	7.5	7.5	8.8	2.0	2.7	3.9	3.7	3.7	3.5	1.9
W	6.9	6.9	4.7	6.1	8.1	11.2	2.2	4.2	3.1	4.0	3.5	3.4
NW	10.1	6.9	5.8	2.6	3.7	3.1	2.9	3.7	3.4	4.5	2.6	1.8

TABLE 3 - DISTRIBUTION OF LAPSE CLASSES AT 1200 AND 0001 GMT AT LEUCHARS

Lapse Class	1	2	3	4	5	6
No. of obs at 1200 GMT	340	482	345	134	33	14
No. of obs at 0001 GMT	24	116	529	367	102	46



TABLE 4 - ANNUAL AND DIURNAL VARIATION OF COMPONENT RATIOS

		Ship "Juliett"*			Heathrow			Leuchars		
		p	q	No. of obs.	p	q	No. of obs.	p	q	No. of obs.
Winter	Day	.78	.08	672	.38	.16	554	.31	.11	348
	Night	.78	.07	659	.26	.17	542	.27	.12	327
Spring	Day	.75	.12	682	.55	.09	552	.49	.08	346
	Night	.78	.13	685	.25	.16	478	.32	.13	292
Summer	Day	.79	.11	675	.58	.08	494	.48	.11	310
	Night	.77	.16	671	.28	.15	461	.25	.17	271
Autumn	Day	.78	.13	641	.47	.13	518	.43	.15	344
	Night	.78	.12	638	.24	.18	483	.30	.14	294
Year	Day	.78	.11	2670	.49	.12	2118	.42	.11	1348
	Night	.78	.12	2653	.26	.17	1964	.29	.14	1184

\* Values for Ship J include those on occasions of 900 mb winds between 4 and 9 kt incl.

TABLE 5 MONTHLY MEAN WIND SPEEDS (KNOTS) AT "INDIA" AND "JULIETT" (1948-1952)

	Winter			Spring			Summer			Autumn			Year
	Dec	Jan	Feb	Mch	Apl	May	June	July	Aug	Sept	Oct	Nov	
"India"	20.3	22.9	21.5	21.4	20.0	14.9	14.1	13.6	13.4	15.8	18.0	19.6	17.7
"Juliett"	22.4	22.6	21.2	20.2	17.7	14.7	14.2	13.7	16.1	16.5	20.4	20.3	18.3

TABLE 6 - PERCENTAGE FREQUENCIES (f) OF LAPSE RATE CLASSES AT LEUCHARS AND DERIVED SEASONAL AND DIURNAL VALUES OF COMPONENT RATIOS

Lapse Class		1	2	3	4	5	6	No. of Obs.	$\frac{f\bar{p}}{100}$	$\frac{f\bar{q}}{100}$
Winter	Day	4	33	37	17	5	3	348	.34	.13
	Night	7	8	37	33	10	6	327	.31	.14
Spring	Day	39	34	16	10	2	$\frac{1}{3}$	346	.45	.09
	Night	0	15	46	27	9	3	292	.31	.13
Summer	Day	47	32	14	5	1	$\frac{1}{3}$	310	.46	.08
	Night	1	6	53	29	8	4	271	.30	.15
Autumn	Day	13	44	34	7	2	$\frac{1}{3}$	344	.40	.11
	Night	0	11	44	35	8	3	294	.30	.15
Mean annual $\bar{p}$		.56	.44	.32	.25	.21	.13			
Mean annual $\bar{q}$		.04	.10	.15	.17	.16	.05			



TABLE 7 - COMPARISON OF MONTHLY MEAN WIND SPEEDS  
AT AUCHTERHOUSE AND LEUCHARS

1960	JAN	FEB	MCH	APL	MAY	JUNE	JLY	AUG	SEPT	OCT	NOV	DEC	YEAR
Auchterhouse	8.6	9.2	12.3	10.7	8.9	8.5	6.9	5.9	7.3	11.6	8.4	7.9	8.9
Leuchars	8.3	7.3	10.1	8.5	6.0	7.1	5.3	6.9	8.2	10.2	7.2	7.9	7.7
Difference	+0.3	+1.9	+2.2	+2.2	+2.9	+2.4	+1.6	-1.0	-0.9	+1.4	+1.2	0.0	+1.2
1961													
Auchterhouse	8.6	10.0	12.0	9.2	7.6	9.4	8.1	8.1	7.2	9.5	7.2	7.7	8.7
Leuchars	8.8	10.6	13.2	8.8	8.7	11.2	8.9	9.5	8.7	10.9	8.1	7.0	9.5
Difference	-0.2	-0.6	-1.2	+0.4	-1.1	-1.8	-0.8	-1.4	-1.5	-1.4	-0.9	+0.7	-0.8

TABLE 8 - SMOOTHED VALUES OF  $V_0$  (KNOTS) AND ANGLE  $\alpha$  (DEGREES) FOR CLASSES  
OF 900 MB WIND SPEED AND LAPSE RATE - SHIPS "INDIA" AND "JULIETT"

Lapse	900mb Speed	10-19		20-29		30-39		40-49		$\geq 50$	
		$V_0$	$\alpha$	$V_0$	$\alpha$	$V_0$	$\alpha$	$V_0$	$\alpha$	$V_0$	$\alpha$
1		15	0	22	0	30	0	37	0	42	0
2		14	5	21	5	28	5	34	5	40	5
3		13	10	20	12	25	15	30	12	35	10
4		12	15	18	18	23	20	28	22	33	20
5		11	15	17	18	22	20	27	22	30	25
6		12	25	18	25	23	20	28	20	-	-

TABLE 9 - SMOOTHED VALUES OF  $V_0/V_{900}$  AND ANGLE  $\alpha$  (DEGREES) FOR CLASSES  
OF 900 MB WIND DIRECTION AND LAPSE RATE - HEATHROW

Lapse	900mb Dirn.	N		NE		E		SE		S		SW		W		NW	
		$V_0/V_{900}$	$\alpha$	$V_0/V_{900}$	$\alpha$	$V_0/V_{900}$	$\alpha$	$V_0/V_{900}$	$\alpha$	$V_0/V_{900}$	$\alpha$	$V_0/V_{900}$	$\alpha$	$V_0/V_{900}$	$\alpha$	$V_0/V_{900}$	$\alpha$
1		.55	0	.60	0	.65	0	.65	0	.60	0	.70	0	.65	0	.60	0
2		.50	5	.55	5	.60	5	.60	10	.60	10	.60	10	.60	95	.55	10
3		.35	25	.45	20	.50	15	.45	35	.40	30	.40	25	.40	20	.40	20
4		.25	25	.35	25	.40	30	.40	45	.35	50	.35	30	.35	30	.35	35
5		.20	50	.30	15	.40	40	.35	50	.25	60	.30	40	.30	30	.30	45
6		.20	35	.30	10	.40	40	.35	60	.25	60	.30	40	.30	30	.30	45



TABLE 10 - SMOOTHED VALUES OF  $V_0/V_{900}$  AND ANGLE  $\alpha$  (DEGREES) FOR CLASSES OF 900 MB UPPER WIND DIRECTION AND LAPSE RATE - LEUCHARS

900 mb Dirn. Lapse	N	NE	E	SE	S	SW	W	NW
	$\frac{V_0}{V_{900}}$ $\alpha$	$\frac{V_0}{V_{900}}$ $\alpha$	$\frac{V_0}{V_{900}}$ $\alpha$	$\frac{V_0}{V_{900}}$ $\alpha$	$\frac{V_0}{V_{900}}$ $\alpha$	$\frac{V_0}{V_{900}}$ $\alpha$	$\frac{V_0}{V_{900}}$ $\alpha$	$\frac{V_0}{V_{900}}$ $\alpha$
1	.40 -20	.60 -20	.70 10	.80 10	.55 10	.55 0	.60 10	.50 10
2	.30 10	.45 0	.60 10	.55 10	.40 30	.40 10	.45 20	.40 20
3	.25 40	.35 20	.50 20	.50 30	.35 30	.30 10	.35 20	.30 40
4	.25 80	.20 80	.45 40	.45 40	.30 30	.30 10	.30 20	.35 60
5	.10 90	.05 90	.40 50	.35 60	.25 30	.25 10	.35 20	.45 60
6	- -	- -	.10 100	.30 90	.10 -30	.20 -10	.20 0	- -



## FIGURES

### Notes

1. Lapse classes are labelled in Arabic numerals 1 to 6.
2. Where numbers of observations are shown, these are printed in Italics and, if following other numerals indicating lapse or wind speed classes, are also placed in brackets.
3. Speed classes are labelled as follows for brevity:-

Speed class	Label in Figures
10-19kt	15
20-29kt	25
30-39kt	35
40-49kt	45
≥ 50kt	≥ 50

Where speed class is plotted along the ordinate or abscissa, the classes are spaced at equal intervals.

- FIG 1 - OVERALL MEAN VALUE OF COMPONENT RATIOS OF SURFACE TO 900 MB WIND
- FIG 2 - VARIATION OF p and q WITH LAPSE RATE CLASS
- 2a - Ships India and Juliett
- 2b - Heathrow and Leuchars
- FIG 3 - VARIATION OF p and q WITH 900 MB WIND SPEED
- 3a - Ship India
- 3b - Ship Juliett
- 3c - Heathrow
- 3d - Leuchars
- FIG 4 - VARIATION OF p and q WITH 900 MB WIND DIRECTION
- 4a - Ship India
- 4b - Ship Juliett
- 4c - Heathrow
- 4d - Leuchars
- FIG 5 - VARIATION OF p and q WITH LAPSE RATE CLASS AND 900 MB WIND SPEED
- 5a - Ship India
- 5b - Ship Juliett
- FIG 5c - Heathrow Day
- 5d - Heathrow Night
- FIG 5e - Leuchars Day
- 5f - Leuchars Night
- FIG 6 - VARIATION OF p and q IN 900 MB WIND DIRECTION CLASSES, FOR SPECIFIC LAPSE RATE AND 900 MB WIND SPEED CLASSES. SHIPS INDIA AND JULIETT
- 6a - Lapse class 2 - speed class 20-29
- 6b - Lapse class 3 - speed class 20-29
- 6c - Lapse class 2 - speed class 30-39
- 6d - Lapse class 3 - speed class 30-39
- FIG 4a,b - Repeated.
- FIG 7 - VARIATION OF p and q WITH 900 MB WIND DIRECTION, 900 MB WIND SPEED CLASSES 10-19 KT AND ≥ 20 KT SEPARATELY. SHIP INDIA.

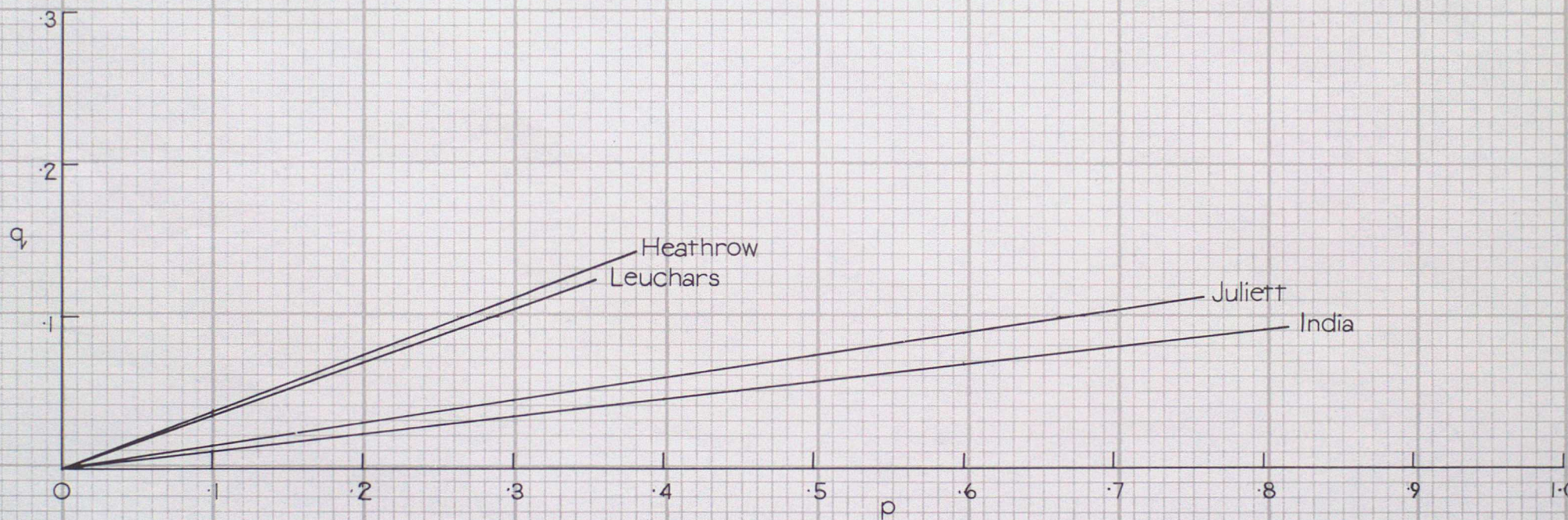


FIGURES (contd.)

