Wind Structure in Relation to Air Navigation.

Summary of Paper read by Captain F Entwistle, B Sc, before the Institution in the Lecture Room of the Junior Institution of Engineers, 39, Victoria Street, London, S W 1, on 9th December, 1926 Mr W L Cowley, A R C Sc, D I C, (Member), in the Chair

AN important application of the science of Meteorology to Aviation is in connection with the provision of accurate data for navigation This aspect of the subject involves a knowledge of what may be termed " wind structure," that is, the horizontal variation of wind with place and time, and the variation with height within the atmospheric layer in which flying normally takes place

Variation of Wind with Height

In discussing the variation of wind with height it is desirable first to assume a standard of reference The wind near the surface of the ground is of little use in this respect since it is subject to many local variations The most convenient standard is the undisturbed wind in the lowest layer which is free from fluctuations caused by the upward propagation of disturbances from the surface of the earth

Fig 1 is a reproduction of a weather chart of N W Europe based on observations made by a large network of stations at 7 a m G M T. on November 11th The most important feature of the chart from the point of view of the present discussion is the series of lines known as isobars which show the distribution of atmospheric pressure at mean sea level, being based on the individual barometer readings of the various stations, corrected in each case for temperature and reduced to mean sea level If we consider the flow of air along a great circle at a sufficient height above the earth's surface to eliminate the damping forces due to surface effects we can regard the motion as maintained by balanced forces due on the one hand to the earth's rotation, and on the other to the pressure gradient, that is, the rate of change of pressure in a direction perpendicular to the isobars It can easily

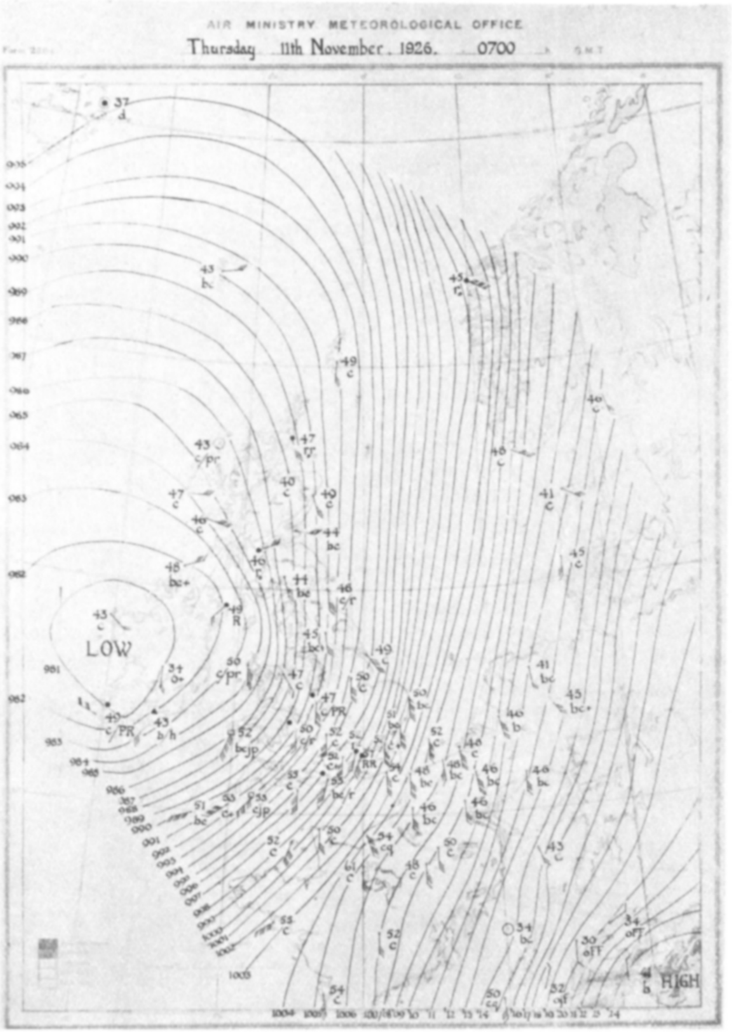
AIR MINISTRY METEOROLOGICAL OFFICE
Thursday 11th November. 1926. 0700 G.M.T.
LOW
HIGH

