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ON THE OBJECTIVE DETERMINATION OF MINIMUM DENSITY AND FREQUENCY OF UPPER AIR OBSERVATIONS TO MEET STATED REQUIREMENTS

BY
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Abstract: It is shown how a knowledge of the average, maximum, etc. variablility of a meteorological magnitude as a function of distance d and time τ permits the determination of the maximum distance d from a station and interval τ from the time of observation for which a particular value of the magnitude can be accepted with a certain probability as representative within a predetermined accuracy. If a network of stations can be used the distance between stations can be greater than 2d and the interval between observations longer than τ without loss of accuracy. It is also shown how the appropriate values may be determined. Values of the variability in space and time of the height of the 500, 300 and 100 mb levels and of the temperature and vector wind at the same isobaric levels in the neighbourhood of Valentia Observatory, are given.

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1. Purpose and limitations of this study

1. In the following paragraphs the aim is to find an objective method for the determination of the maximum distance between stations and the maximum time interval between observations which permit the value of a meteorological magnitude at any point and time to be estimated within a predetermined range of accuracy ξ.

2. If the time for which the estimated value is required is later than T and earlier than $T + \tau$, where T is the last synoptic hour and τ the interval between two synoptic hours, the estimated value will be taken as a forecast value. Consideration of accuracy of forecast values is beyond the purpose of this paper as the average accuracy of forecasts appears to depend, not only on the skill of the forecaster, but, even when objective methods of forecasting are used, on the density and frequency of observations of the network on which the forecast is based.

However it appears logical to assume that the forecast fields of the meteorological magnitudes are not of greater accuracy than the actual fields of these magnitudes on which the forecasts are based. In the best case, and if the methods of forecasting were perfect, the accuracy of the forecast and actual charts would be the same and therefore the values of d and τ found for actual meteorological situations would be valid also for the necessary density (in time and space) of the network of observations required for forecasting purposes.

3. In Sections II and III of this paper the instrumental errors of the observations will be ignored, i.e. the actual values of the observations will be considered as the correct values of the meteorological magnitudes. But it will be shown in Section IV that the solution found under this simplifying assumption may be used to solve the general problem taking into account the error of the observations.

II. Variability of meteorological magnitudes

1. If $A = A(X,Y,Z,T)$ represents the value of the meteorological magnitude A at time T and altidude Z at the station S, with coordinates X and Y the expressions

$$\Delta(x) = A(X + x, Y,Z,T) - A(X,Y,Z,T)$$

$$\Delta(y) = A(X,Y + y, Z,T) - A(X,Y,Z,T)$$

$$\Delta(z) = A(X,Y,Z + z, T) - A(X,Y,Z,T)$$

and

$$\Delta(t) = A(X,Y,Z,T + t) - A(X,Y,Z,T)$$

give the variations of the magnitude for an increment, x, y, z or t, of one of the independent variables, the others remaining constant. Of the three spatial coordinates, Z is taken in the vertical direction and X and Y eastwards and northwards respectively; X and Y may be either longitude and latitude or cartesian coordinates in a plane tangential to the earth, or along the intersections of two vertical planes with isobaric surfaces. At relatively short distances from the origin the difference is of no significance for the purpose of this study.

2. Although meteorological stations are situated on the earth's surface, observations are taken at different altitudes and in order to have a three dimensional representation of meteorological situations within a certain degree of accuracy ε_z, the maximum value d_z of z should also

have to be considered.

Due to practical difficulties the synoptic representation of meteorological data is generally carried out on a series of charts drawn for horizontal or quasi-horizontal surfaces at different altitudes. The selection of these altitudes has so far been made mainly on the basis of the operational requirements of civil aviation without considering the theoretical advantages of drawing charts for certain levels of physical significance, i.e. those levels such as the isopycnic level, the levels of zero horizontal divergence, of horizontal flow, etc. where oneor other of the meteorological variables is on the average zero or its variation attains a minimum value.

In the following paragraphs it will be understood that the argument applies to any value of Z; in the practical application of the method three pressure levels, 500, 300 and 100 mb., have been selected.

3. The values of $\Delta(x)$, $\Delta(y)$ and $\Delta(t)$ can be studied statistically and curves drawn for the mean variability, $\bar{\Delta}$, maximum variability Δ_M, etc. as functions of x, y and t. Therefore, $\Delta_M(x)$, for instance, is a value of the variability of the meteorological magnitude A which, so far as is known, has a 100% probability of not being surpassed at the distance x in an eastwards direction from a certain station; while if the distribution of the Δ is Gaussian, there is approximately a 42.5% probability of any individual value of Δ being greater than $\bar{\Delta}$. Curves for other probability levels can also be drawn.

On general considerations it is deduced that the curves representing $\bar{\Delta}$ and Δ_M, etc. as funcions of x, y or t for not too great values of these variables have normally the schematic form of Figure 1. Once these curves for station S and meteorological magnitude A are available they can be used to determine the maximum

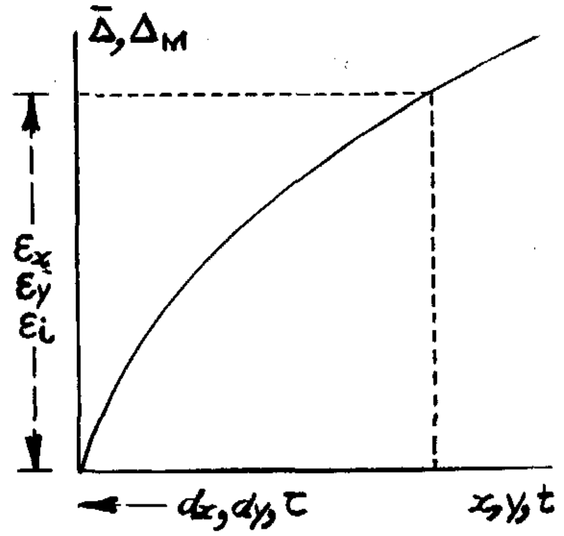

Fig. 1.

distance d_x eastwards, d_y northwards, and the maximum time interval τ, for which the particular value of the meteorological magnitude A at station S can be accepted with a certain probability as representative within a predetermined accuracy. For instance, the value of x for which $\varepsilon_x = \bar{\Delta}(x)$ gives d_x. Accordingly the observed value of A at S and time T can be substituted for the value of A at distances up to d_x from S along the x-axis with an average absolute error $\leq \varepsilon_x$; at least in 57.5% of the cases in which the substitution is made the absolute error will be less than ε_x. It should be noted that d_x and d_y so determined are not necessarily equal for equal values of the predetermined accuracies ε_x and ε_y.

The curves of Fig. 1 can be drawn approximately by utilising observed values at the existing stations and therefore the reliability of the values of d_x, d_y and τ so determined will vary from region to region. But there can be little doubt that in some regions at least the curves could be drawn with a high degree of accuracy.

4. The values of d_x, d_y and τ determined as indicated in the previous paragraph apply when one observation of a single station is available. It will be shown in the following section that if a network of stations exists, the distances between these can be greater than $2d_x$ and $2d_y$ and observations can be taken at intervals greater than τ without loss of accuracy.

III. Use of the $\bar{\Delta}$ curves for determining the density and frequency of observations of a network of stations

1. Let us consider a rectangular lattice of j rows with i meteorological stations in each row (Fig. 2). The distance between stations in each row is d_x and the distance between rows d_y. The value of a meteorological magnitude at the point x, y, at time T + t ($t < \tau$) for not too large values of x, y and t is (Fig. 2):

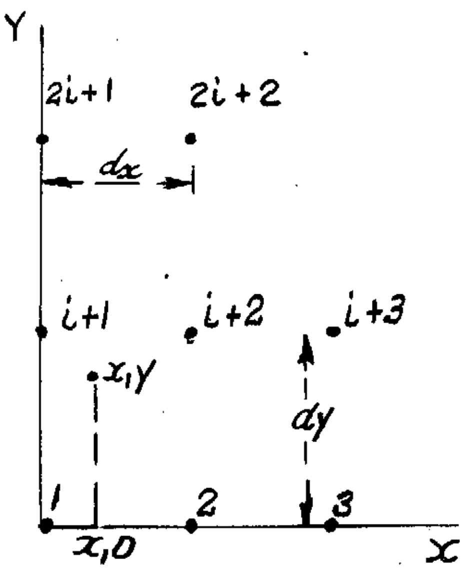

Fig. 2.

$$A(x,y,T+t) = A(o,o,T) + \frac{\partial A}{\partial x}x + \frac{\partial A}{\partial y}y + \frac{\partial A}{\partial t}t$$
$$= A(o,o,T) + \Delta(x) + \Delta(y) + \Delta(t)$$

If the value $A(o,o,T)$ of the meteorological magnitude at Station 1 is taken for the value $A(x,y,T+t)$ the error

$$\Delta(x,y,t) = A(x,y,T+t) - A(o,o,T) = \Delta(x) + \Delta(y) + \Delta(t)$$

is made. Assuming that the values of $\Delta(x)$, $\Delta(y)$ and $\Delta(t)$ are independent random variables which follow Gauss's law, the same relationship exists between the average errors as between the standard deviations and therefore

$$\bar{\Delta}^2(x,y,t) = \bar{\Delta}^2(x) + \bar{\Delta}^2(y) + \bar{\Delta}^2(t)$$