- FIG 8 - SEASONAL VARIATION OF p and q  
8a - Ship India  
8b - Ship Juliett  
8c - Heathrow  
8d - Leuchars  
FIG 9 - COMPARISON OF SEASONAL MEANS, DAY AND NIGHT SEPARATELY  
WITH VALUES DERIVED FROM LAPSE RATE FREQUENCIES - LEUCHARS.  
FIG 10 - DIURNAL VARIATION OF p and q BY LAPSE CLASS  
HEATHROW AND LEUCHARS.  
  
FIG 11 - SURFACE WIND FREQUENCIES IN TWELVE 30° SECTORS.  
  
FIG 12 - FORECASTING DIAGRAM FOR SHIPS-900 MB WIND SPEED/SURFACE  
WIND SPEED AND  $\alpha$   
12a - Ship India  
12b - Ship Juliett  
  
FIG 13 - FORECASTING DIAGRAM FOR HEATHROW-900 MB WIND DIRECTION  $V_0/V_{900}$   
RATIO AND  $\alpha$   
  
FIG 14 - FORECASTING DIAGRAM FOR LEUCHARS-900 MB WIND DIRECTION/  
 $V_0/V_{900}$  RATIO AND  $\alpha$



FIG 1. OVERALL MEAN VALUE OF COMPONENT RATIOS OF SURFACE TO 900MB WIND





### CORRIGENDA

The following errors appear in the figure headings:-

- FIG 9            -        "SEASON" should read "SEASONAL"
- FIGS 12        -        "FORCASTING" should read "FORECASTING"  
and 14