FIG 1

be deduced from first principles that the first of these forces acting in a direction perpendicular to the flow of air may be expressed algebraically as

$$2\ \omega \rho V \sin \phi$$

where ω = the angular velocity of the earth's rotation,
ρ = the density of the air,
V = the velocity of the wind
and ϕ = the latitude of the place of observation

If we denote the pressure gradient by P then the condition for the balance of these forces becomes

$$P = 2\ \omega \rho V \sin \phi$$

$$\text{or} \quad V = \frac{P}{2\ \omega \rho \sin \phi}$$

The wind calculated from this equation is known as the " geostrophic " wind and is the wind which we are assuming as our standard of reference

It has been shown, and is now generally recognized, that the geostrophic wind agrees closely with the observed wind at a height of about 1,500 feet above the earth's surface Hence, if from a synoptic chart one measures the direction of the isobars at a given point and also the pressure gradient at that point one can obtain a close approximation to the direction and speed of the wind at 1,500 feet This is an important practical result

Reverting to the chart of November 11th, it is observed that the direction of the surface wind, indicated on the chart by arrows, is inclined to the isobars towards the side of lower pressure The average inclination is of the order of two points, *i e*, 22½° The deviation from the direction of the isobars is due to friction between the lower layer of air and the earth's surface, which acts as a retarding force reducing the speed of the flow The result is that, on the average, wind velocity increases from the surface upwards, at first quickly and afterwards more slowly until the geostrophic wind velocity is reached , this occurs usually at a height of about 1,500 feet At the same time the direction veers until the direction of the geostrophic wind is approached Above this level changes are more irregular

Various formulæ have been put forward from time to time to express the relation between wind velocity and height in the lowest layers While in some cases a formula may give a close approximation to the actual wind distribution on a particular day, no one formula can be taken to apply universally This will be evident when we consider that the relation between the surface wind and the geostrophic wind does not remain constant during the course of the day The wind near the surface tends to veer and increase in speed during the day, reaching a maximum in the early afternoon and falling off again at night when the speed is at its minimum At a certain height above the ground, on the other hand, the actual height depending on the strength of the wind and the season of the year, the wind actually backs and decreases during the day, reaching its maximum speed at night The diurnal variation of wind direction is illustrated by the following table based on three years' observations at Cranwell, Lincolnshire —

TABLE I —VEER FROM SURFACE WIND IN DEGREES AT CRANWELL, 1920-1923

	7h				13h				18h			
Height	200	700	1200	1700	200	700	1200	1700	200	700	1200	1700
Summer	14	26	32	36	8	10	13	13	8	10	11	13
Winter	12	25	32	35	10	17	22	25	10	18	24	28

The table illustrates very clearly the large veer with height in the early morning which, in summer, is more than double the corresponding veer in the middle of the day, but in winter only about one-third as large

The diurnal change in wind speed is shown by Fig 2 which gives the average speed in January and July at the top of the Eiffel Tower (approximately 1,000 feet)