2. Using $A(o,o,T)$ as an estimate of $A(x,o,T)$ the average error committed is $\bar{\Delta}(x)$. Similarly, we could take for the value of the meteorological magnitude A at the point x,o and time T the observed value $A(d_x,o,T)$ at the same time at station 2. The average error of this estimated value would be $\bar{\Delta}(x')$ where $x' = x - d_x$. But the function $\bar{\Delta}(x')$ for station 2 is zero for $x' = o$ and for $x' = -d_x$ is equal to the value of $\bar{\Delta}(x)$ for station 1 when $x = d_x$. For continuity reasons it can be taken in general

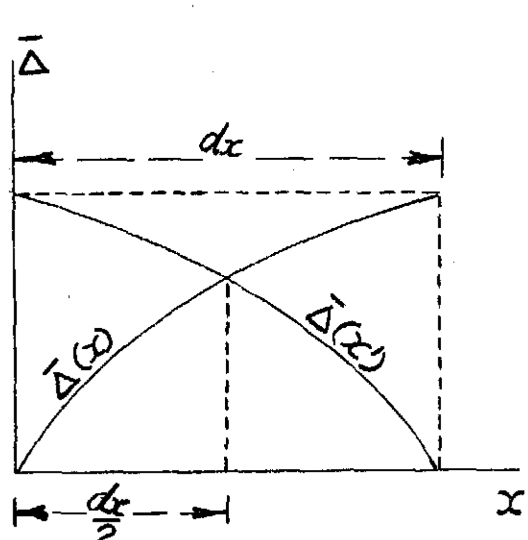

Fig. 3.

that the curves $\bar{\Delta}$ for stations 1 and 2, if they are not too far apart, are symmetrical with relation to the line (Fig. 3) parallel to the ordinate axis at the abscissa $d_x/2$. On this basis

$\bar{\Delta}(x) < \bar{\Delta}(x')$ for $x < \frac{d_x}{2}$ and

$\bar{\Delta}(x) > \bar{\Delta}(x')$ for $x > \frac{d_x}{2}$

i.e. the more accurate estimated value of $A(x,o,T)$ is obtained by using the observed value at the nearer station.

Therefore the value of x for which $\bar{\Delta}(x) = \varepsilon_x$ gives half the distance between stations which will permit the value of A at any point of the axis of abscissae to be known with an accuracy ε_x or greater.

3. In practice, however, particular values of $A(x)$ are obtained by interpolation between simultaneously observed values at stations 1 and 2, and this practice permits the attainment of the same accuracy with stations spaced at greater distances than that obtained in the preceding paragraph.

In effect, it has been shown that in general the average errors of the values estimated for $X = \frac{d_x}{2}$ by means of simultaneous observations at stations 1 and 2 are equal. Therefore if the values A(o,o,T), A(d_x,o,T) and A(x,o,T) were independent of each other the average error of the mean of these two estimated values would be $\bar{\Delta}\left(\frac{d_x}{2}\right)/\sqrt{2}$

The method of interpolation which on the basis of general considerations, confirmed by experience, is generally reasonable for not too large distances, amounts to assuming a linear variation of the meteorological magnitude between the stations. Therefore as A(x,o,T) is not independent of A(o,o,T) and of A(d_x,o,T) the average error of the interpolated value of A for the point $\frac{d_x}{2}$ is smaller than $\bar{\Delta}\left(\frac{d_x}{2}\right)/\sqrt{2}$ and it appears reasonable to infer that the average error of the interpolated value is everywhere smaller than $\bar{\Delta}\left(\frac{d_x}{2}\right)/\sqrt{2}$.

Accordingly if on the basis of the experimental curves of $\bar{\Delta}(x)$ the curves of $\bar{\Delta}(x)/\sqrt{2}$ are drawn, they can be used to find a distance d_x such that a linear network of stations situated along the X axis at that distance would permit by simple interpolation of estimating the value of the meteorological magnitude A with average error not greater than any predetermined value ε_x. In effect, the point where the line $\bar{\Delta}(x) = \varepsilon_x$ intersects the curve $\bar{\Delta}(x)/\sqrt{2}$ (Fig. 4) gives the value $\frac{d_x}{2}$ which satisfies this condition. Alternatively the intersection of the line $\bar{\Delta}(x) = \sqrt{2}\,\varepsilon_x$ with the curve $\bar{\Delta}$ (x) could be used to obtain $\frac{d_x}{2}$.

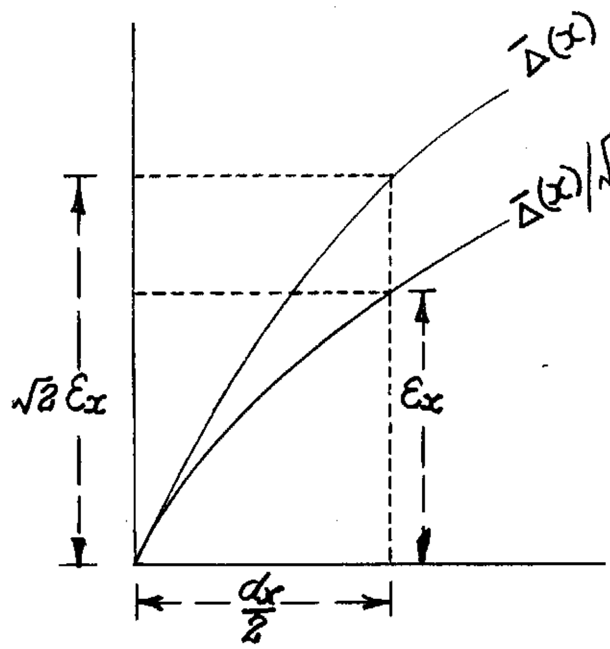

Fig. 4.

4. Similarly a value can be found for d_y, the minimum distance between rows of stations which would permit of estimating the value of a meteorological magnitude with average error not greater than any

predetermined value ε_y in the direction of the meridians.

5. In the case of variation with time the conditions are different. With the spatial variables recourse has been had to interpolation, as in a network of stations covering the earth any point for which a value of the magnitude A has to be estimated is comprised between two stations in the direction of each coordinate axis. When dealing with time - and excluding the trivial case of having to estimate the value of the magnitude at a time previous to the last synoptic hour - only one estimation of the magnitude can be made from the observed value at T, i.e. the estimated value is in all cases an extrapolated value, as the synoptic observation at time T $+\tau$, the next synoptic hour, will not yet have been made. Therefore the curve $\bar{\Delta}$ (t) and the predetermined value of ε_t should be used for obtaining τ.

6. However in any particular occasion the average expected error of the estimated value for T + t as given by the appropriate curve $\bar{\Delta}(t)$ can in general be reduced, since the spatial distribution of the meteorological magnitude at time T is known and its displacement forecast within certain accuracy. In effect the local variation $\frac{\partial A}{\partial t}t$ during the time t of the magnitude A is the sum of two terms: one term is the variation of A due to the transport of the field of A, i.e., t.c. ∇A where c is the velocity of the field and ∇A its gradient; and the other term is $\frac{\delta A}{\delta t}t$, the development of the field of A during the time t due to the evolution of the meteorological situation. Therefore if in any particular occasion appropriate values of c and ∇A are known, the average error $\bar{\Delta}$ (t) expected when data from a single station are available may be substituted by the closer approximation $\frac{\delta A}{\delta t}t$ given by $\frac{\delta A}{\delta t}t = \bar{\Delta}(t) - t.c.\nabla A$. The values of $\frac{\partial A}{\partial t}t$, t.c. ∇A and $\frac{\delta A}{\delta t}t$ are in general independent so that betweeen their average values the following relationship exists:

$$\overline{\frac{\partial A}{\partial t}t} = \bar{\Delta}(t) = \sqrt{\overline{\frac{\delta A}{\delta t}}^2 t + \overline{t.c.\nabla A}^2}$$

The curve $\overline{\frac{\delta A}{\delta t}t}$ drawn with values computed by means of this expression may be substituted for the curve $\bar{\Delta}$ (t) when computing the maximum interval between observations compatible with a predetermined accuracy ε_t.

7. The total average absolute error $\bar{E}$ (or predetermined accuracy ε) of the estimated value of the magnitude A at the point x,y and time T + t is made up

of the partial errors $\bar{E}_x$, $\bar{E}_y$ and $\bar{E}_t$ (or partial accuracies $\varepsilon_x, \varepsilon_y, \varepsilon_t$). Assuming that these partial errors are mutuallly independent

$$\bar{E} = \sqrt{\bar{E}_x^2 + \bar{E}_y^2 + \bar{E}_t^2} = \sqrt{\bar{E}_{xy}^2 + \bar{E}_t^2}$$

where $\bar{E}_{xy} = \sqrt{\bar{E}_x^2 + \bar{E}_y^2}$ is the total spatial average error. The question arises as to how the total error $\bar{E}$ should be divided between the errors due to the spatial distribution of stations and to the frequency of observations.