FIG 2 VARIATION OF  $p$  AND  $q$  WITH LAPSE RATE CLASS

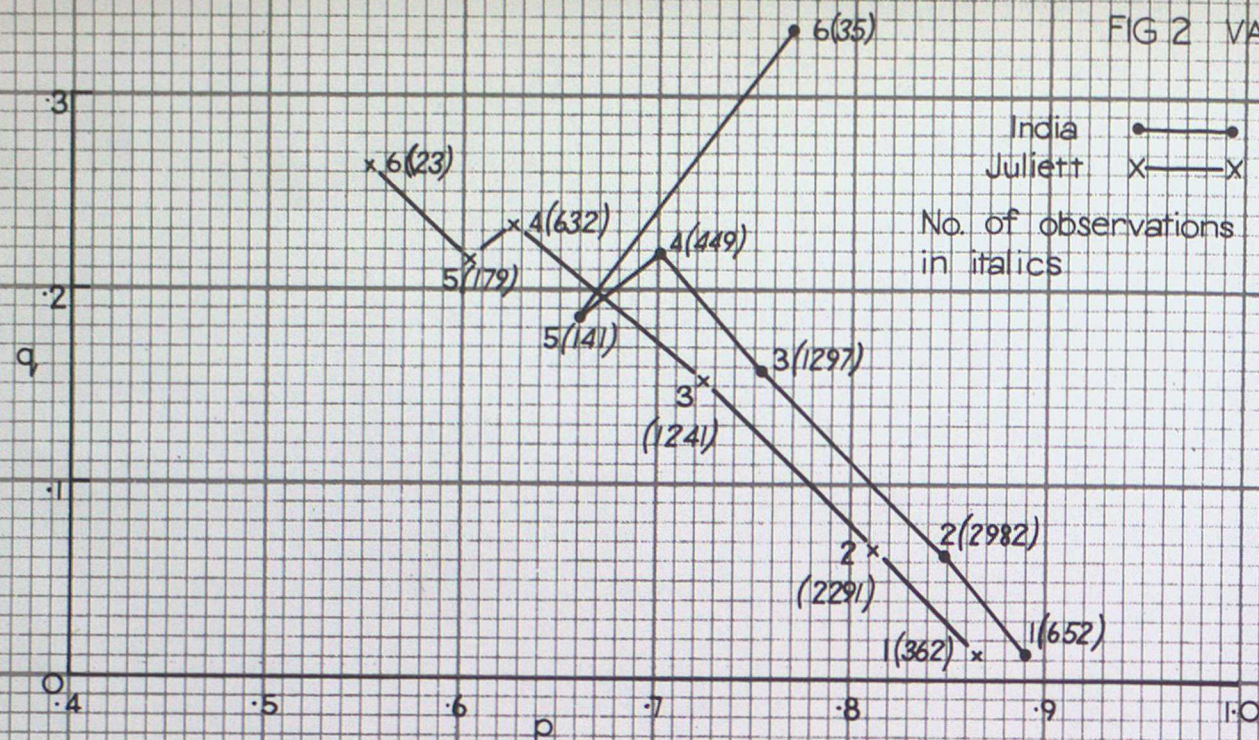


Fig 2a Ships India and Juliett

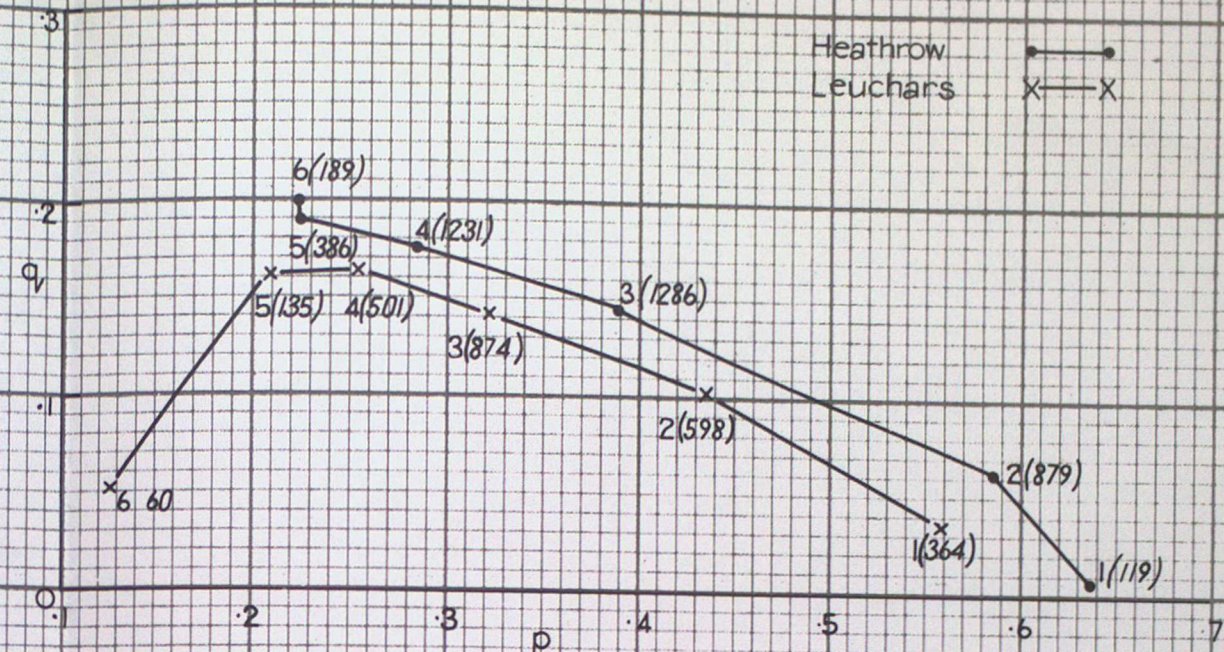


Fig 2b Heathrow and Leuchars

FIG 3 VARIATION OF  $p$  AND  $q$  WITH 900MB WIND SPEED

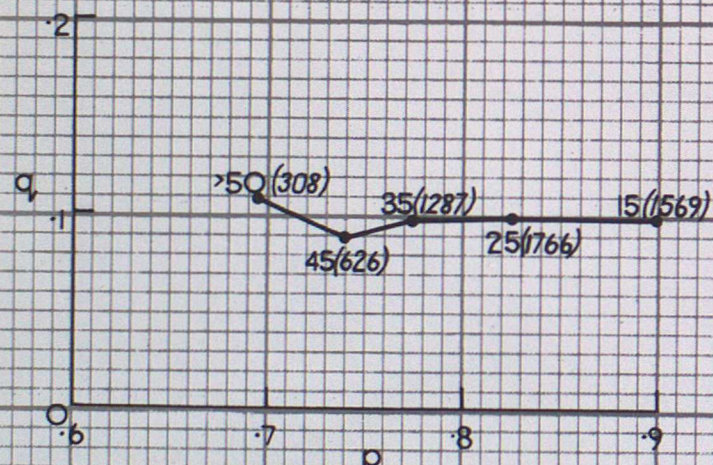


Fig 3a Ship India

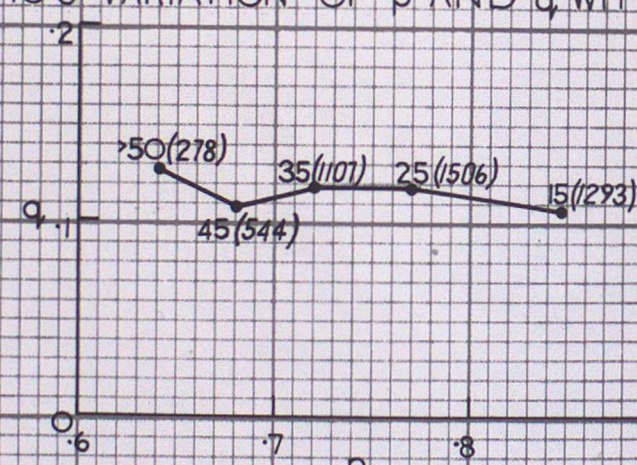


Fig 3b Ship Juliett

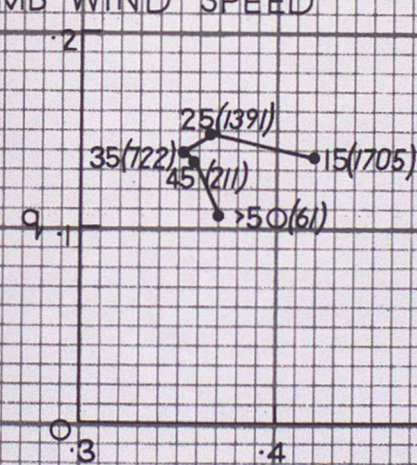


Fig 3c Heathrow

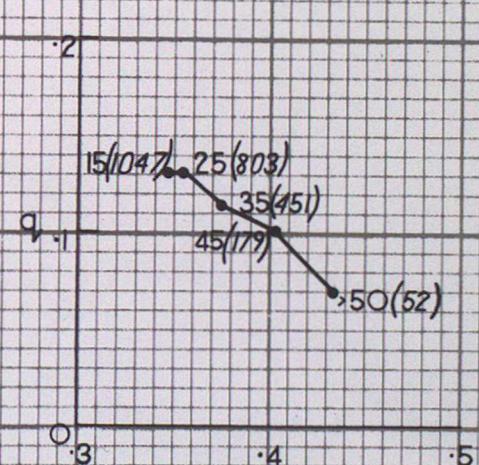


Fig 3d Leuchars

FIG 4 VARIATION OF  $p$  AND  $q$  WITH 900MB WIND DIRECTION

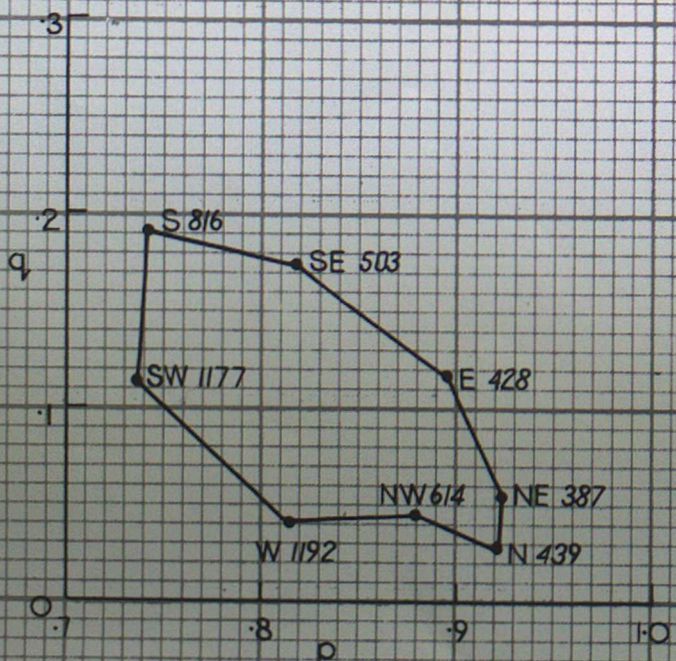


Fig 4a Ship India

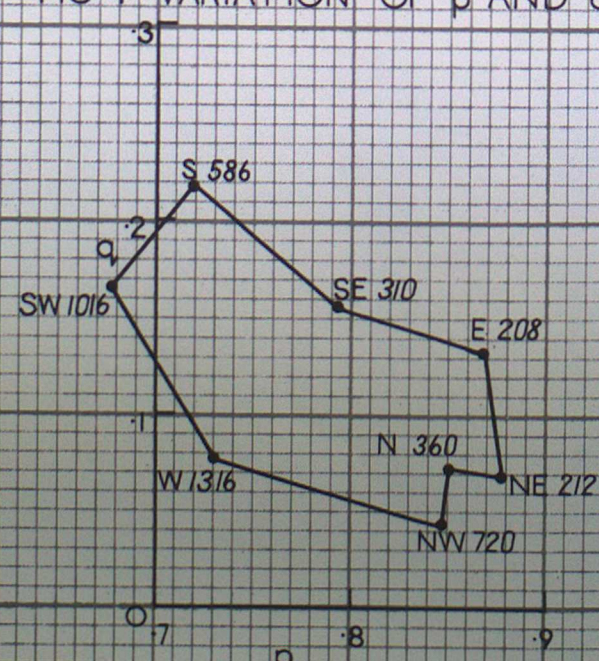


Fig 4b Ship Juliett

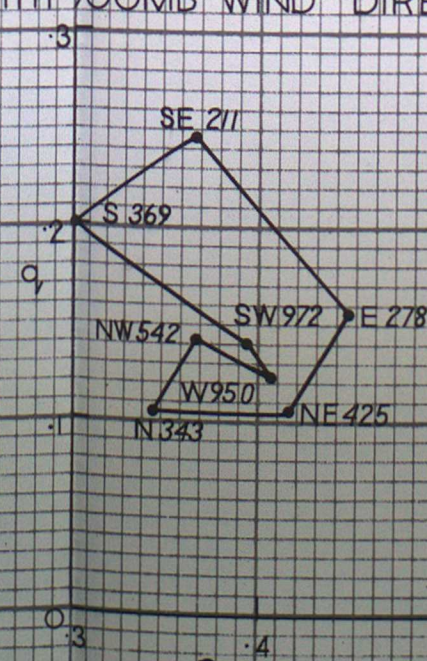


Fig 4c Heathrow

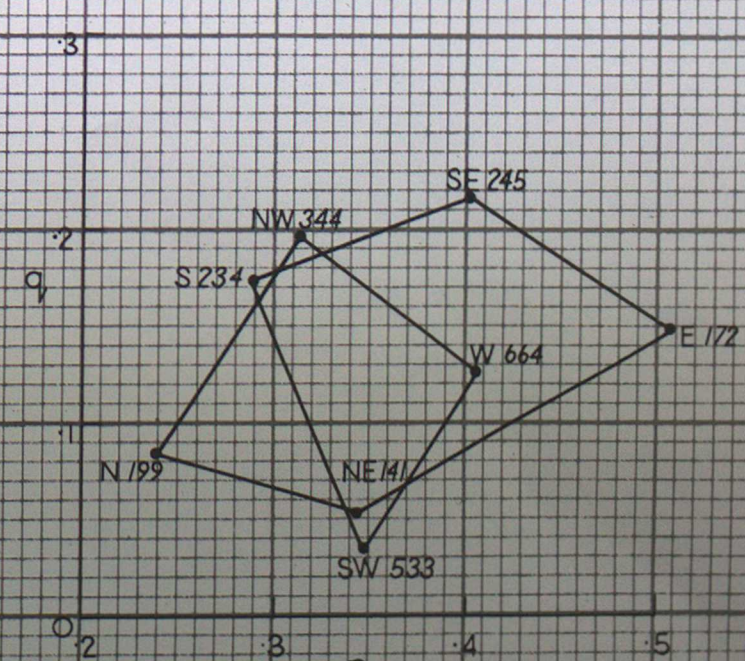


Fig 4d Leuchars



FIG 5 (contd) VARIATION OF  $p$  AND  $q_1$  WITH LAPSE RATE AND 900MB WIND SPEED

900mb wind speed  
kts

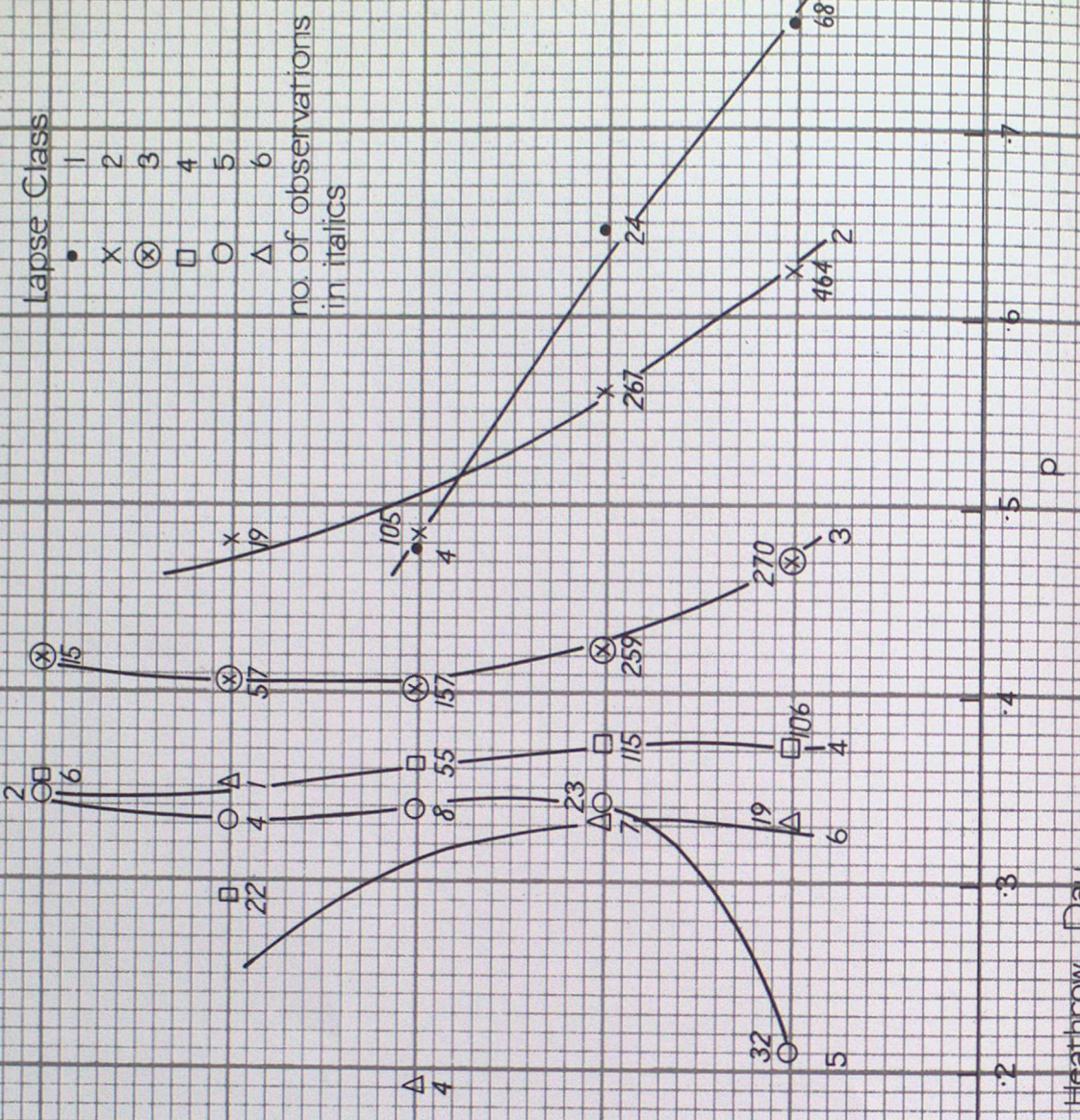
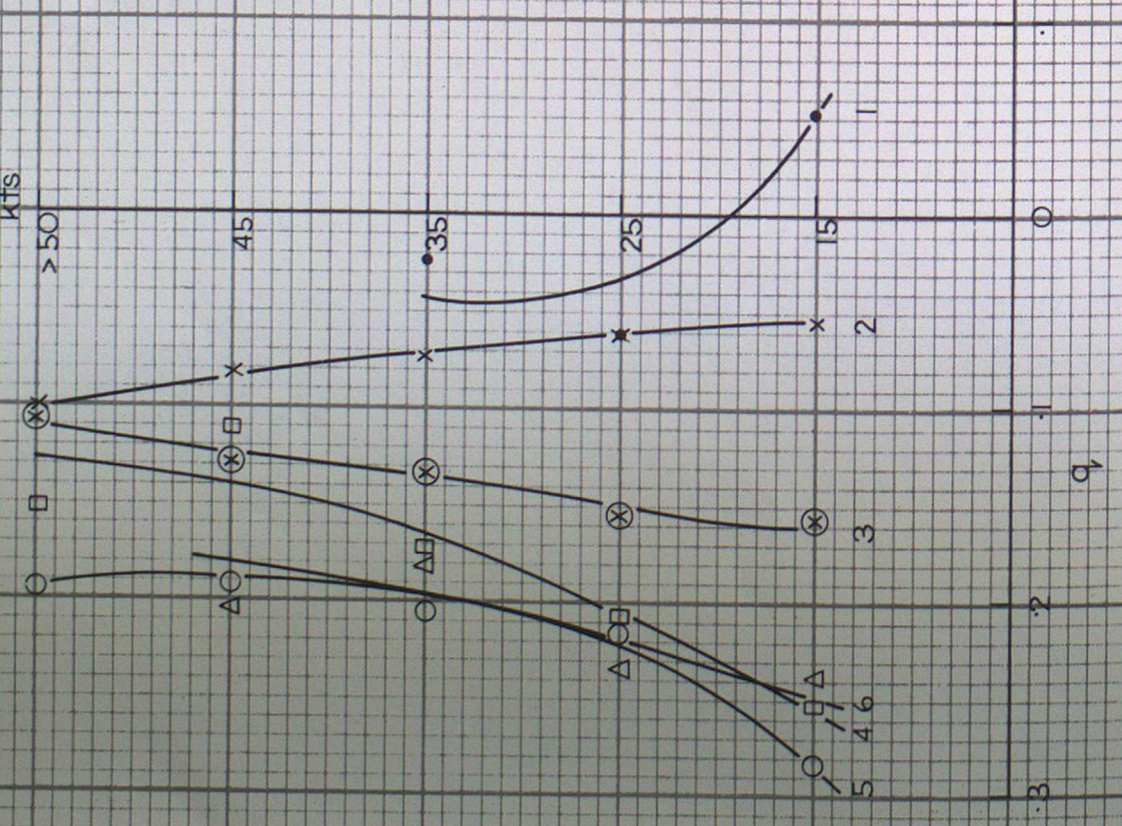