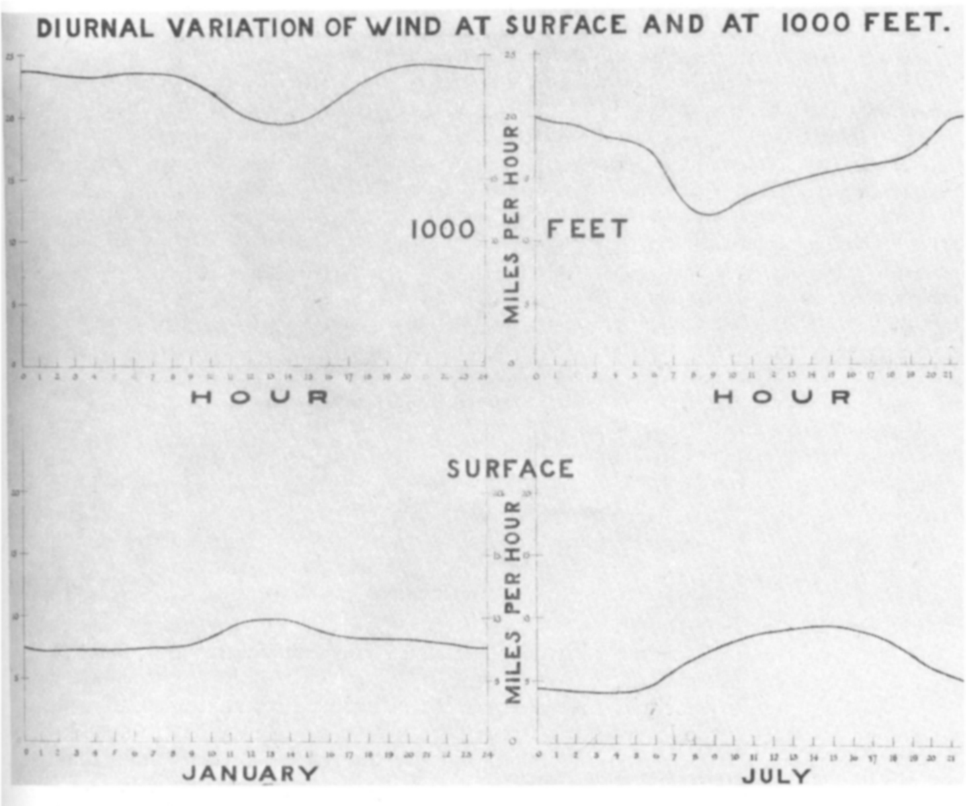

FIG 2

and the corresponding speeds at the ground station As in the case of direction the marked decrease in the diurnal change in winter at the former height is noteworthy

Further, it may be noted that the wind near the ground depends very much on the nature of the surface over which the air is flowing Fig 3, which is a reproduction of a trace from a recording anemometer, shows that the velocity and direction are not recorded by straight lines as they would be in the case of a steady wind but by a series of up and down oscillations the period of which is a fraction of a minute These oscillations which are the effect of eddies or gusts become greater as the mean speed of the wind increases The gustiness also depends largely on the exposure of the anemometer It would approach a minimum in the case of a flat open situation, but would increase considerably in a situation obstructed by houses, trees, etc The relation between the surface wind and the geostrophic wind may also vary with different wind directions and for different wind speeds

The physical causes of the variation of wind with height in the lower layers have been discussed by G I Taylor and others, the variation with height being directly attributed to turbulence in the atmosphere produced by friction between the air and the ground The eddies formed in this way become the mechanism which transmits upwards the surface effects, whether mechanical or thermal The eddy conductivity varies with the nature of the surface over which the wind passes For example, it is less over the sea than over grass-land while obstructions such as hedges, trees or houses considerably increase the eddying and consequently the height through which the surface effects are propagated

The nature of the variation of wind with height in the lowest layers is thus very complex, depending, as it does on the actual direction and strength of the wind, the time of day and season of the year, and the local topography A further complication is introduced by the fact that near the surface the wind may be practically independent of the pressure distribution An example is to be found in the sea breeze which occurs near the coast in the daytime during summer, and also in the case of air which is cooled by radiation at night flowing down the slope of a hill under gravity It is of interest to note that in such circumstances the speed of the surface wind may, under favourable conditions, exceed the geostrophic wind speed

Passing now to the layers above the geostrophic wind level, that is the region above the layers affected by surface turbulence, the results of observations of the wind in the upper air which have been made at different places point to the following general characteristics

(*a*) *As regards Direction*

N E winds tend to fall off with height and above 3,000 feet to be replaced by winds from a westerly point

S E winds tend to veer with increasing height, the speed remaining steady

S W winds show the largest veer with height and also an increase in speed

N W winds also veer with increasing height though to a less extent than S W winds , the increase in mean wind speed is, however, more pronounced