It may be considered convenient to take the spatial and time errors as equal and to further divide the spatial error equally between the errors due to the spacing of stations along the meridians and parallels. Then substituting the predetermining accuracies for the corresponding average errors

$$\varepsilon_{xy} = \varepsilon_t = \frac{\varepsilon}{\sqrt{2}} \text{ and } \varepsilon_x = \varepsilon_y = \frac{\varepsilon_{xy}}{\sqrt{2}} = \frac{\varepsilon}{2}$$

Another simple distribution of the total error between the three variables x, y and t consists of taking the three as equal. In this case

$$\varepsilon_x = \varepsilon_y = \varepsilon_t = \frac{\varepsilon}{\sqrt{3}}$$

For each of these divisions of the total error or any other which may be favoured d_x, d_y and τ can be determined.

IV. Effect of Instrumental Errors.

The observed variability Δ of a meteorological magnitude is made up of the true variability δ of the actual value of the magnitude and the random instrumental error e. Assuming that δ and e are independent of each other

$$\bar{\delta} = \sqrt{\bar{\Delta}^2 - \bar{e}^2}$$

As it has been supposed that the observations were correct, i.e., e = o, the values of d_x, d_y and τ computed from the $\bar{\Delta}$ curves are smaller than they need to be if the predetermined accuracy were that of the true value of the meteorological magnitude considered. If e were not zero, curves $\bar{\delta}$ could be drawn which for the same predetermined accuracy would give values of d_x, d_y and τ greater than those found assuming that there are no instrumental errors.

V. Examples of $\bar{\Delta}$ curves.

1. The current practice of publishing upper air data at pressure levels made it easier to compute the average variation of the height of and temperature and wind at isobaric surfaces than the average variation of pressure, temperature and wind at level surfaces. Three isobaric surfaces, those for the standard pressures 500, 300 and 100 mb. have been selected in the present case.

For the computation of the average variation in space upper air data for the year 1952 from the stations included in Table I and Fig. 5 have been considered. Except for Valentia the data are those published in "The Daily Aerological Record" of the Meteorological Office, London. The data for Valentia have been taken from the "Monthly Weather Report" published by the Irish Meteorological Service. For the computation of the average variation in time data for Aldergrove as published in "The Daily Aerological Record" for 1950 have been used. When errors in the published data have been detected the corresponding ascents have been ignored, unless it has been possible to deduce the correct value from available information.

The individual wind speed variation has been obtained by plotting on a polar diagram the corresponding wind velocities and measuring the scalar value of the vector difference.

2. As shown in Fig. 5, the stations considered are not situated exactly at the same latitude and therefore the average variation along the Valentia parallel is substituted by the average variation along the line AB (Fig. 5). For the drawing of the corresponding $\bar{\Delta}$ curves the actual position of the stations is substituted by their projections on line AB. Similarly the average variation along the meridian is substituted by the average variation along the line AC. The angles between the Valentia meridian and lines AB and AC, counted in clockwise direction, are 72^{0} and 17^{0} respectively. The average variations so determined can however be taken as reasonable approximations to the average variation in an Eastwards and Northwards direction respectively from Valentia.

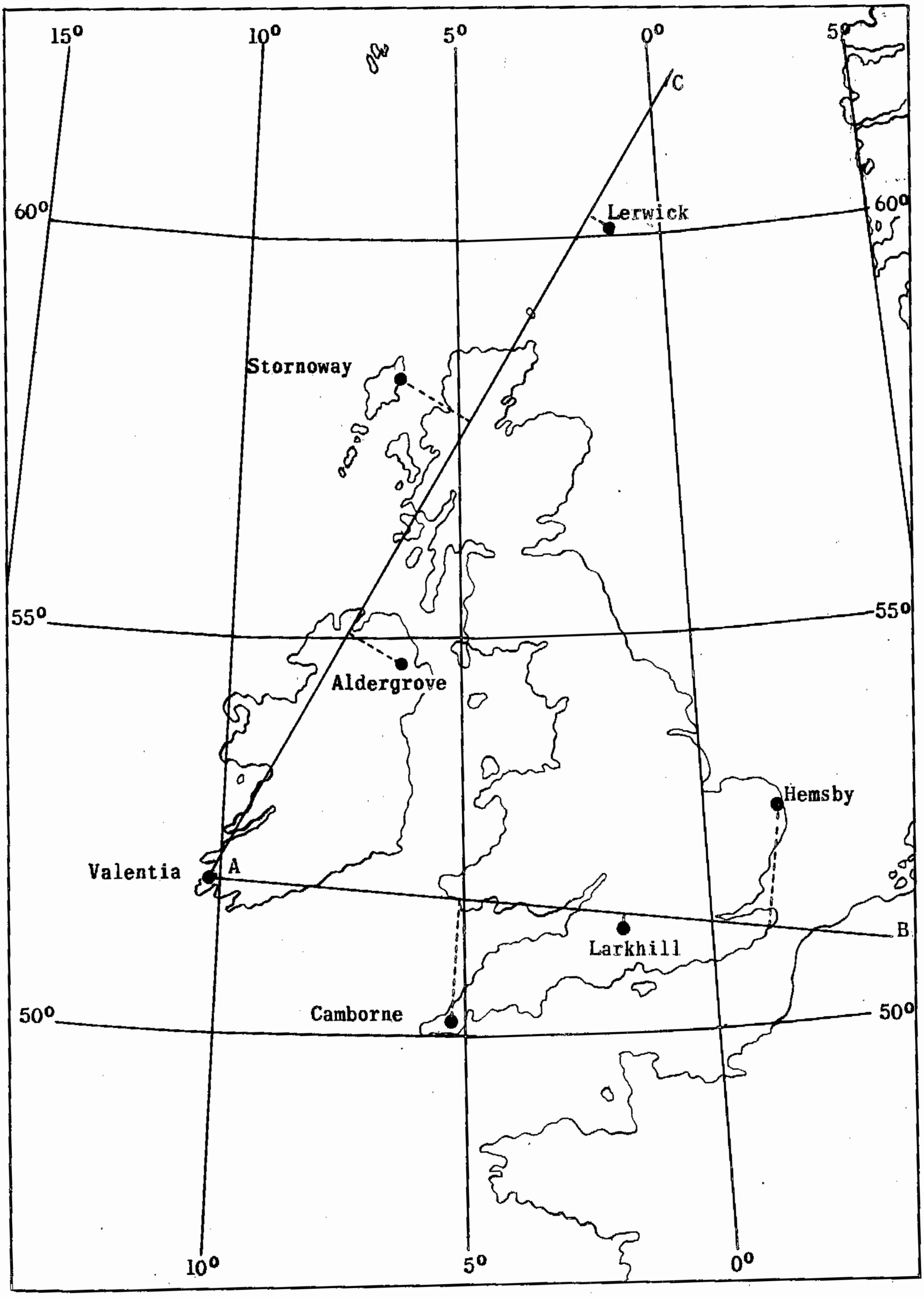

FIG. 5. POSITION OF UPPER AIR STATIONS.

3. Table 2 gives the average variations in space of the height of the 500, 300 and 100 mb. and Tables 3 and 4 the average variations in space of the temperature and vector wind at the same isobaric surfaces. Tables 5, 6 and 7 give the corresponding variations in time. In Figures 6 to 11 the annual $\bar{\Delta}$ curves have been plotted.

As data for only one year have been used the seasonal means are not very reliable. The annual averages, however, can be considered as fairly representative of the actual variations except for the time variations at the 100 mb. level, where the effect of a periodicity is apparent. This periodicity is the result of the radiation errors of the temperature element of the radiosonde and of a possible diurnal variation.

VI. Utilisation of $\bar{\Delta}$ curves.

1. Let us assume that for a certain purpose it is necessary to know in the neightbourhood of Shannon Airport the field of temperature at 300 mb. at any time with an average error not greater than $\bar{E} = \varepsilon = 4^{o}F$. It will also be assumed that the part of this error which may be due to the distance between the radiosonde stations is equal to that part of the error which may be due to the time interval since the last observation; that the stations are equally spaced along the meridians and parallels and that the observations are free of instrumental errors. On this basis the maximum permissible errors are:

along the parallels and meridians: $2^{o}F$;

in time : $\frac{4^{o}F}{\sqrt{2}} = 2.8^{o}F$ approximately.

Figures 7a and 7b give $\frac{d_y}{2} = 110$ and $\frac{d_x}{2} = 90$ nautical miles for the $2^{o}F$ ordinates and figure 10 for an ordinate of $2.8^{o}F$ gives $\tau = 3$ hours, approximately.

Therefore stations forming a rectangular lattice at 220 nautical miles distance in the direction of the meridians and at 180 nautical miles in the direction of the parallels and making observations every three hours would satisfy the requirements.

2. The $\bar{\Delta}$ curves can also be used to compute the average accuracy with which the value of a meteorological magnitude can be estimated with the present density of observations.