Fig 5c Heathrow Day

900mb wind speed  
kts

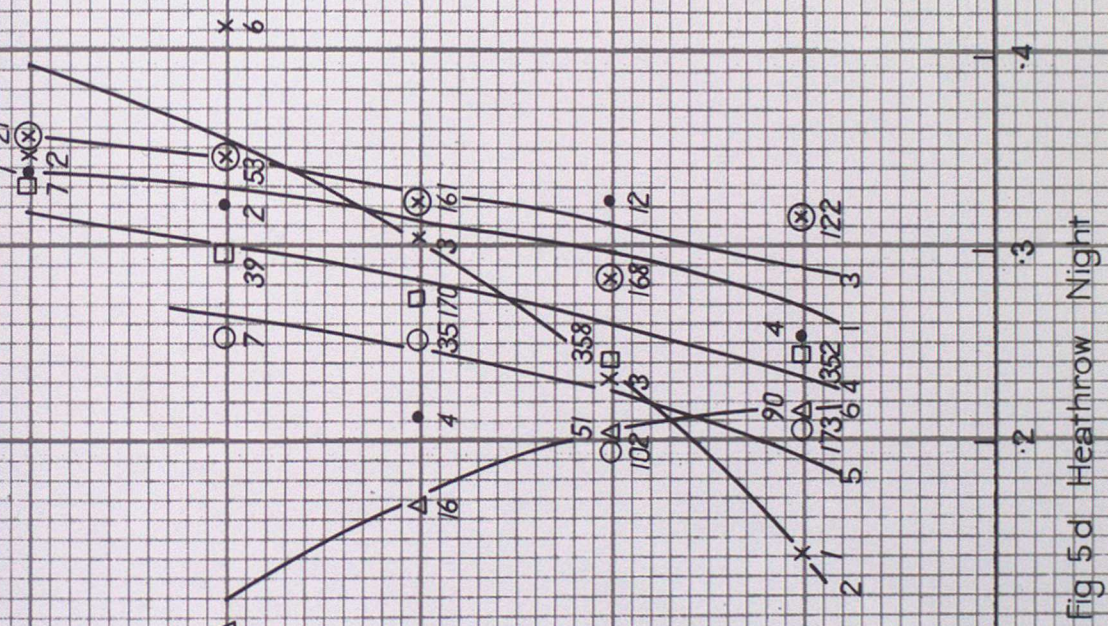
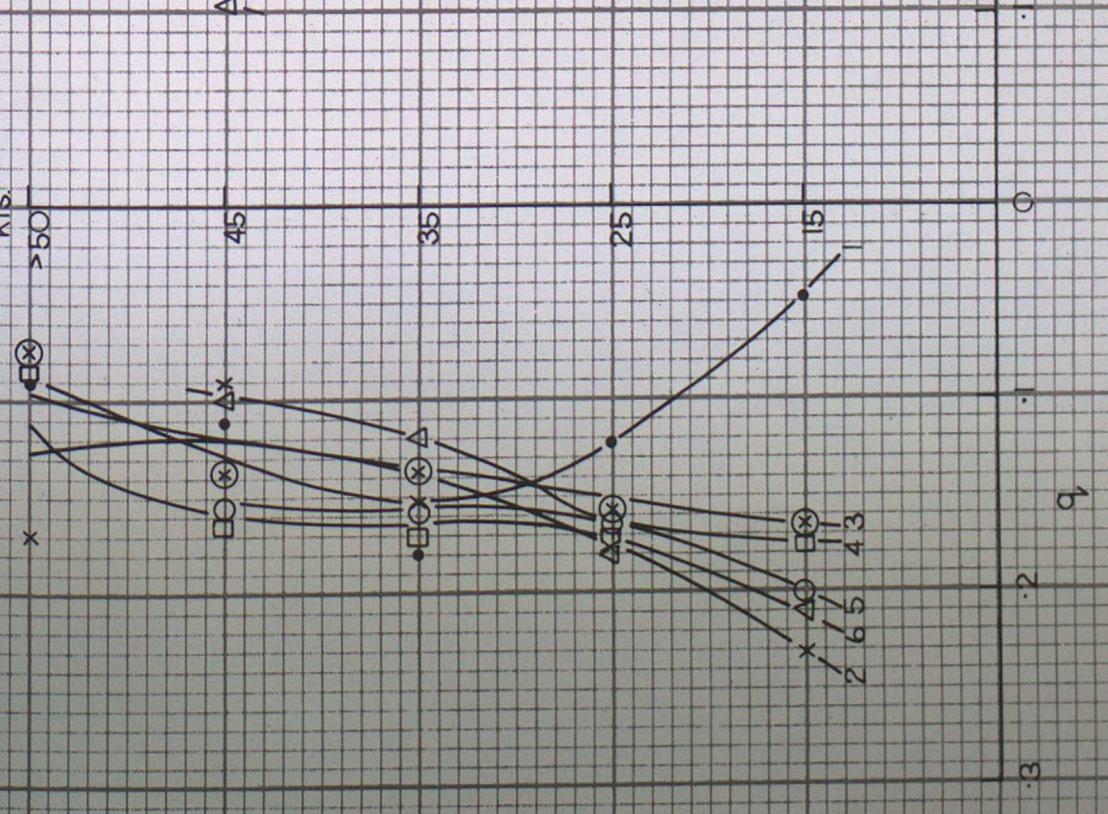
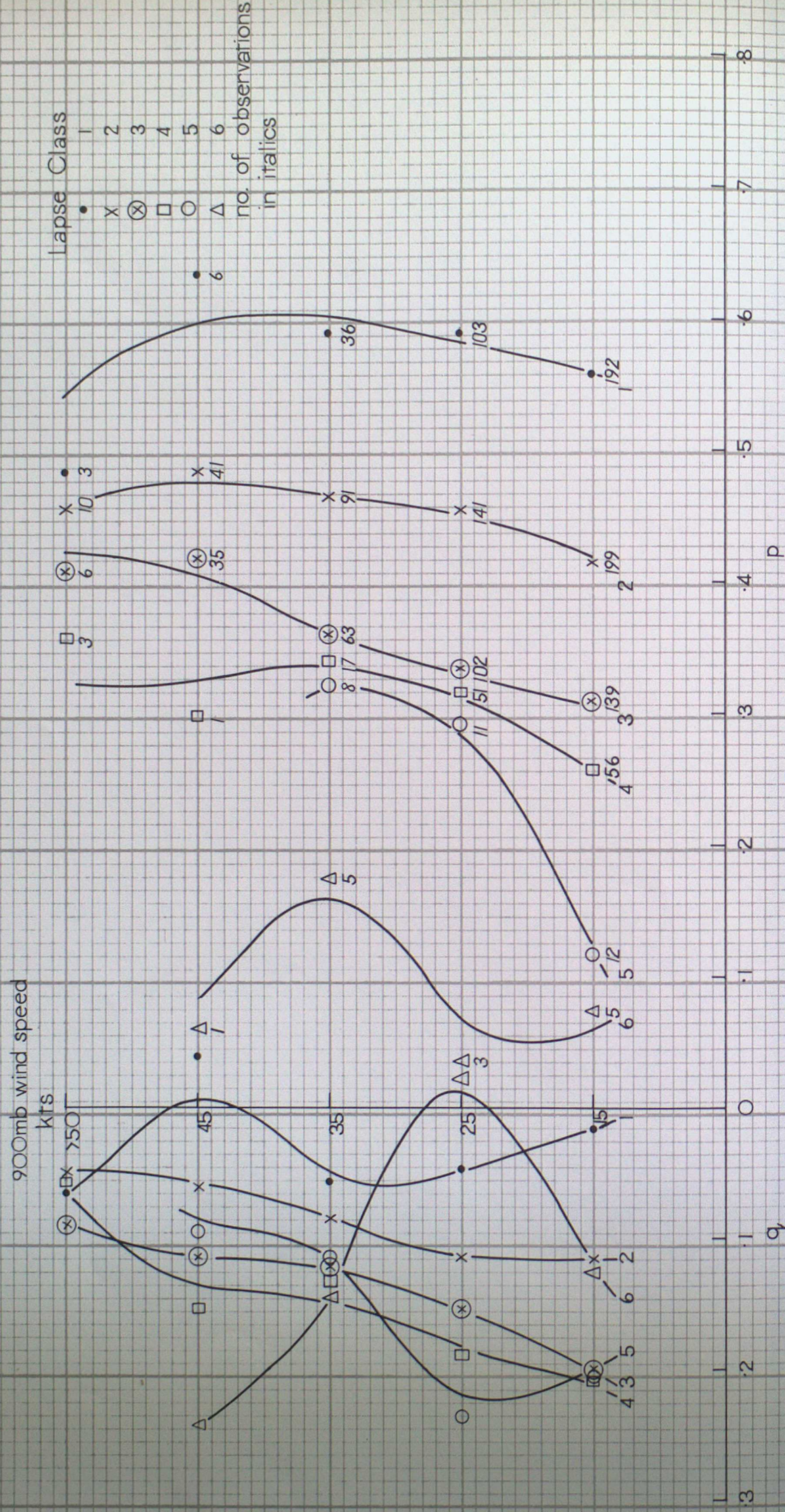


Fig 5d Heathrow Night

Lapse Class  
 • 1  
 x 2  
 ⊗ 3  
 □ 4  
 ○ 5  
 △ 6  
 no. of observations  
 in italics



FIG 5 (contd) VARIATION OF  $p$  AND  $q$  WITH LAPSE RATE AND 900 MB WIND SPEED



900mb wind speed  
kts

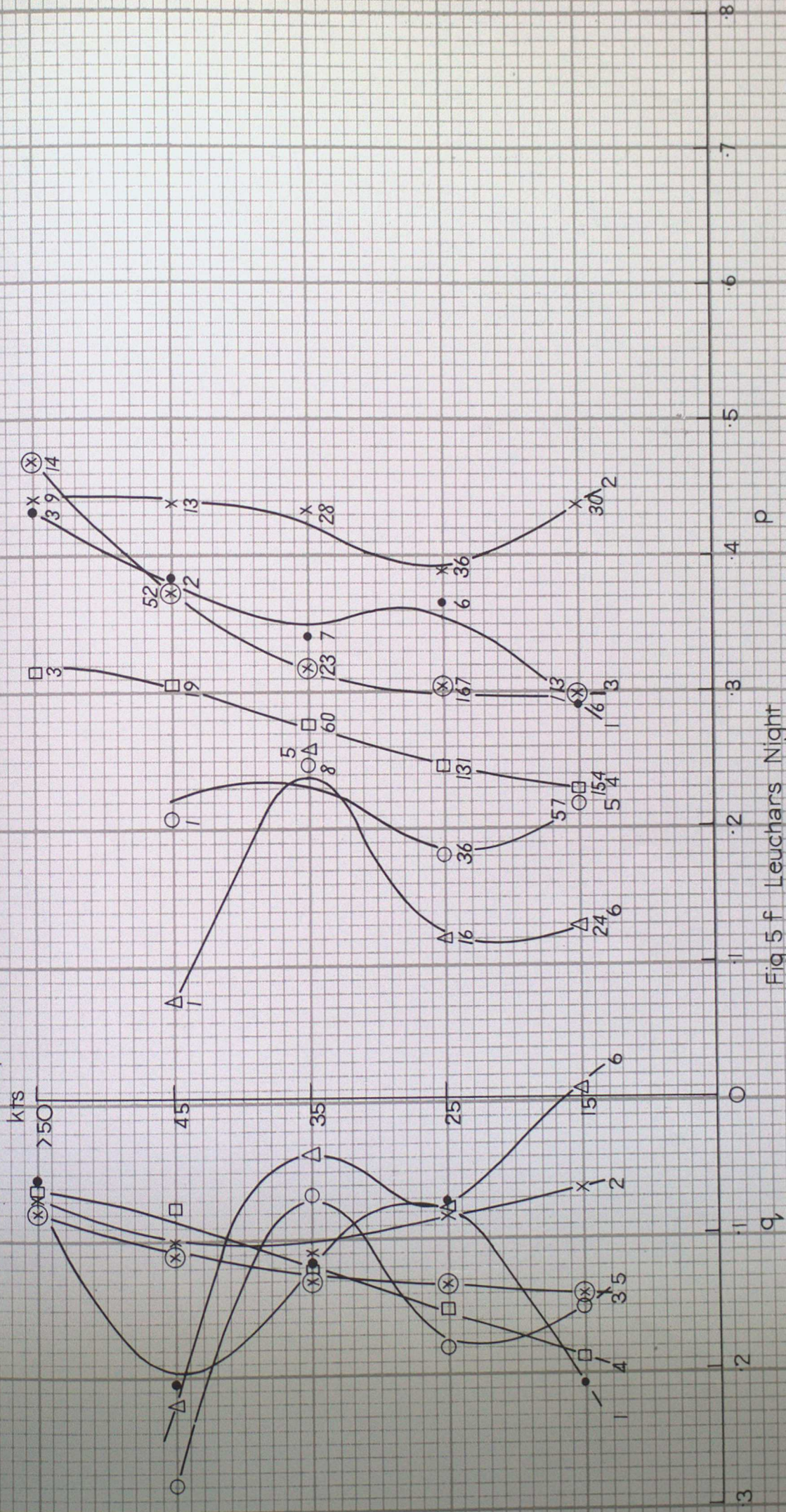
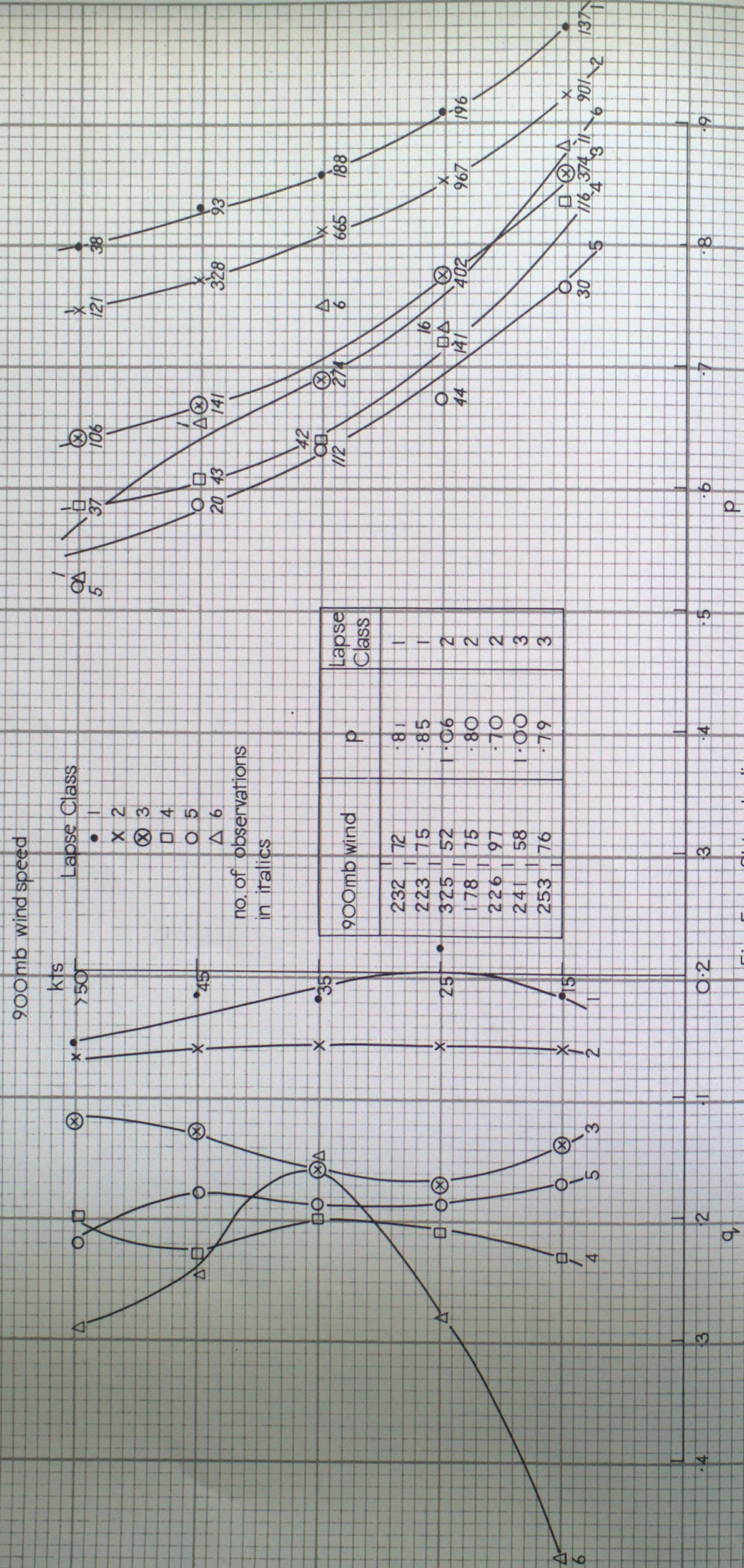