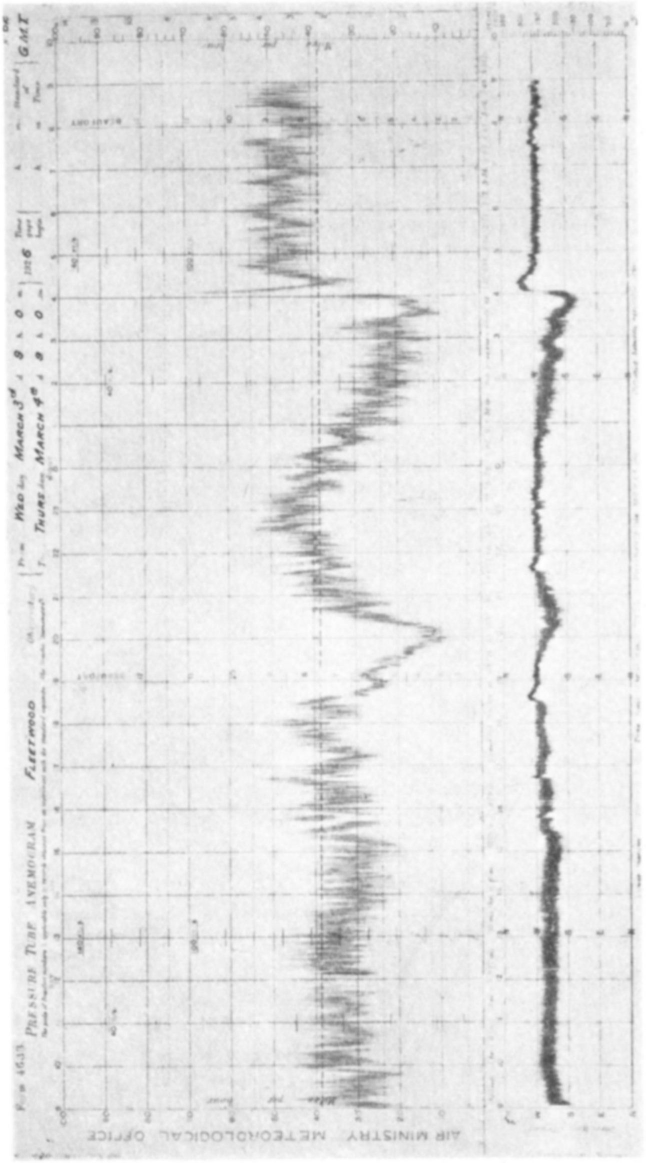
Pressure Tube Anemogram
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Fig 3

(*b*) *As regards Mean Wind Speed*

In general, light winds show less increase of speed or change of direction with height than is shown by moderate or strong winds

It may be stated as a general principle that the wind in any layer will approximate to the wind computed from the pressure gradient for that particular level Now the distribution of pressure at any level depends not only on the distribution of pressure at mean sea level, but also on the distribution of temperature in the intervening layers A large horizontal temperature gradient will thus affect appreciably the wind distribution in the upper layers It can be shown that the effect of such a temperature gradient is to superpose on the geostrophic wind a wind blowing round the lower temperature in the same way that the geostrophic wind circulates round low pressure Thus a decreasing temperature gradient from west to east would give an added northerly component to the geostrophic wind at greater heights

To sum up we may say that generally speaking, mean wind speed increases from the surface upwards until the geostrophic wind is reached at a height of about 1,500 feet Above this height changes are irregular, the wind being controlled partly by the horizontal distribution of temperature In the layers near the surface variations from the general distribution are common, depending on local topography the time of day and season of the year

Horizontal Variation of Wind with Place and Time

Just as it is difficult to formulate definite rules with regard to the variation of wind with height, so it is difficult to express numerically the horizontal variation of wind with place and time In these latitudes the distribution of pressure and temperature rarely remains appreciably constant for a long period and the wind distribution in one part of the country is frequently different from that in another part Investigations of wind changes for short periods of time and for short distances, however, have shown a certain amount of agreement, and it is possible to arrive at approximate formulæ for the average vector changes in these conditions

The following results for the mean vector change of wind with time are based on data from five stations in the British Isles

TABLE II —MEAN VECTOR CHANGE OF WIND WITH TIME

(Velocities in m p h Direction in degrees)

Period of time	HEIGHT											
	1,000 ft		2,000 ft		3,000 ft		5,000 ft		8,000 ft		Mean all heights	
	Vel	Dir	Vel	Dir	Vel	Dir	Vel	Dir	Vel	Dir	Vel	Dir
6 hours	8 5	25	8 6	24	8 5	24	8 9	25	8 4	27	8 6	26
12 hours	11 6	39	12 1	37	12 3	36	12 6	41	11 8	36	12 1	38
24 hours	14 3	50	15 4	50	15 7	50	16 1	53	17 2	67	15 7	54

The table shows remarkable agreement for heights from 1,000 feet to 8,000 feet For periods less than 12 hours, the following approximate formulæ would appear to hold for the vector change with time