For instance, at the 500 mb. level the average scalar value at a ~~synoptic hour~~ of the vector difference between the actual wind velocity and the wind estimated from the corresponding synoptic chart is 11 knots. In effect, from figure 8a for the mid point between Valentia and Aldergrove, $\bar{\Delta}_y$ = 11.5 knots and from figure 8b for the mid point between Valentia and Camborne, $\bar{\Delta}_x$ = 11 knots; therefore the total average spatial error ε_{xy} is:

$$\varepsilon_{xy} = \sqrt{\left(\frac{11.5}{\sqrt{2}}\right)^2 + \left(\frac{11}{\sqrt{2}}\right)^2} = 11 \text{ knots approximately.}$$

If it is required to know the average vector difference at any moment it is necessary to take also into account the error due to time. With wind ascents every 12 hours and a 3 hours delay in transmission of the data, the estimated wind value may be based on observations up to 15 hours old. Figure 11 gives for t = 15 hours, $\bar{\Delta}_t$ = 25 knots and therefore

$$\varepsilon = \sqrt{\left(\frac{11.5}{\sqrt{2}}\right)^2 + \left(\frac{11}{\sqrt{2}}\right)^2 + 25^2} = 27 \text{ knots approximately.}$$

There are no data available for the computation of the product $t.c.\nabla A$, (see III, 6) but it may be said that consideration of the prevailing situation at the last synoptic hour may improve the accuracy to, say, 20 knots.

VII. Acknowledgments.

Most of the computations have been carried out by Messrs. G. McAuliffe, F.L. Donaldson, J.F. Murphy and Miss B. Dillon. Messrs. P.M.A. Bourke and W.A. Morgan have helped in the preparation of the text. To all I wish to express my appreciation.

Table I.

Geographical coordinates of stations for which data have been used

Name	Index Number	Latitude	Longitude
Valentia	03953	51° 56' N	10° 15' W
Camborne	03808	50 13 N	05 19 W
Larkhill	03743	51 12 N	01 48 W
Hemsby	03496	52 41 N	01 41 E
Aldergrove	03917	54 39 N	06 13 W
Stornoway	03026	58 13 N	06 19 W
Lerwick	03005	60 08 N	01 11 W

TABLE II.

Average Variation of Height of the 500, 300 and 100 mb. Levels between Valentia and Specified Stations

		500 mb.						300 mb.						100 mb.					
		Camborne	Larkhill	Hemsby	Aldergrove	Stornoway	Lerwick	Camborne	Larkhill	Hemsby	Aldergrove	Stornoway	Lerwick	Camborne	Larkhill	Hemsby	Aldergrove	Stornoway	Lerwick
Winter (Dec-Feb)	Feet	171	275	386	271	449	612	247	412	568	387	646	964	248	353	516	422	660	966
	No. of cases	178	180	180	176	177	180	166	167	174	162	165	169	98	99	87	82	89	96
Spring (Mar-May)	Feet	170	227	293	162	292	395	254	321	390	239	410	550	206	189	231	181	254	252
	No. of cases	184	183	184	180	180	184	174	172	175	167	169	174	94	106	103	90	99	96
Summer (Jun-Aug)	Feet	121	172	255	207	416	561	193	279	395	302	584	744	201	233	216	237	293	300
	No. of cases	181	181	184	179	182	184	173	173	174	165	170	173	106	96	88	99	83	98
Autumn (Sept-Nov)	Feet	186	303	418	245	417	584	291	456	643	384	587	823	246	376	486	339	434	625
	No. of cases	181	182	182	182	175	180	170	170	167	170	162	169	101	90	99	87	86	98
Year	Feet	162	244	337	221	393	538	246	366	497	328	556	744	225	285	360	290	407	535
	No. of cases	724	726	730	717	714	728	683	682	690	664	666	685	399	391	377	358	357	388

TABLE III.

Average Variation of Temperature between Valentia and specified stations at the 500, 300 and 100 mb. levels

		500 mb.						300 mb.						100 mb.					
		Camborne	Larkhill	Hemsby	Aldergrove	Stornoway	Lerwick	Camborne	Larkhill	Hemsby	Aldergrove	Stornoway	Lerwick	Camborne	Larkhill	Hemsby	Aldergrove	Stornoway	Lerwick
Winter (Dec-Feb)	°F	3.9	6.0	7.1	5.0	7.0	10.2	3.8	5.1	5.7	4.7	6.4	7.6	3.9	5.0	5.7	3.9	5.6	5.8
	No. of cases	180	180	182	176	177	180	166	168	174	163	165	168	98	99	87	81	90	96
Spring (Mar-May)	°F	4.3	5.4	6.4	3.8	5.9	7.9	3.5	3.9	5.1	3.6	4.9	5.7	4.0	4.0	5.1	4.2	5.9	6.8
	No. of cases	184	183	184	180	180	184	174	174	175	167	169	174	95	107	104	90	98	96
Summer (Jun-Aug)	°F	3.4	4.3	5.5	4.3	7.2	9.2	3.9	4.6	5.3	4.1	5.4	7.0	3.2	4.7	5.3	5.3	8.4	10.0
	No. of cases	180	181	184	180	180	184	173	173	173	167	170	175	107	98	88	102	84	100
Autumn (Sept-Nov)	°F	4.9	6.4	9.2	5.5	7.7	11.0	4.7	5.9	7.7	5.3	6.1	8.2	4.4	4.7	5.9	5.2	6.2	7.3
	No. of cases	181	182	182	182	175	181	170	170	167	170	162	169	103	96	97	87	86	100
Year	°F	4.1	5.5	7.0	4.6	6.9	9.6	4.0	4.9	5.9	4.4	5.7	7.1	3.9	4.6	5.5	4.7	6.5	7.5
	No. of cases	725	726	732	718	712	729	683	685	689	667	666	686	403	400	376	360	358	392

TABLE IV.

Average Variation of Vector Wind between Valentia and specified stations at the 500, 300 and 100 mb. levels

		500 mb.						300 mb.						100 mb.					
		Camborne	Larkhill	Hemsby	Aldergrove	Stornoway	Lerwick	Camborne	Larkhill	Hemsby	Aldergrove	Stornoway	Lerwick	Camborne	Larkhill	Hemsby	Aldergrove	Stornoway	Lerwick
Winter (Dec-Feb)	Knots	23.3	31.7	37.7	23.5	30.9	40.5	36.1	42.8	54.5	34.1	45.3	54.9	8.9	13.1	15.8	10.9	18.7	21.5
	No. of cases	78	81	83	79	76	64	68	73	71	66	68	54	17	17	17	15	19	10
Spring (Mar-May)	Knots	23.3	28.8	33.5	21.8	32.3	39.4	35.7	43.9	50.5	36.5	50.2	54.3	13.1	11.9	14.7	10.1	15.5	15.2
	No. of cases	81	88	88	52	83	72	78	84	85	45	80	68	35	39	41	17	40	28
Summer (Jun-Aug)	Knots	17.4	22.2	27.6	18.3	28.7	31.3	28.2	34.2	44.9	28.7	48.3	51.7	9.7	12.2	14.1	9.3	6.1	14.3
	No. of cases	84	82	83	75	83	77	78	76	75	65	76	71	34	37	36	30	46	25
Autumn (Sept-Nov)	Knots	20.9	29.5	34.5	22.2	31.5	36.9	33.6	47.0	52.9	33.4	49.8	51.9	19.6	21.0	21.4	19.5	19.0	24.8
	No. of cases	82	83	83	82	80	75	69	69	68	65	65	60	18	19	18	16	26	22
Year	Knots	21.2	28.0	33.3	21.5	30.8	36.8	33.3	41.9	50.6	32.8	48.5	53.2	12.4	13.8	15.8	11.9	13.3	18.2
	No. of cases	325	334	337	288	322	288	293	302	299	241	289	253	104	112	112	78	131	85

TABLE V.

Average Variation of height of the 500, 300 and 100 mb. level at Aldergrove during specified intervals

		500 mb.					300 mb.					100 mb.				
		6h	12h	18h	24h	30h	6h	12h	18h	24h	30h	6h	12h	18h	24h	30h
Winter (Dec-Feb)	Feet	97	163	217	257	286	163	249	324	375	415	264	304	315	308	353
	No. of cases	351	350	350	349	348	322	322	322	320	321	131	130	130	136	129
Spring (Mar-May)	Feet	110	166	207	240	273	177	246	284	323	371	315	392	340	266	334
	No. of cases	356	354	352	350	349	329	327	324	322	321	174	185	168	175	171
Summer (Jun-Aug)	Feet	90	139	170	201	230	164	224	264	310	386	365	428	341	269	381
	No. of cases	368	368	368	368	368	354	356	354	355	354	205	211	208	203	202
Autumn (Sept-Nov)	Feet	131	201	259	301	339	231	338	421	482	520	266	372	331	334	399
	No. of cases	352	352	353	352	352	317	317	316	316	314	157	156	143	157	145
Year	Feet	107	167	213	249	281	183	263	321	370	422	309	382	334	292	367
	No. of cases	1427	1424	1423	1419	1417	1322	1322	1316	1313	1310	667	682	649	671	647

TABLE VI.