FIG 5. VARIATION OF  $p$  AND  $q_1$  WITH LAPSE RATE CLASS AND 900MB WIND SPEED



900mb wind speed

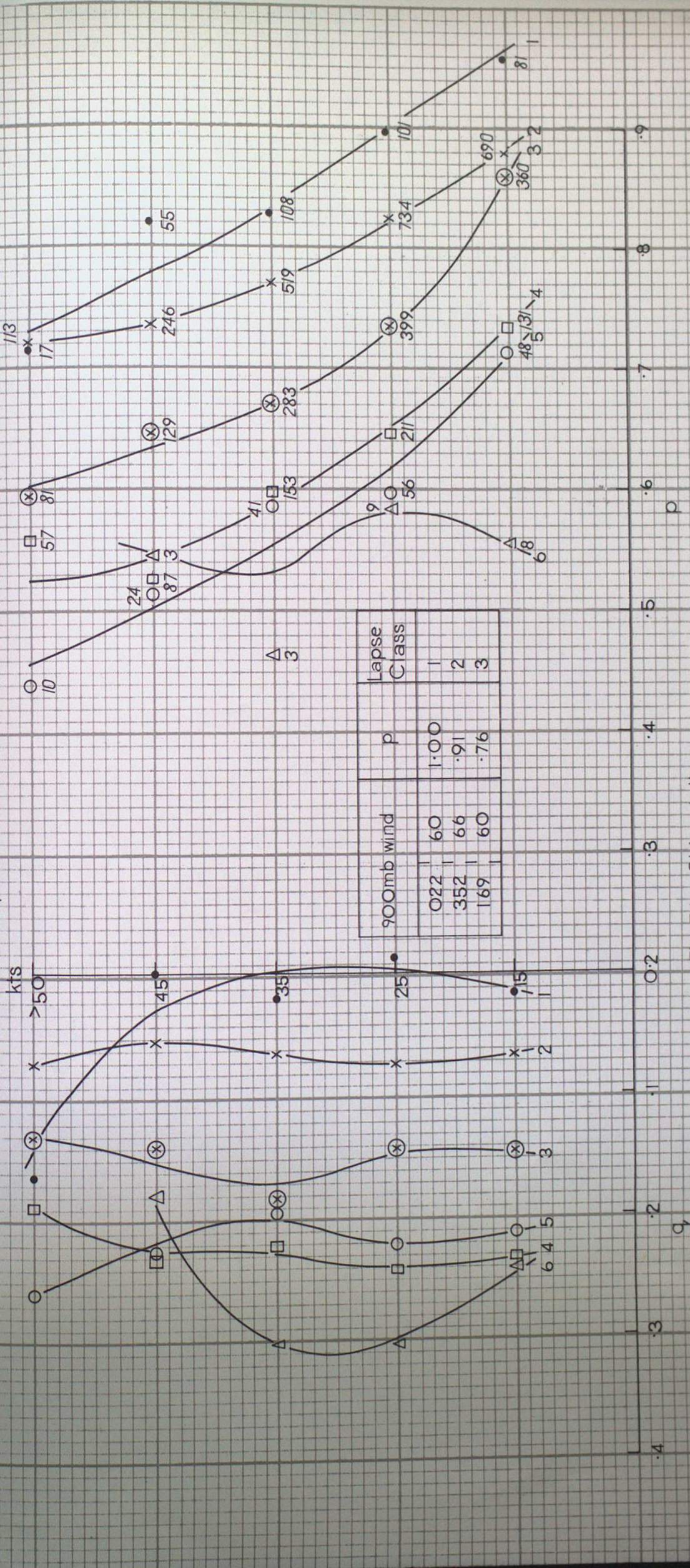




FIG 6 VARIATION OF  $p$  AND  $q$  IN 900MB WIND DIRECTION CLASSES, FOR SPECIFIC LAPSE RATE AND 900MB WIND SPEED CLASSES, SHIPS INDIA AND JULIETT.

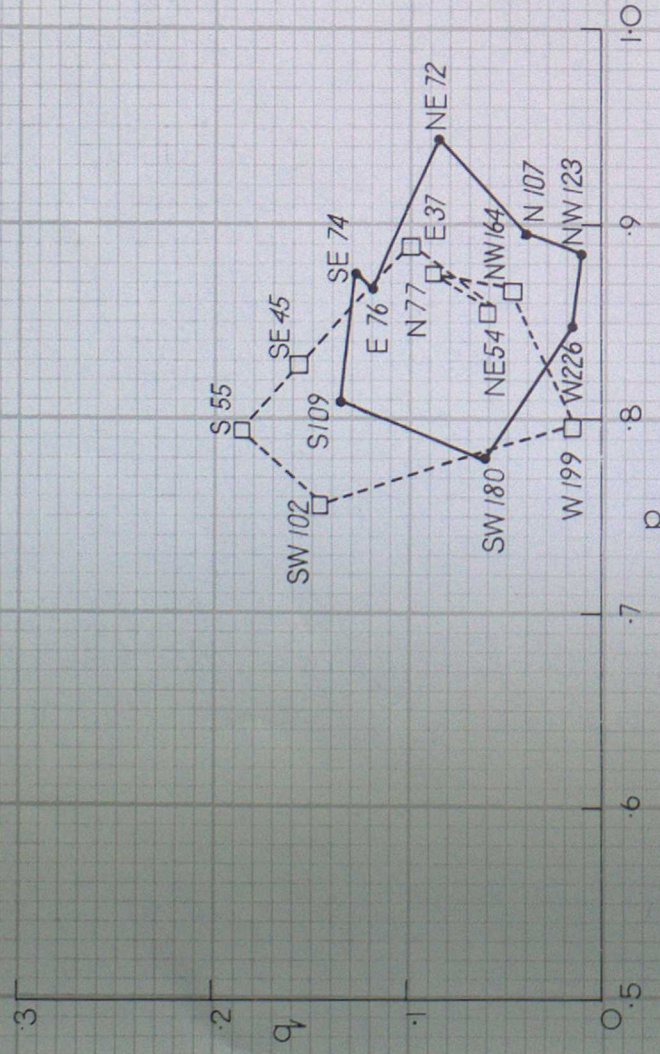


Fig 6a Lapse class 2 - speed class 20-29

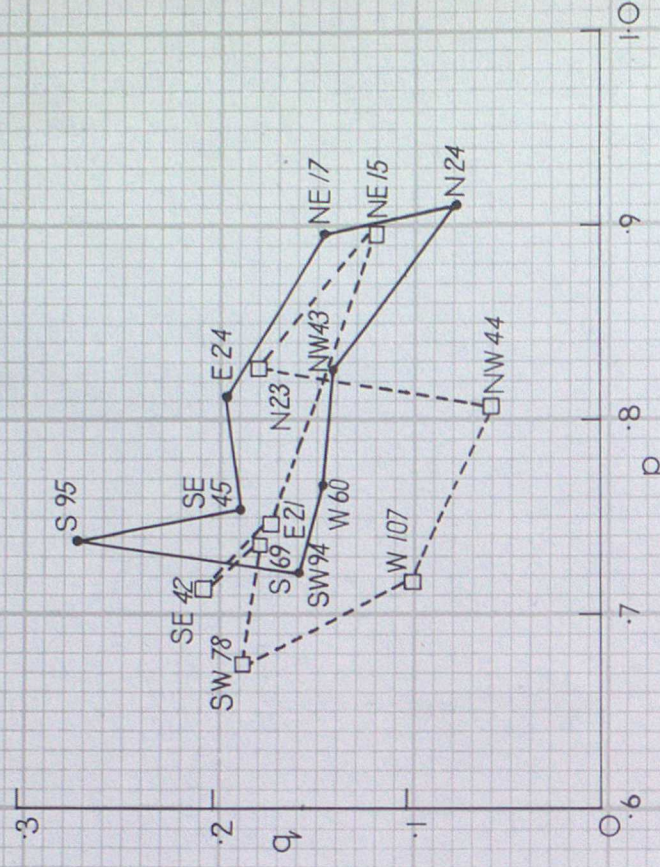


Fig 6b Lapse class 3 - speed class 20-29

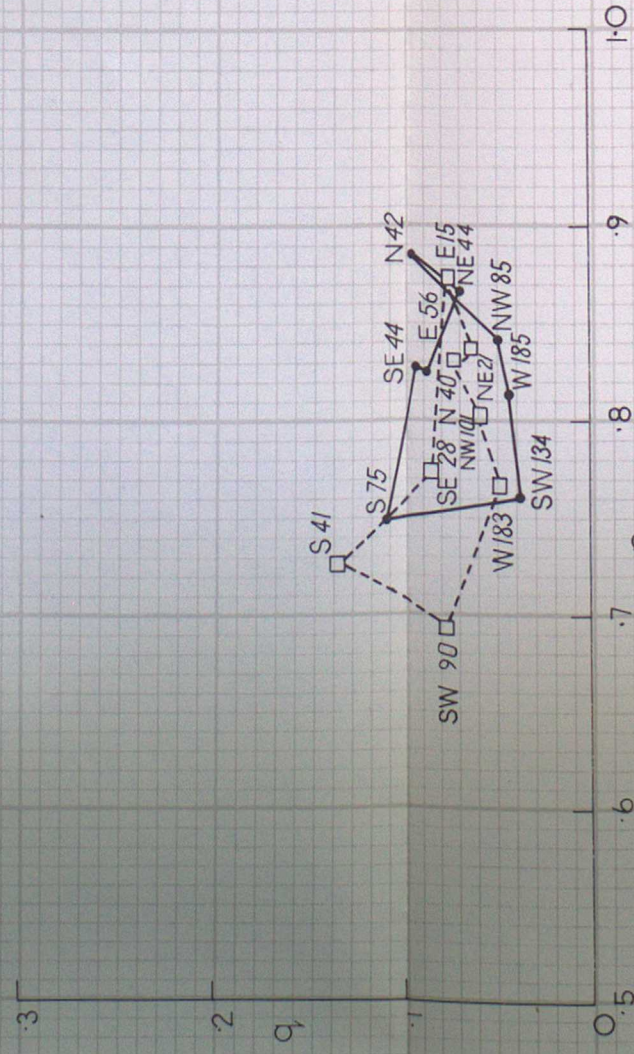


Fig 6c Lapse class 2 - speed class 30-39

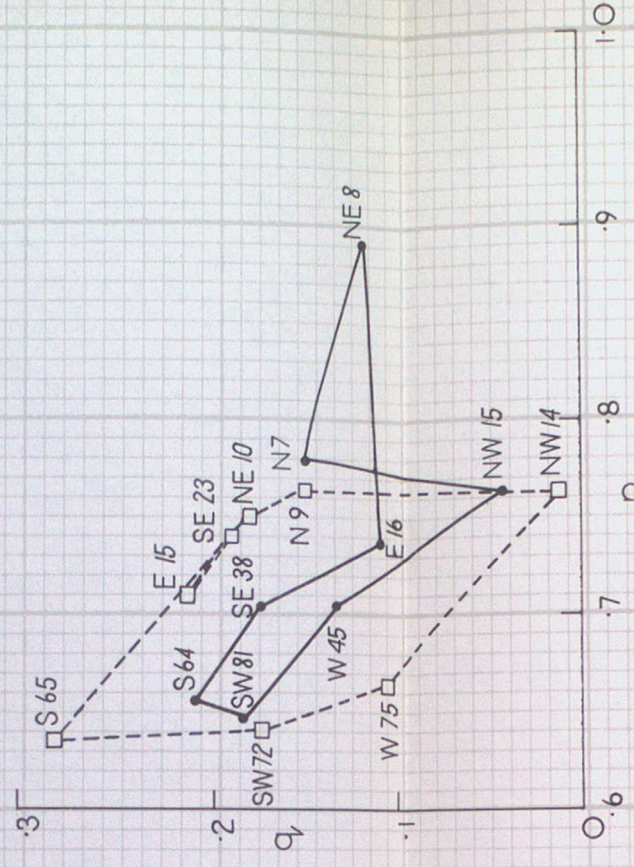


Fig 6d Lapse class 3 - speed class 30-39

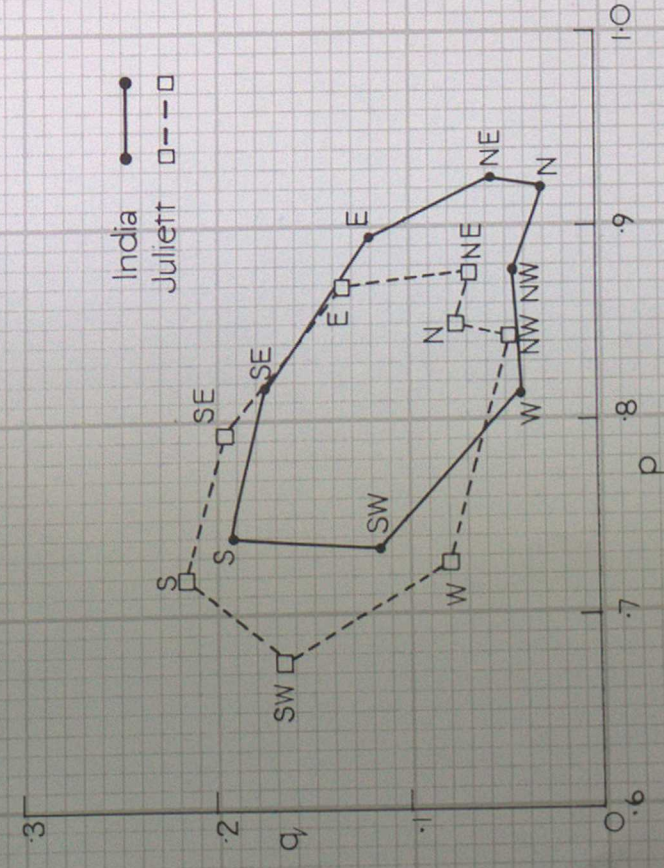


Fig 4a,b (repeated) Overall variation of  $p$  and  $q$  with 900mb wind direction-Ships India and Juliett

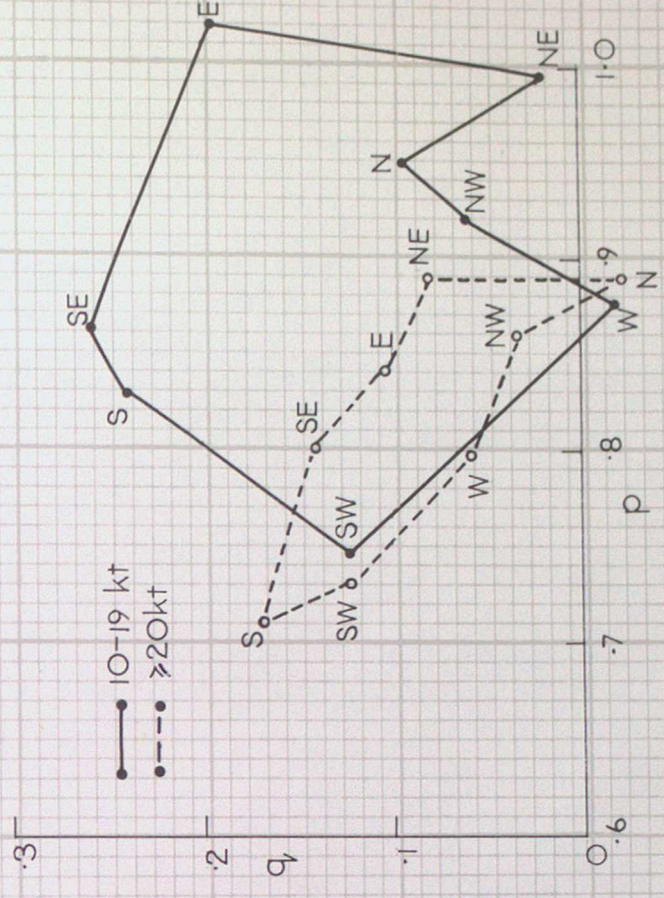




FIG 6 VARIATION OF  $p$  AND  $q_1$  IN 900MB WIND DIRECTION CLASSES, FOR SPECIFIC LAPSE RATE AND 900MB WIND SPEED CLASSES. SHIPS INDIA AND JULIETT.

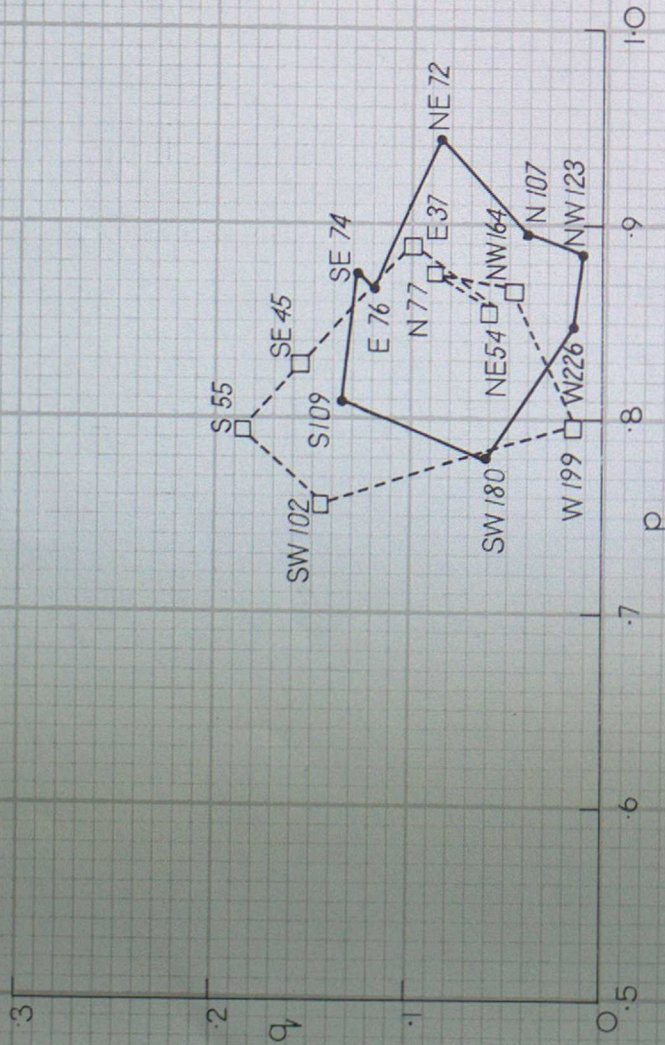


Fig 6a Lapse class 2 - speed class 20-29

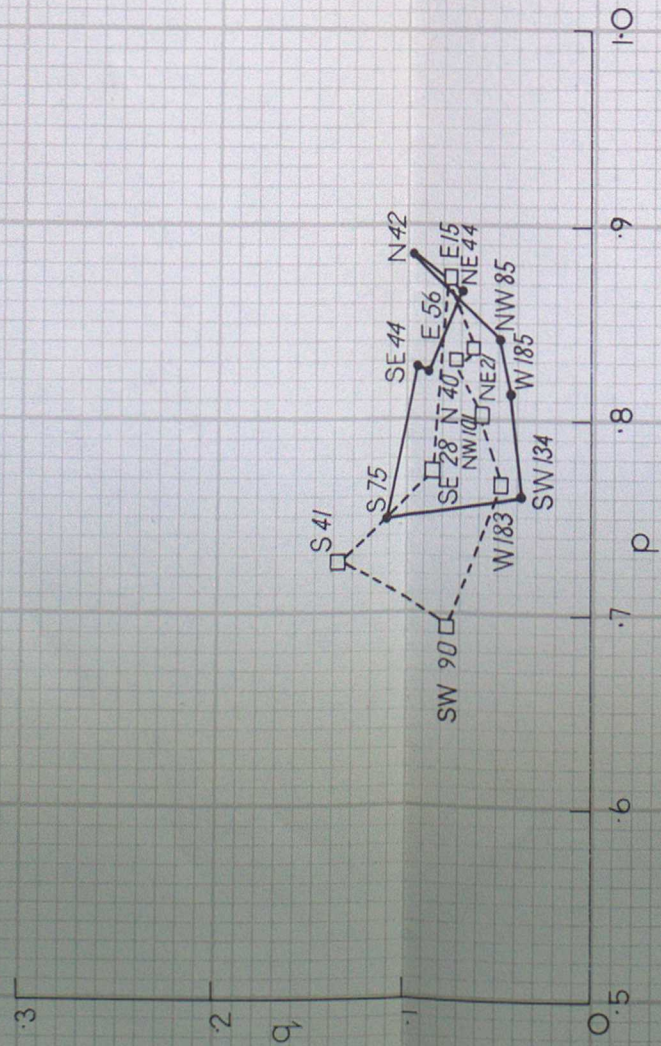


Fig 6c Lapse class 2 - speed class 30-39

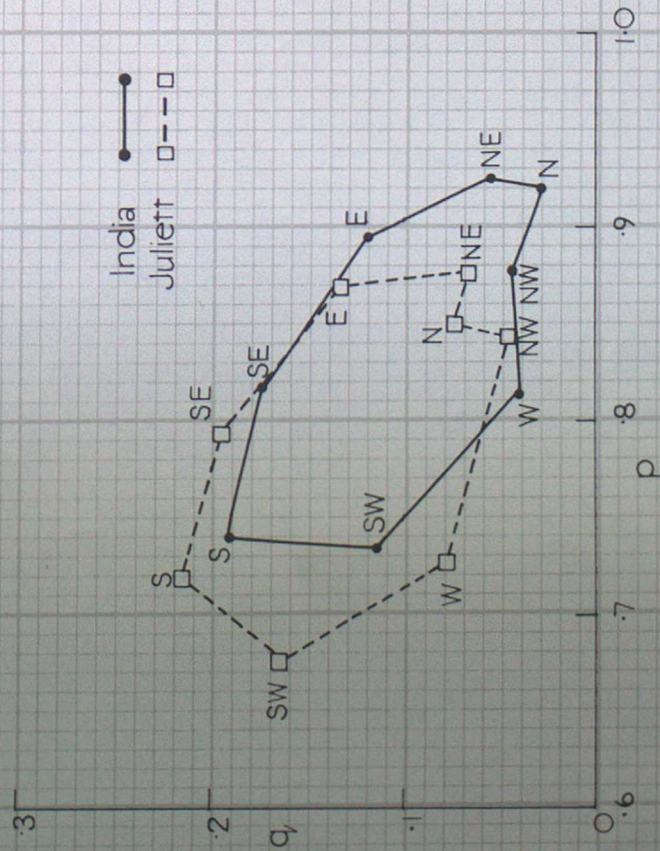


Fig 4a,b(repeated) Overall variation of  $p$  and  $q_1$  with 900mb wind direction-Ships India and Juliett