Average Variation of temperature at the 500, 300 and 100 mb. level at Aldergrove during specified intervals

		500 mb.					300 mb.					100 mb.				
		6h	12h	18h	24h	30h	6h	12h	18h	24h	30h	6h	12h	18h	24h	30h
Winter (Dec-Feb)	°F	3.5	5.0	6.2	7.0	7.5	4.5	5.1	5.5	5.6	5.8	4.3	4.8	5.2	4.8	5.4
	No. of cases	353	352	352	351	350	327	327	327	325	326	139	145	138	144	141
Spring (Mar-May)	°F	3.6	4.6	5.4	5.8	6.2	4.0	4.7	5.0	5.2	5.5	4.5	6.3	5.4	4.3	5.4
	No. of cases	358	356	354	352	351	332	330	327	324	325	177	189	172	181	176
Summer (Jun-Aug)	°F	3.1	4.2	4.8	5.3	5.9	3.9	4.6	5.3	5.5	6.2	4.7	5.9	4.7	4.0	5.3
	No. of cases	368	368	368	368	368	354	356	354	353	354	205	211	211	202	203
Autumn (Sept-Nov)	°F	3.9	5.6	6.6	7.6	8.3	4.2	5.5	6.7	7.4	8.3	4.7	5.3	5.3	5.4	6.9
	No. of cases	344	344	345	344	344	324	325	324	324	319	162	164	151	165	153
Year	°F	3.5	4.9	5.7	6.4	6.9	4.1	5.0	5.6	5.9	6.4	4.6	5.7	5.1	4.6	5.7
	No. of cases	1423	1420	1419	1415	1413	1337	1338	1332	1326	1324	683	709	672	692	673

TABLE VII.

Average Vector Wind Variation with time at the 500, 300 and 100 mb. levels at Aldergrove during specified intervals

		500 mbs.					300 mbs.					100 mbs.				
		6h	12h	18h	24h	30h	6h	12h	18h	24h	30h	6h	12h	18h	24h	30h
Winter (Dec-Feb)	Knots	16.5	23.7	26.3	30.7	33.8	20.3	31.5	37.8	41.7	45.1	7.6	7.5	12.3	13.7	20.4
	No. of cases	222	217	214	213	206	190	185	182	176	175	40	40	31	37	27
Spring (Mar-May)	Knots	15.3	21.3	25.6	29.2	31.3	21.1	30.4	36.6	40.6	43.4	8.1	8.9	8.6	11.3	12.9
	No. of cases	305	302	298	298	296	272	269	266	266	265	66	70	65	72	68
Summer (Jun-Aug)	Knots	12.1	16.9	20.5	22.6	24.0	22.2	31.5	37.8	42.4	43.9	7.8	7.6	9.1	9.0	10.3
	No. of cases	329	326	324	323	322	316	317	312	311	311	117	118	120	115	112
Autumn (Sept-Nov)	Knots	17.0	28.3	34.3	35.2	40.3	25.0	42.4	51.8	58.5	65.4	13.7	15.2	19.9	21.0	23.9
	No. of cases	230	215	221	230	225	206	190	193	204	198	51	56	46	62	52
Year	Knots	15.2	22.5	26.7	29.4	32.4	22.1	34.0	41.0	45.8	49.5	9.3	9.8	12.5	13.8	16.9
	No. of cases	1086	1060	1057	1064	1049	984	961	953	957	949	274	284	262	286	259