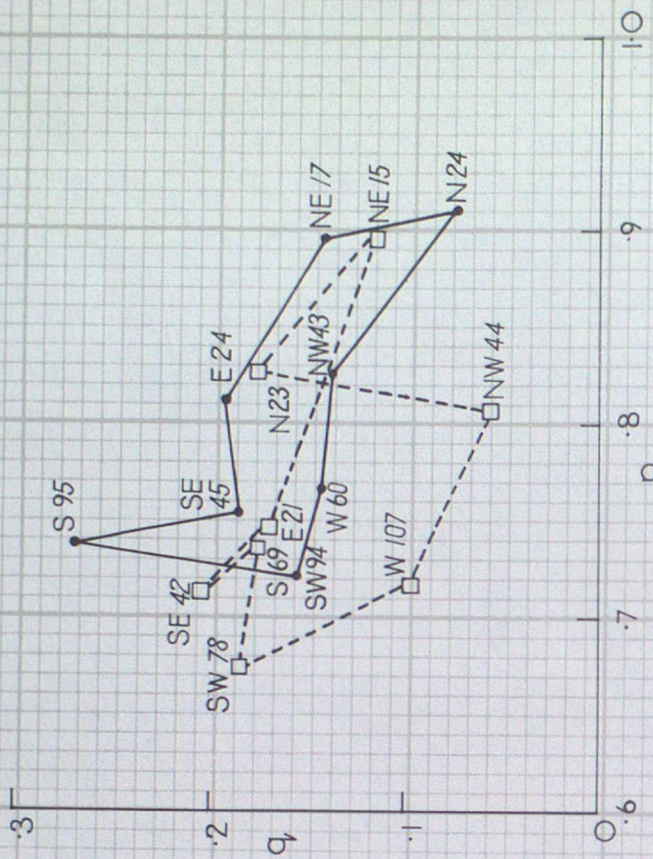


Fig 6b Lapse class 3-speed class 20-29

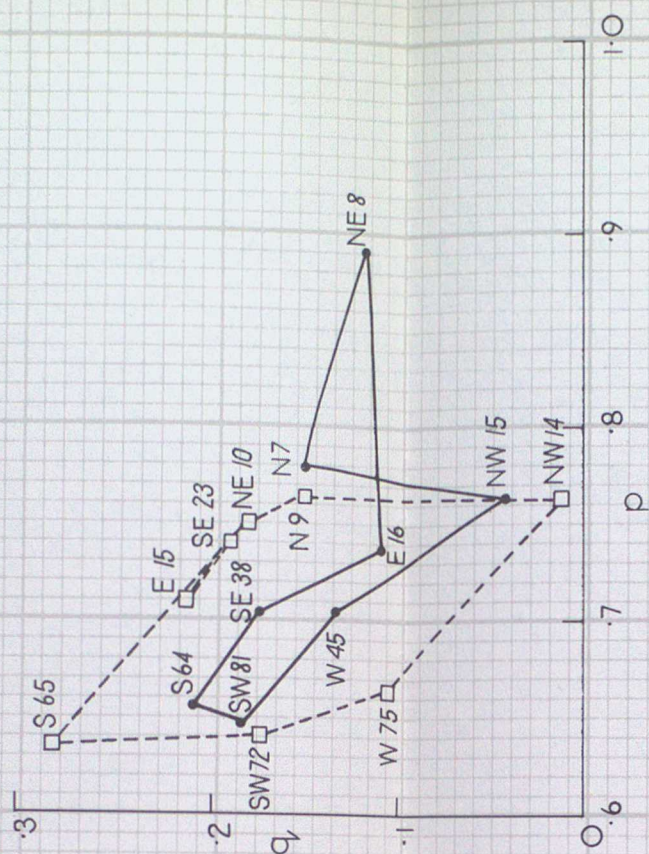


Fig 6d Lapse class 3-speed class 30-39

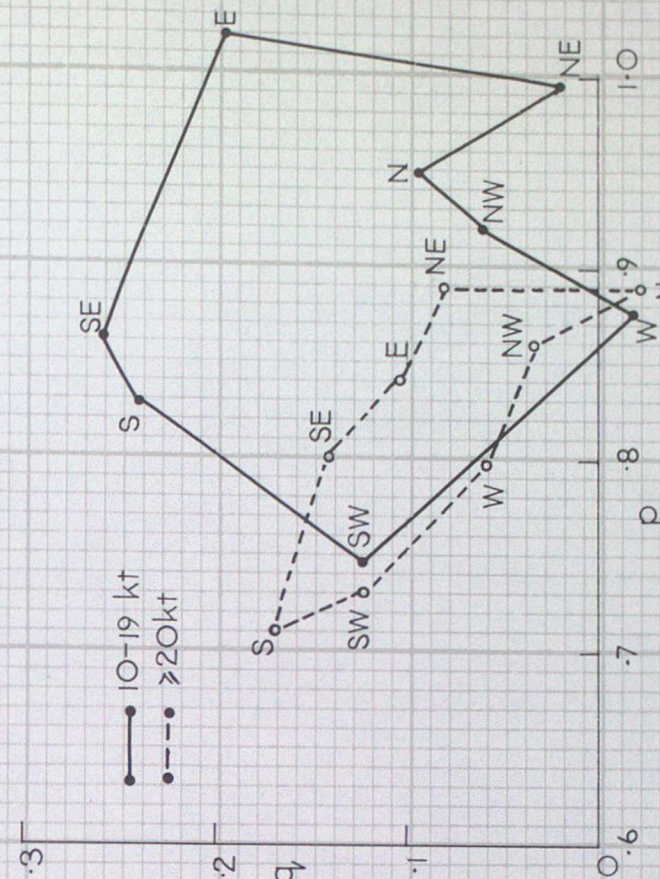
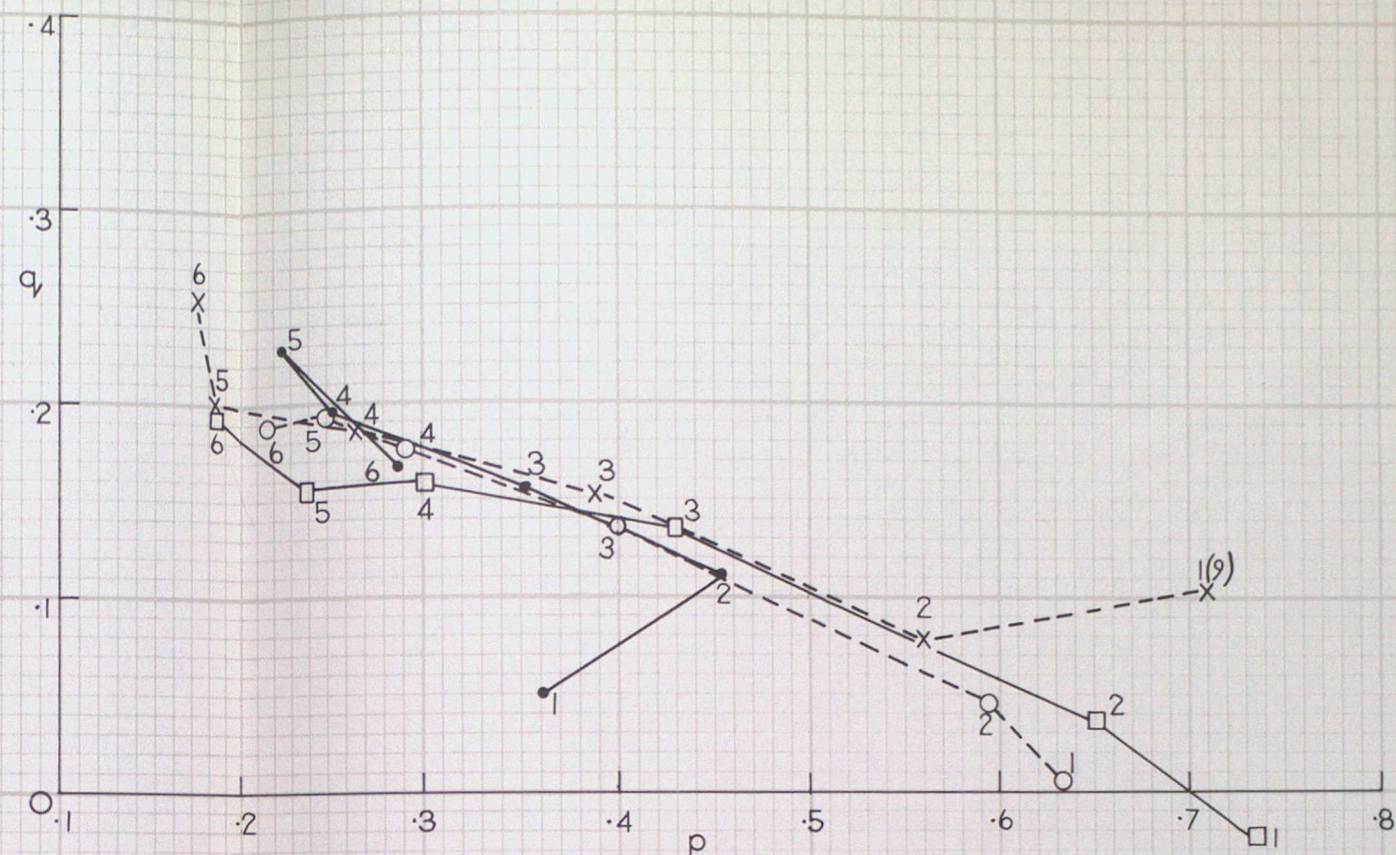
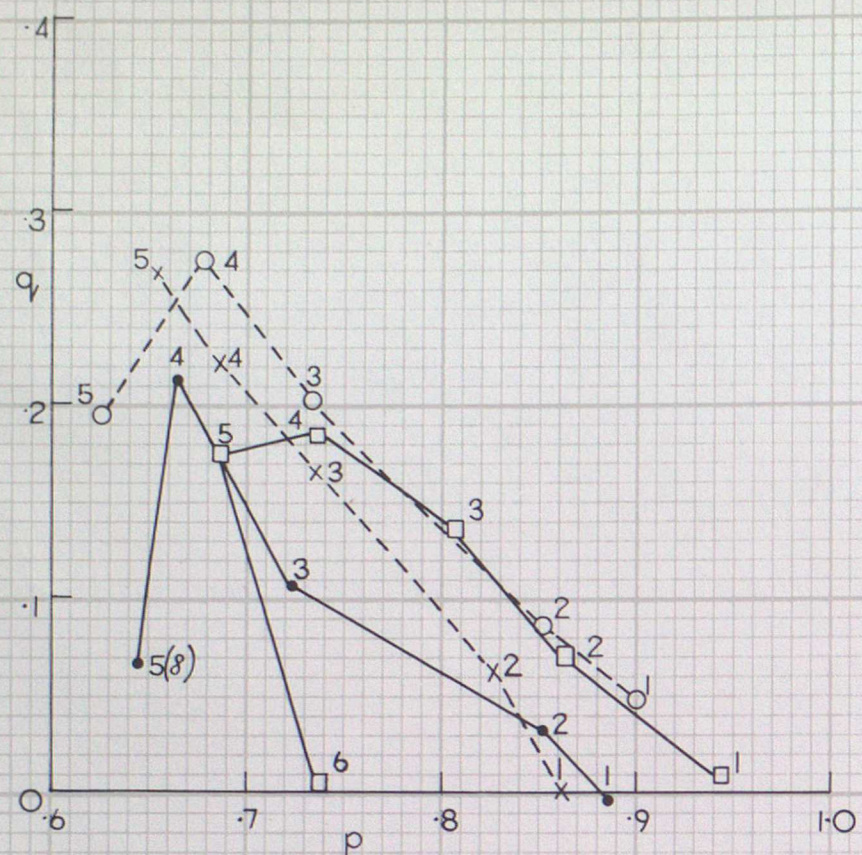


Fig 7 VARIATION OF  $p$  AND  $q_1$  WITH 900MB WIND DIRECTION, 900MB WIND SPEED CLASSES 10-19KT AND ≥20KT. SEPARATELY SHIP INDIA



FIG 8 SEASONAL VARIATION OF  $p$  AND  $q$



●—● Winter  
 ○---○ Spring  
 □—□ Summer  
 x---x Autumn  
 No. of observations  
 in italics

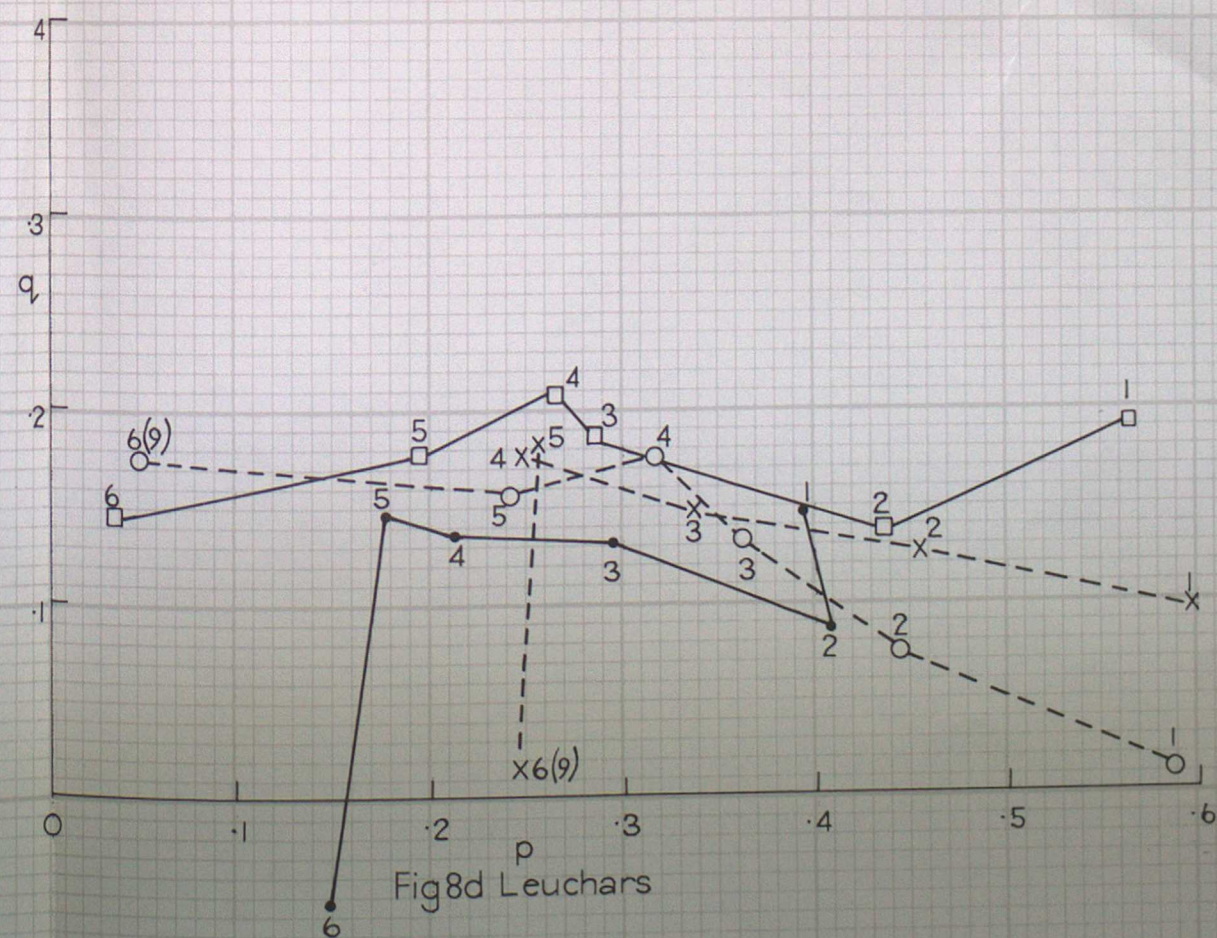
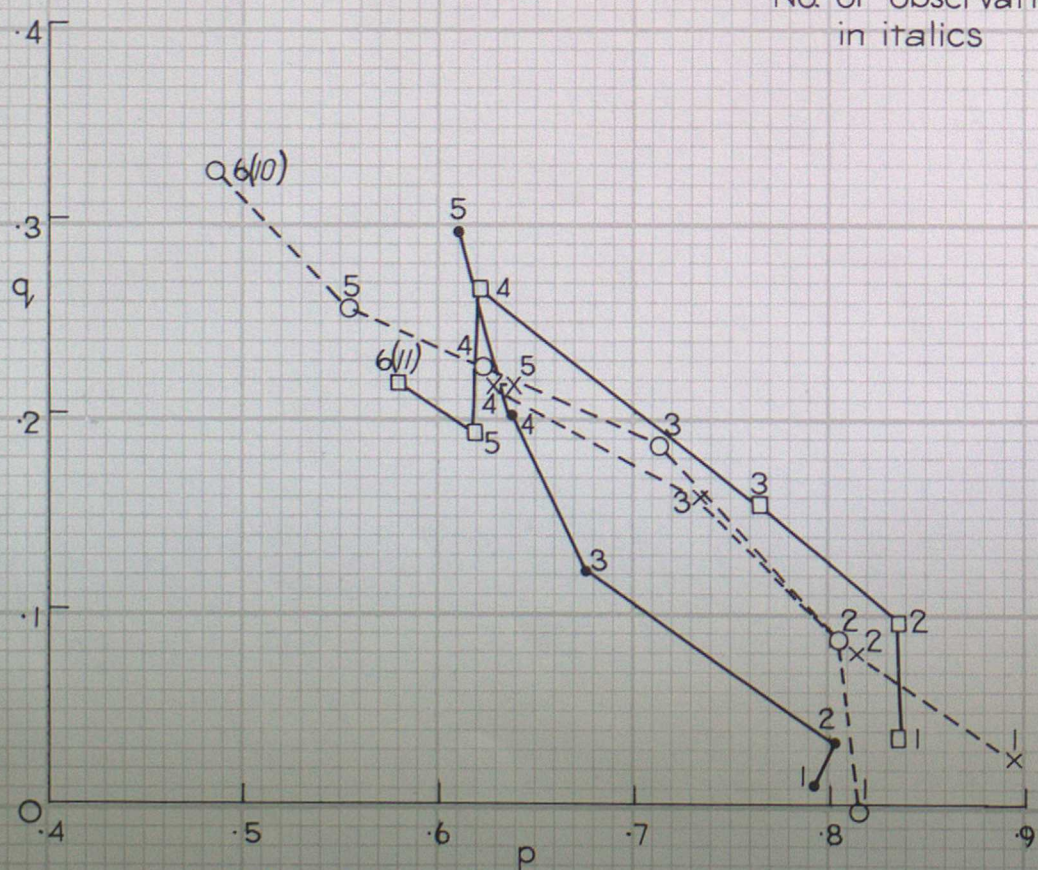