AVERAGE VARIATION OF HEIGHT OF THE 500 (•) 300 (×) AND 100 MB (○) LEVELS BETWEEN VALENTIA AND SPECIFIED STATIONS

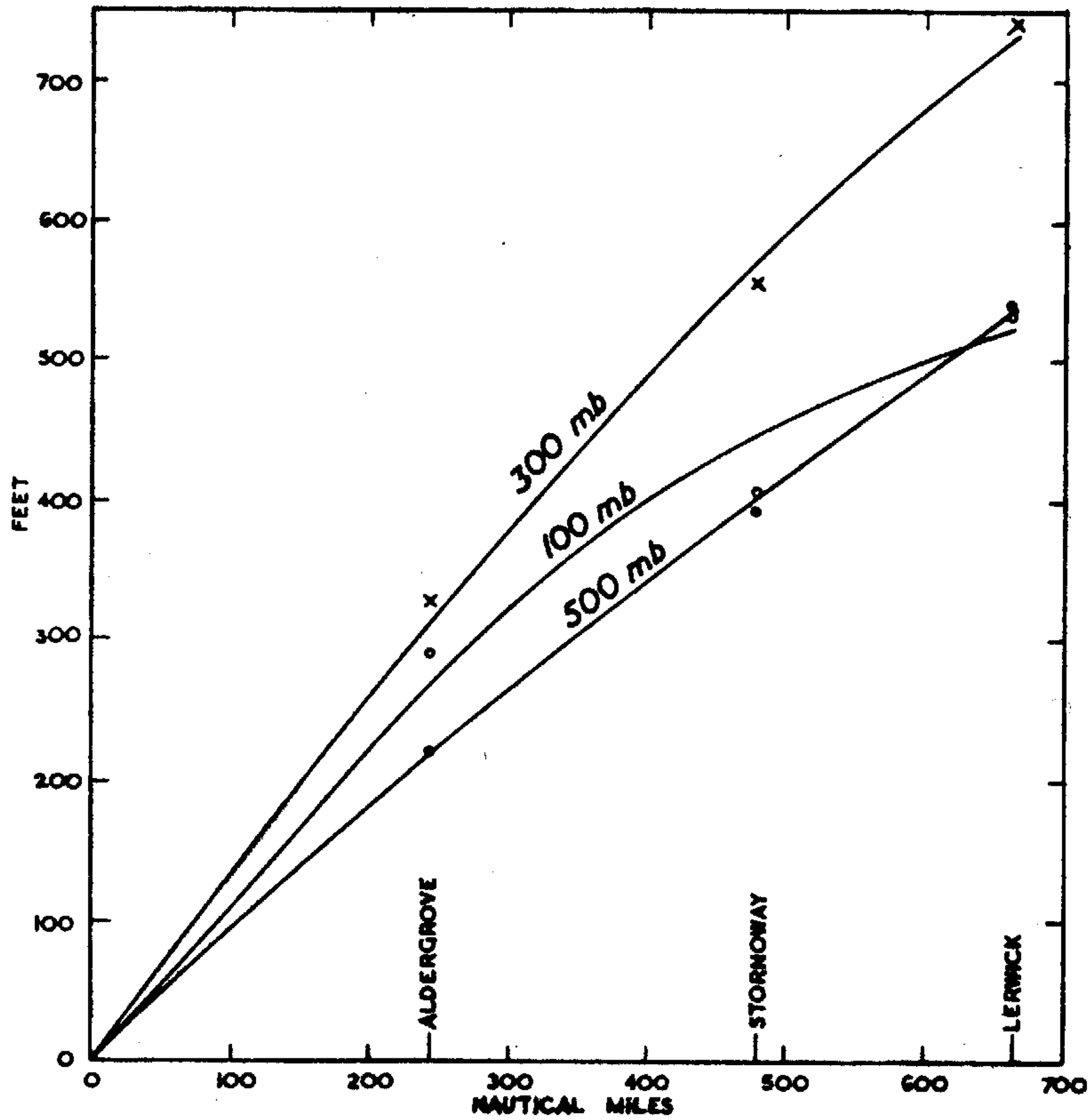

Fig. 6a

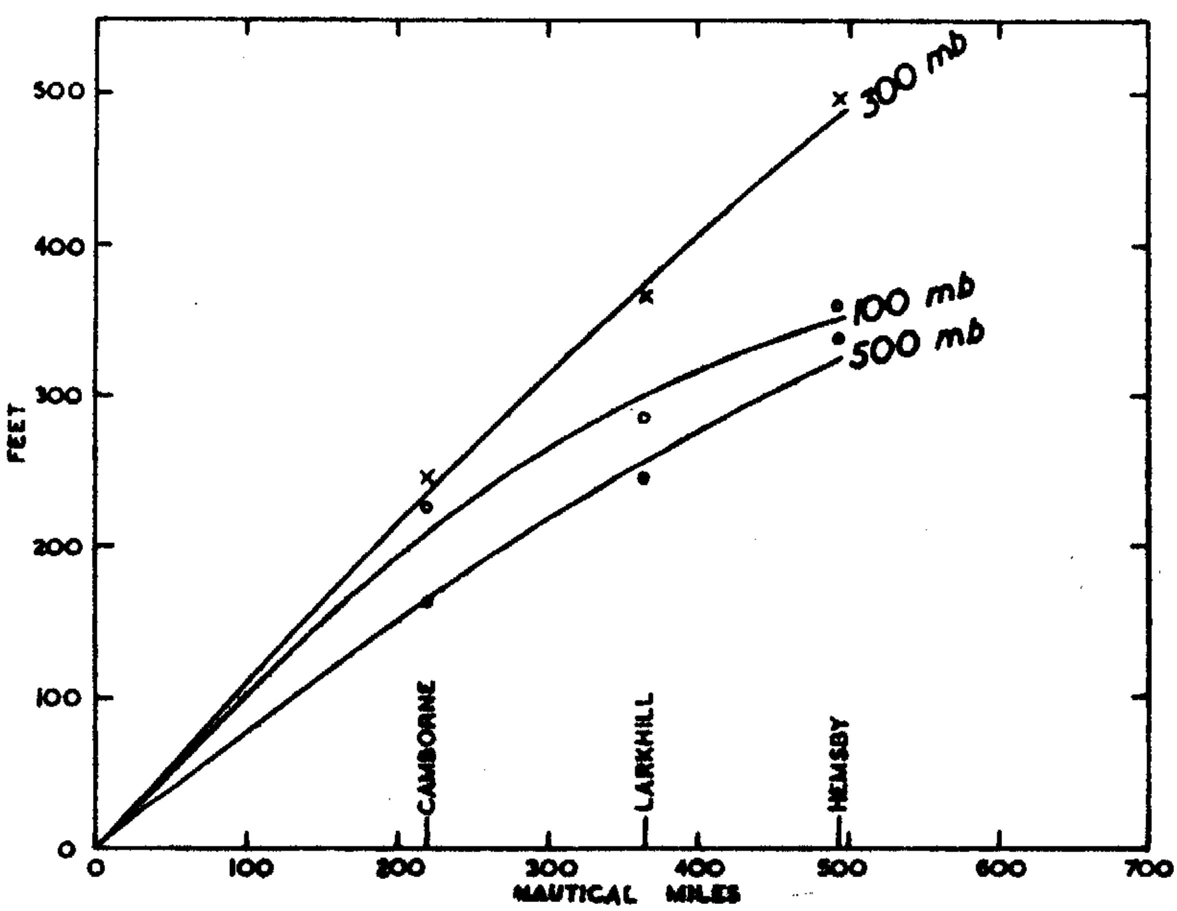

Fig. 6b

AVERAGE VARIATION OF TEMPERATURE BETWEEN VALENTIA AND SPECIFIED STATIONS AT THE 500 (•) 300 (×) AND 100 (∘) MB LEVELS

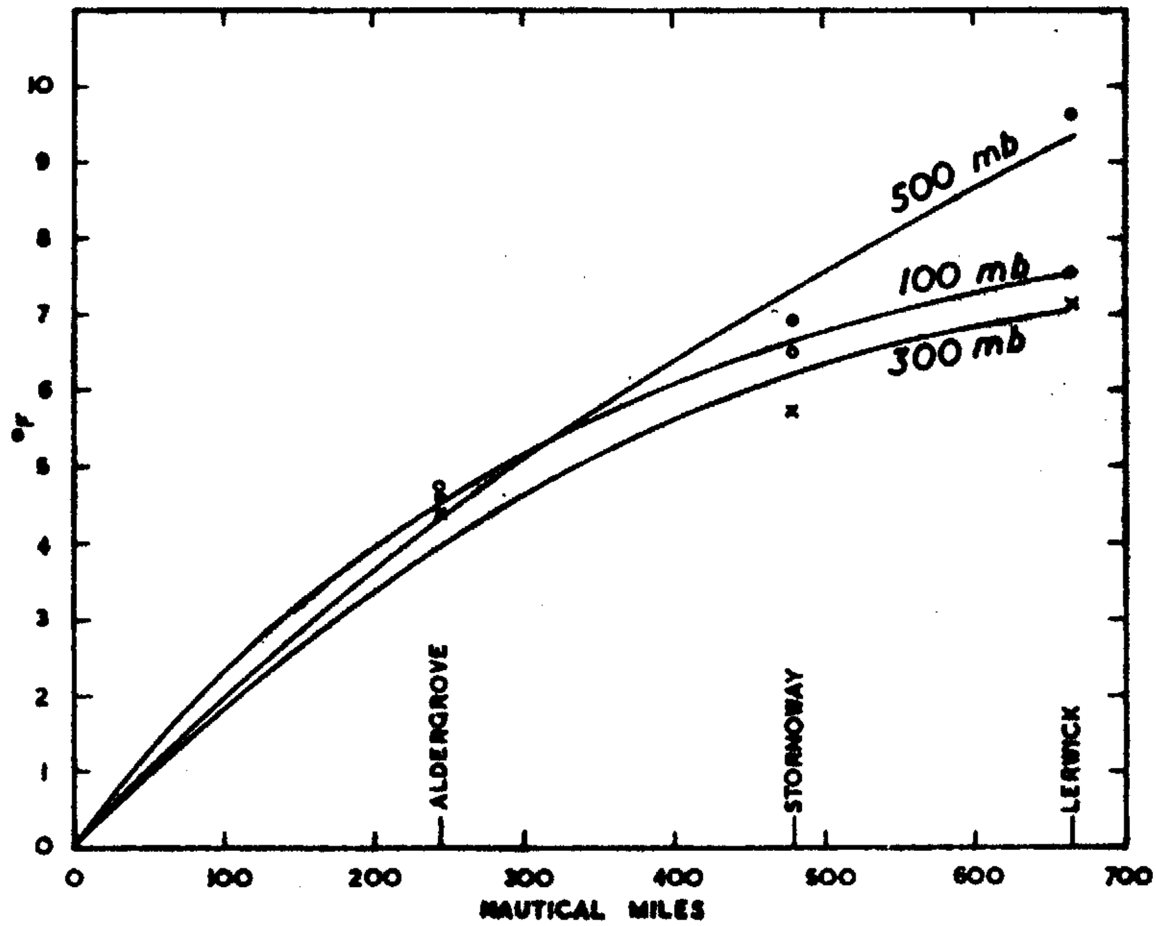