FIG 9 COMPARISON OF SEASON MEANS, DAY AND NIGHT SEPARATELY, WITH VALUES DERIVED FROM LAPSE RATE FREQUENCIES - LEUCHARS

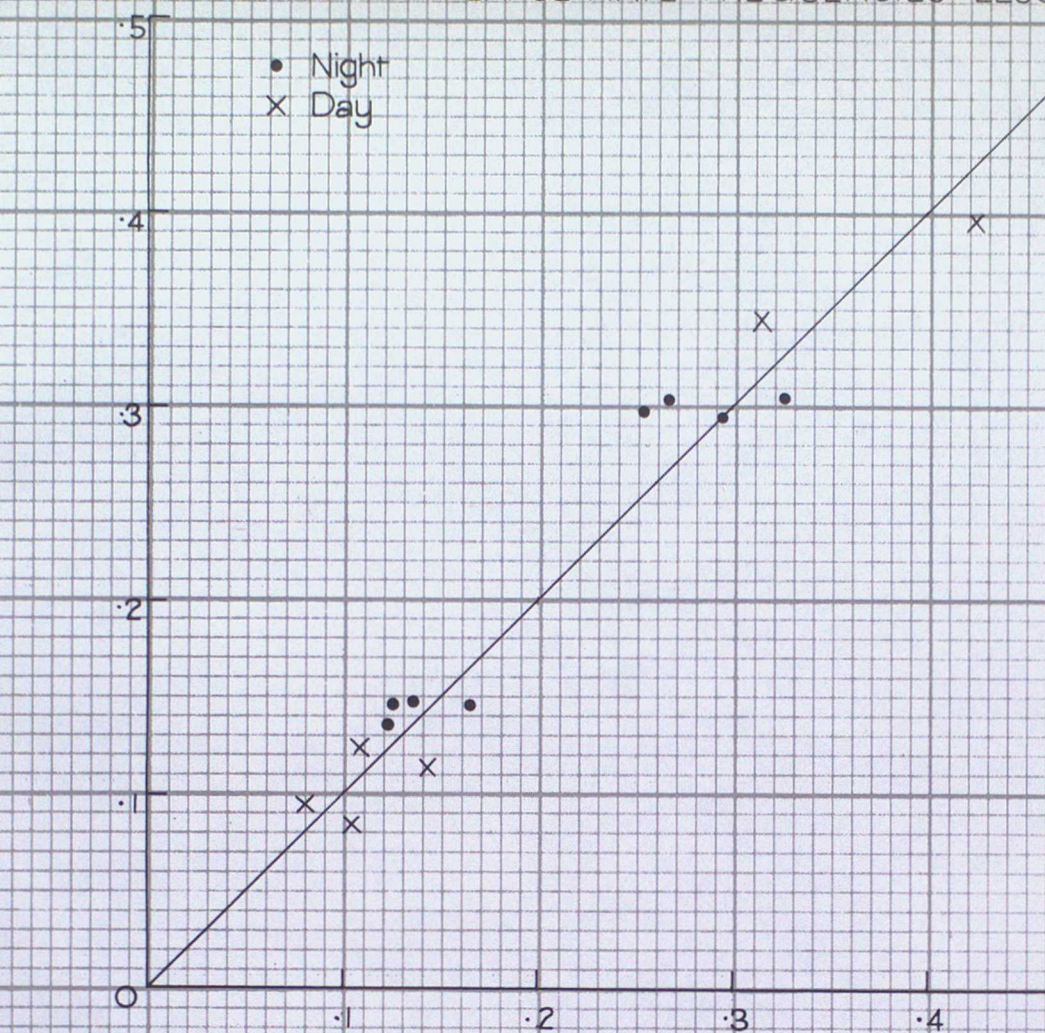


FIG 10 DIURNAL VARIATION OF  $p$  AND  $q$  BY LAPSE CLASS AT HEATHROW AND LEUCHARS

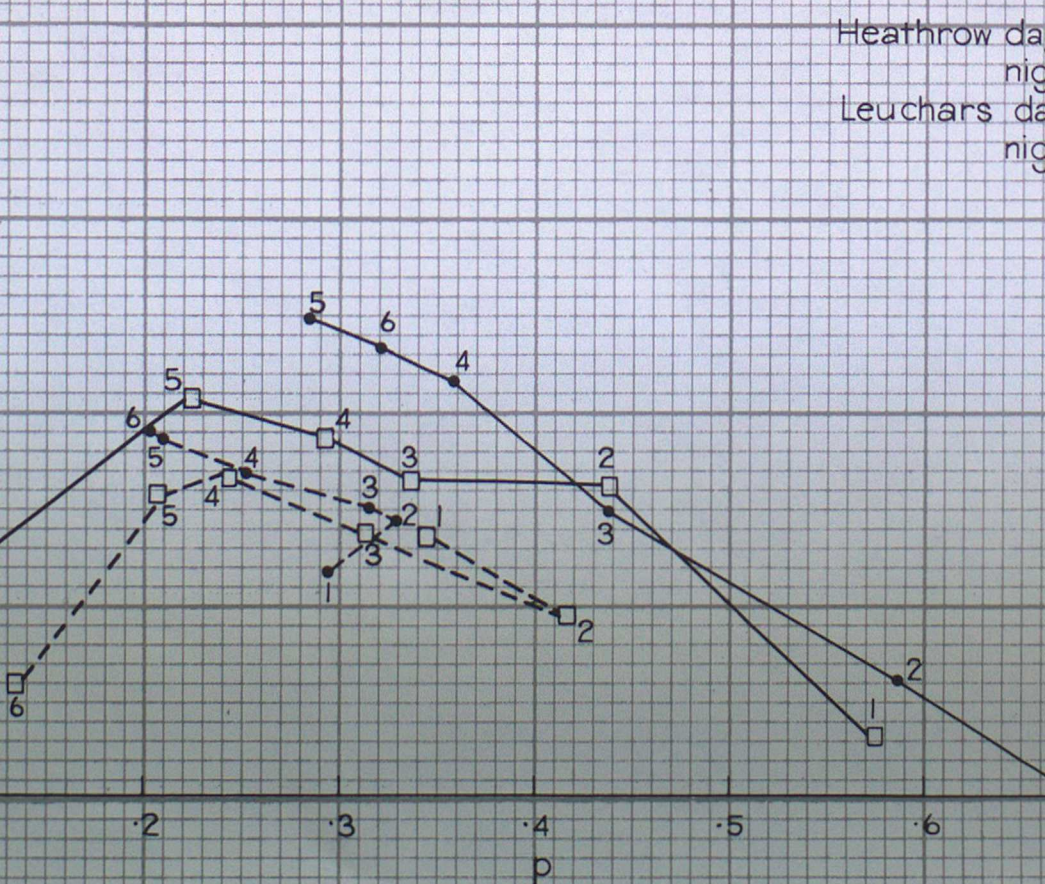




FIG 9 COMPARISON OF SEASON MEANS, DAY AND NIGHT SEPARATELY  
WITH VALUES DERIVED FROM LAPSE RATE FREQUENCIES-LEUCHARS

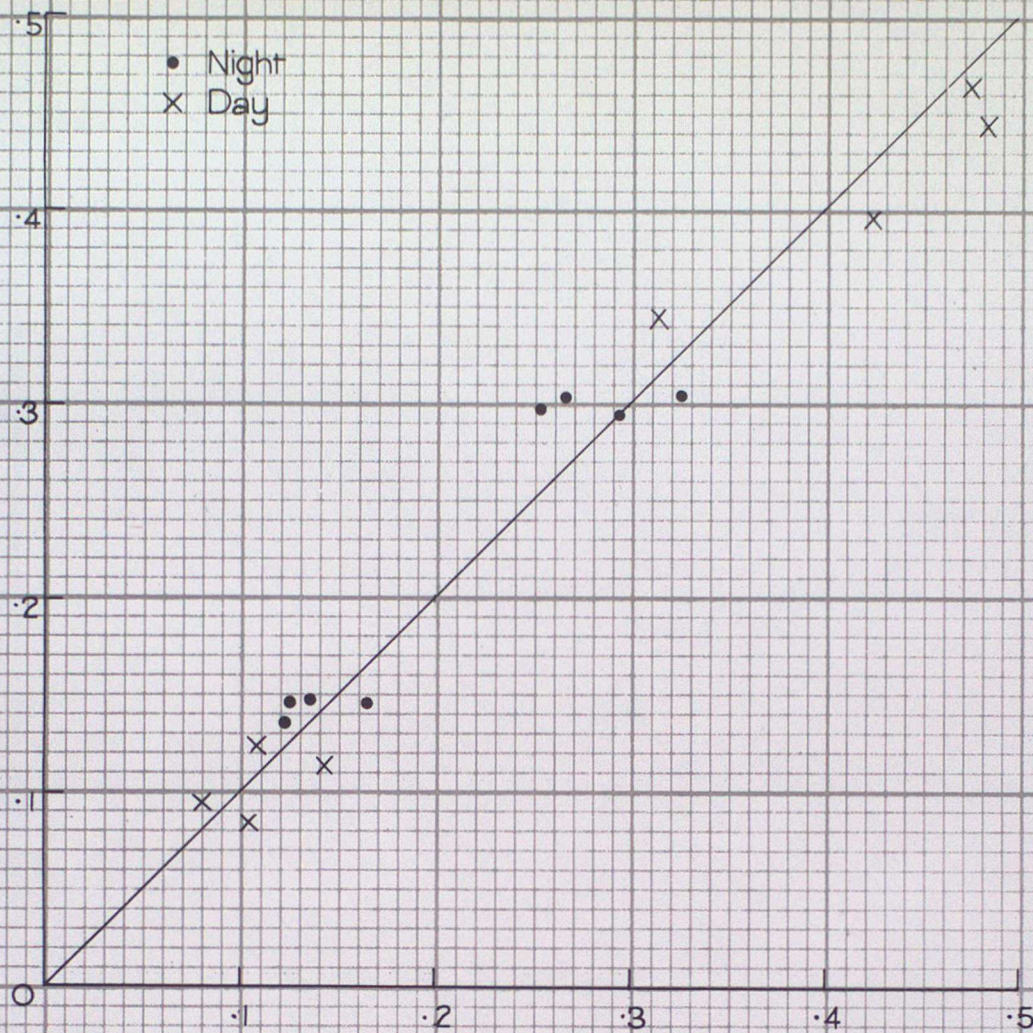


FIG 10 DIURNAL VARIATION OF  $p$  AND  $q$  BY LAPSE CLASS  
HEATHROW AND LEUCHARS