Fig. 7a

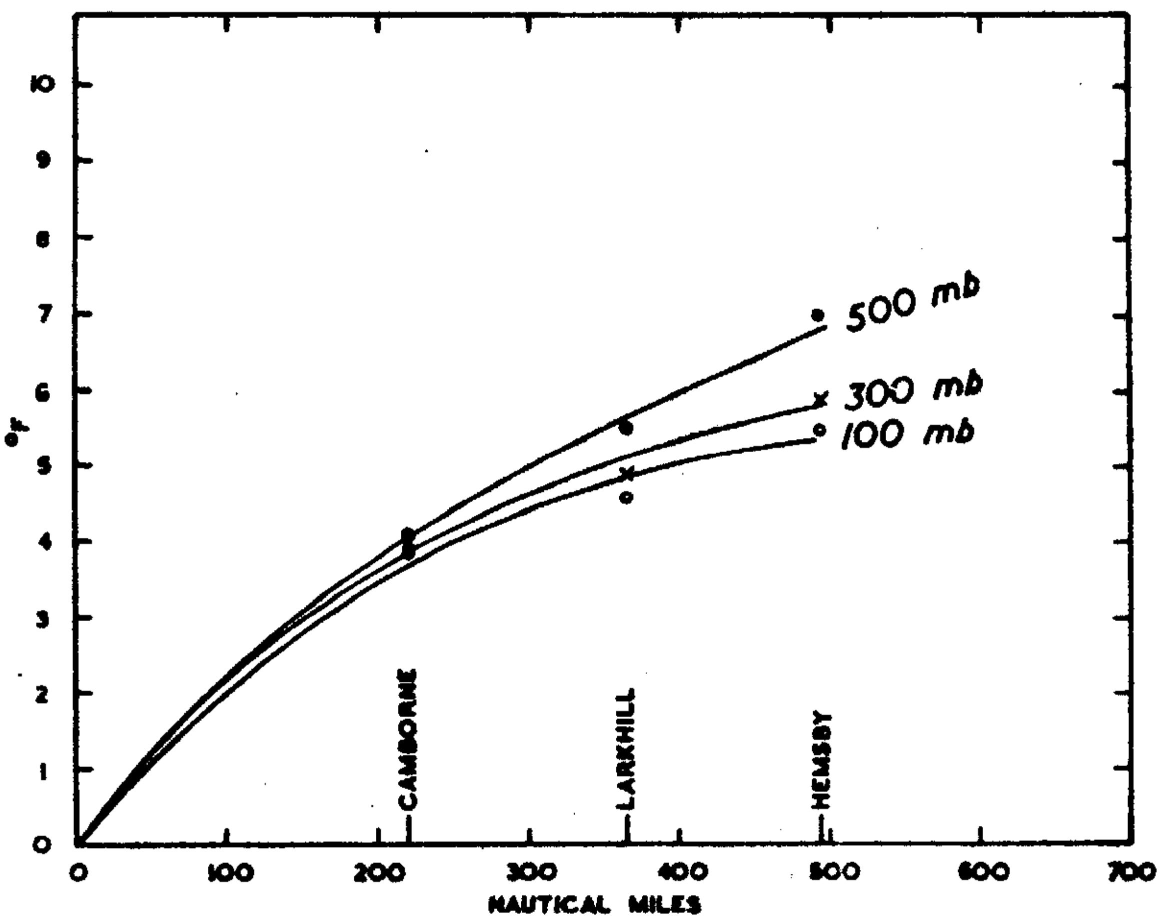

Fig. 7b

AVERAGE VARIATION OF VECTOR WIND BETWEEN VALENTIA AND SPECIFIED STATIONS, AT THE 500 (•) 300 (×) AND 100 (○) MB LEVELS

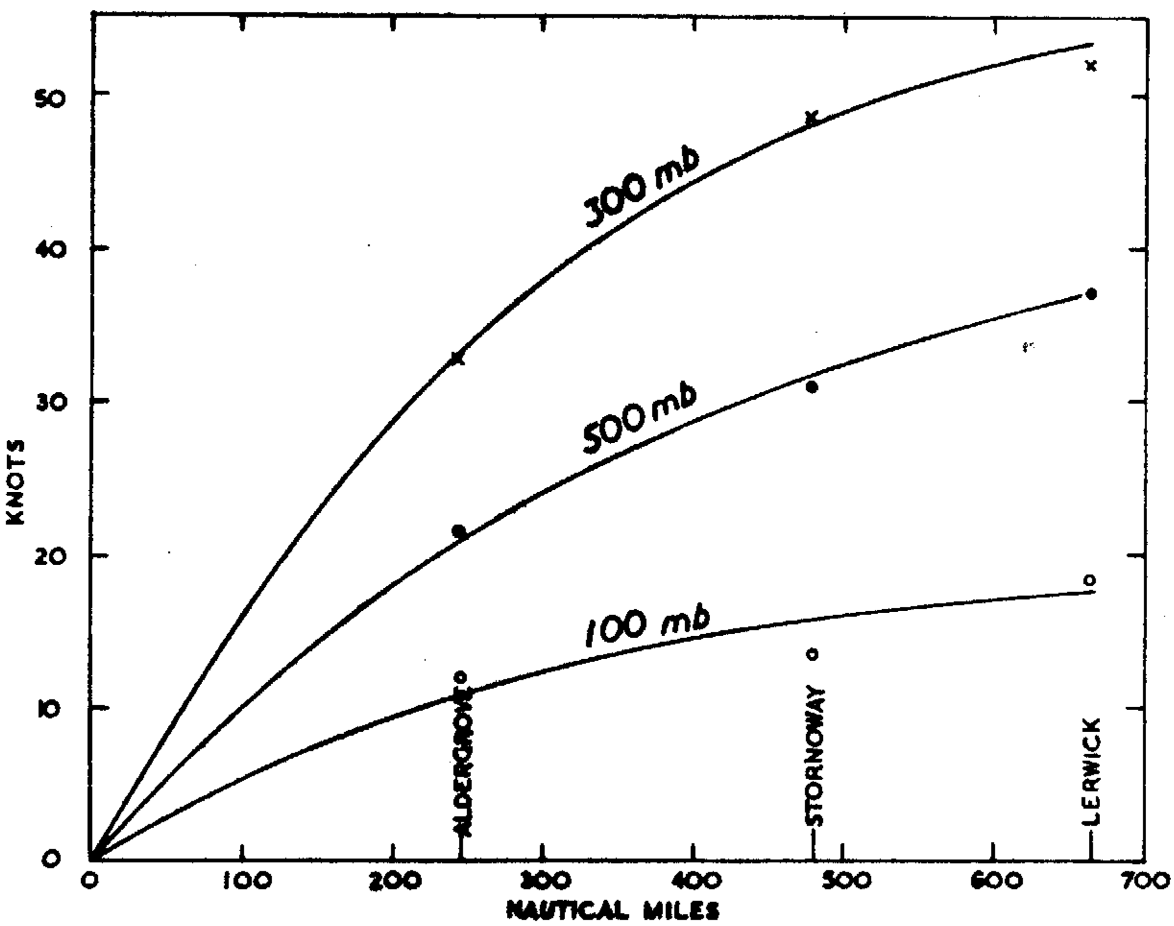

Fig. 8a

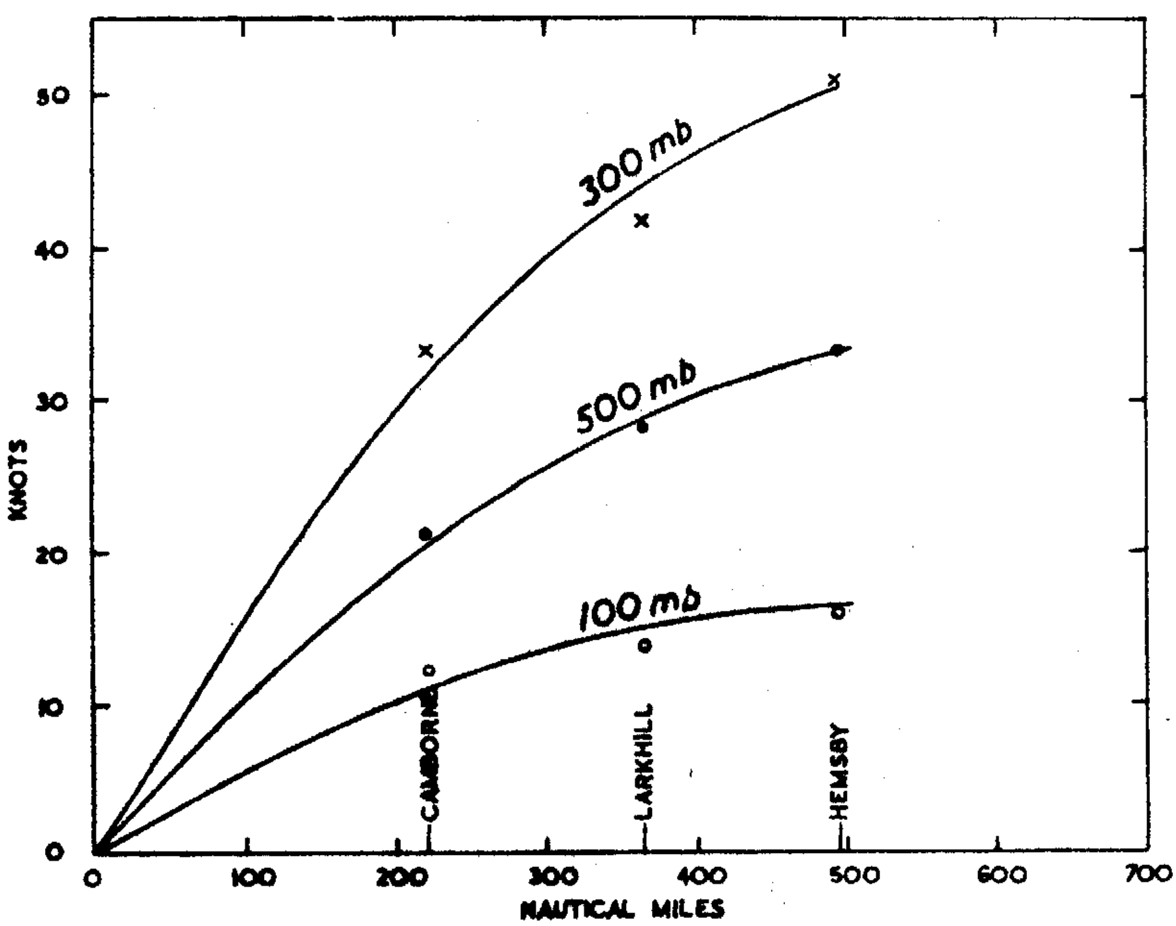

Fig. 8b

AVERAGE VARIATION OF HEIGHT OF THE 500, 300 AND 100 MB. LEVEL AT ALDERGROVE DURING SPECIFIED INTERVALS

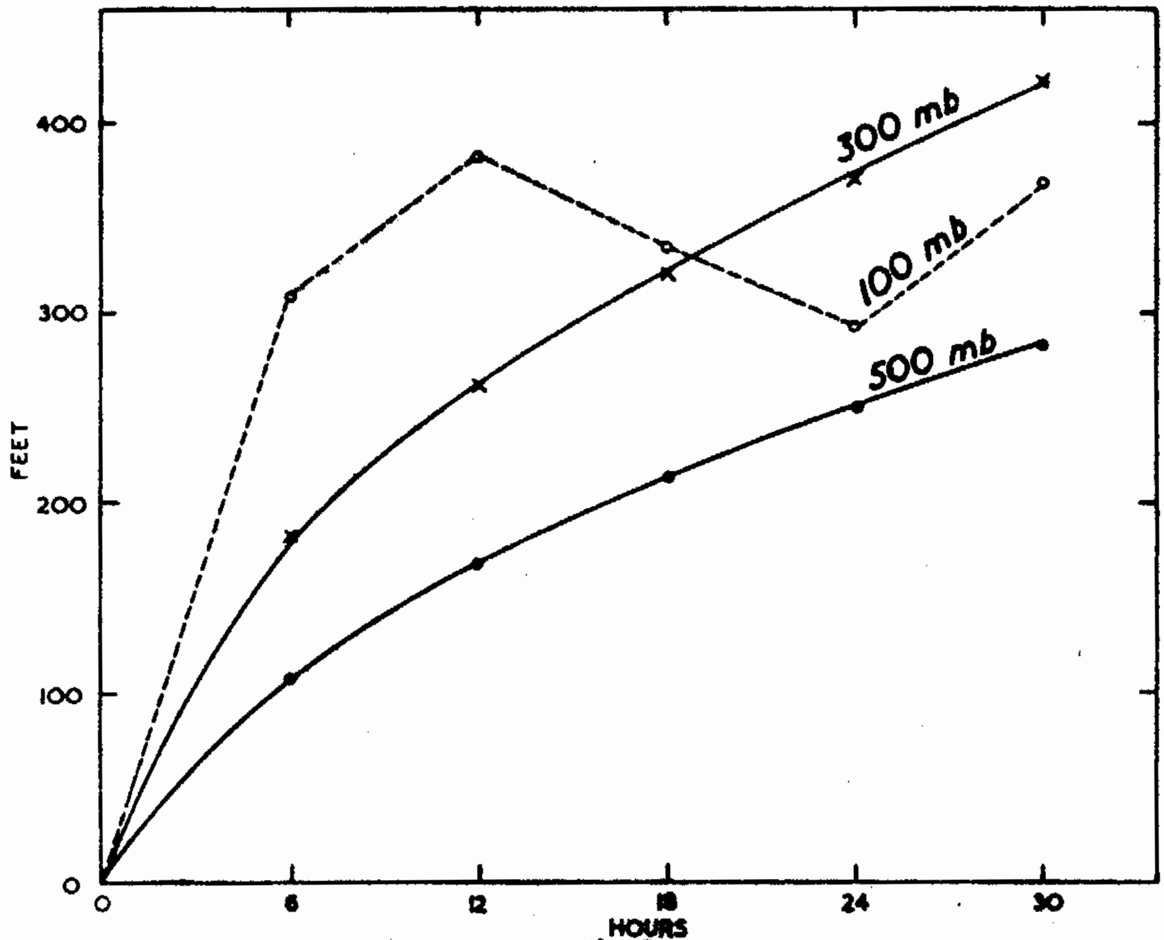

Fig. 9

AVERAGE VARIATION OF TEMPERATURE AT THE 500, 300 AND 100 MB. LEVEL AT ALDERGROVE DURING SPECIFIED INTERVALS

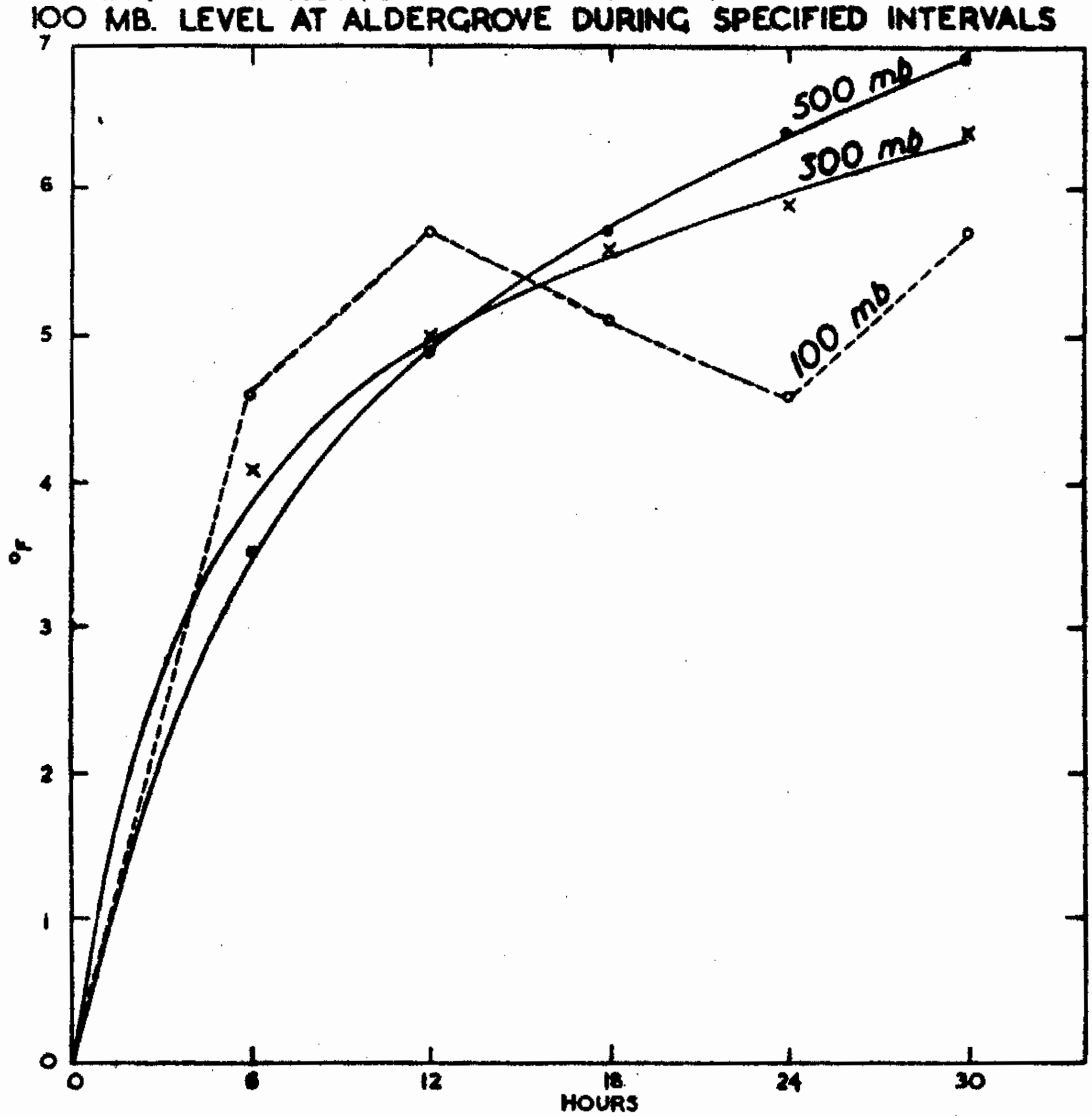

Fig. 10

VECTOR WIND VARIATION WITH TIME AT THE 500, 300 AND 100 MB. LEVELS AT ALDERGROVE DURING SPECIFIED INTERVALS

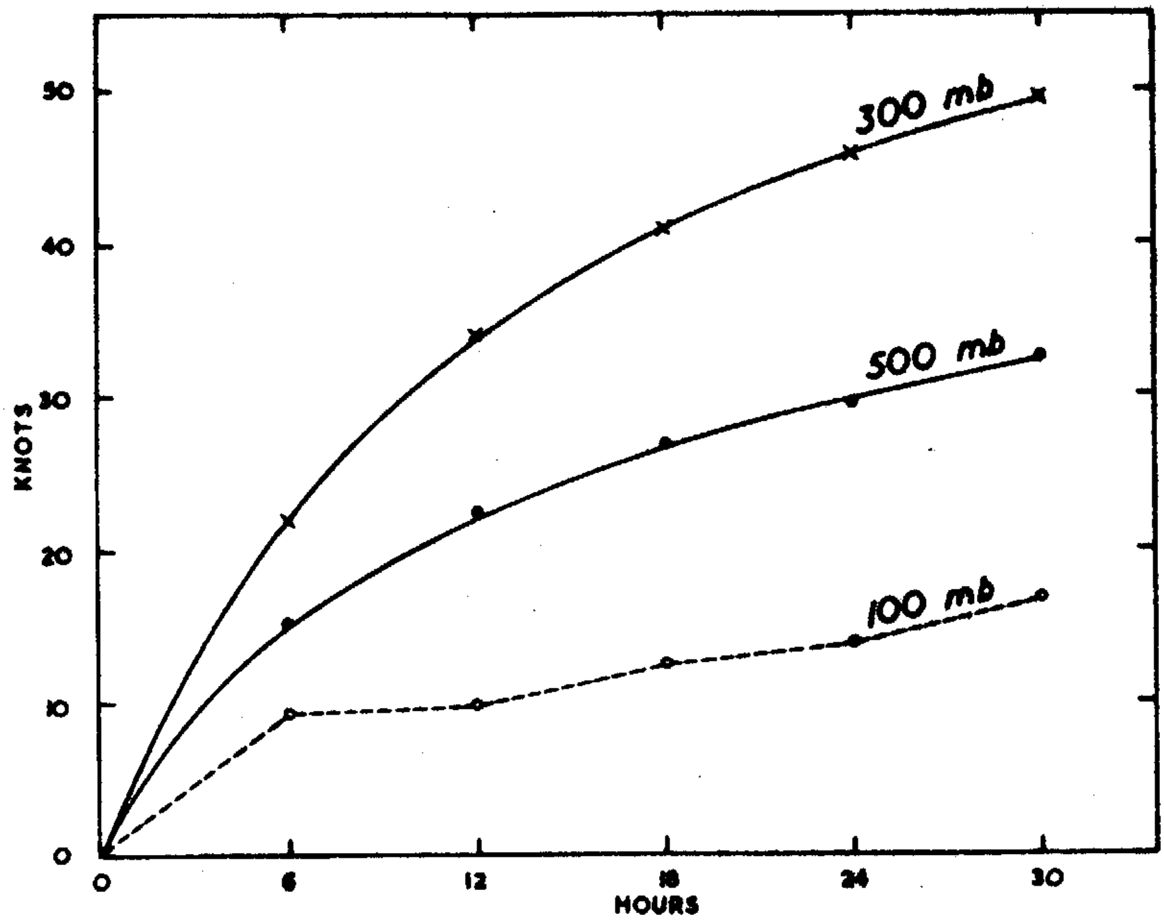

Fig. 11