Change in Velocity $V = 3\ 5\sqrt{t}$ where t = time in hours

Change in Direction $D = 10\ 9\sqrt{t}$

With regard to the variation of wind with place, the following table showing the mean vector change is based on data deduced by Durward,* from observations made during the War in N E France

TABLE III —MEAN VECTOR CHANGE OF WIND WITH PLACES

(Velocities in m p h Directions in degrees)

Distance in miles	13		19		35		41		51		57	
Height in feet	Vel	Dir	Vel	Dir	Vel	Dir	Vel	Dir	Vel	Dir	Vel	Dir
2,000	2 3	8	2 7	10	3 3	12	3 4	12	3 5	13	3 8	14
4,000	2 7	9	2 8	10	3 5	13	3 6	13	3 9	14	4 4	15
6,000	2 1	8	2 7	10	3 1	12	3 9	14	4 1	15	5 1	10
10,000	2 1	10	2 3	10	3 2	15	2 9	15	3 3	16	3 6	18
Mean all heights	2 3	9	2 6	10	3 3	13	3 5	14	3 7	15	4 2	16

Taking mean values for heights from 2,000 feet to 10,000, the following formulæ express approximately the vector change with place for distances up to 50 miles

Change in Velocity $V = 0\ 55\sqrt{d}$ where d = distance in miles

Change in Direction $D = 2\ 2\sqrt{d}$

Wind Measurement

The standard instrument used in this country for measuring winds near the ground is the Dines pressure-tube anemometer which gives continuous records of both the speed and direction of the wind Winds in the upper air are measured by means of pilot balloons These are small rubber balloons which are filled with hydrogen to rise at a pre-determined rate The motion is observed by means of a specially constructed theodolite and readings of the altitude and azimuth are taken every minute Assuming the rate of rise of the balloon it is then possible

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* London, Air Ministry, Meteorological Office Professional Note, No 24 The Variation of Wind with Place, by J Durward 1921

to calculate by a slide rule the speed and direction of the wind in consecutive layers By attaching a long tail to the balloon and observing its length on a graticule in the eye-piece of the theodolite the necessity for assuming the rate of ascent of the balloon is avoided The most accurate method is by using two theodolites at the ends of a measured base line, but this method is less convenient than the single theodolite method as it requires more personnel and a longer time for working up the results

The measurement of wind at sea is rather more difficult than on land Anemometers have been fitted to certain ships, but the records give "relative wind" only, the true wind being obtained from a table Upper winds at sea are also measured by pilot balloons, but a sextant is found to be preferable to a theodolite for following the balloon A specially designed theodolite has been tried experimentally for this purpose

Application of Wind Data to Air Navigation

We now come to the practical application of the results which have been discussed above

There are several aspects to this question, but one or two examples will illustrate the use of wind data in practical aviation Thus, in organizing a regular air route it is important to take into account the average frequencies of different wind directions and strengths along the route, not only from the point of view of calculating time tables and costs, but also from the point of view of estimating *the probable number of days on which it would be impossible to complete the* journey in either direction without landing and re-fuelling An examination of the available data for the Cairo-Karachi route indicates that in the summer months, on the average, it would be necessary to allow for a wind of about 11 m p h from west to east, while in the winter months the average westerly component would only be about 4 m p h On the London-Paris route on the other hand the average wind factor is negligible, being of the order of 1 m p h

As a second application of wind data to navigation the case may be quoted of a flight during which it is desired to steer a definite course at a given height, as, for example, in an air survey flight In such a case the most complete information would be based on actual observations of the direction and speed of the wind at different heights made at various points along the route It would be necessary to supplement this information by an estimate of the probable wind changes during flights as deduced from the current isobaric charts Accurate wind data for the flight would thus be obtained If there were no information available apart from observations at the home station, the figures already quoted for the vector change of wind with place and time could be used It would be unsafe, however, to apply these generalisations for distances much above 50 miles As an example of the magnitude of the corrections involved in the application of the data already deduced for the vector change of wind, the case may be cited of a flight to a place 50 miles due north from the starting point, the wind at the latter place being N W , 15 m p h If this were assumed to be the wind throughout the flight, the drift would be about 1·5 miles, assuming the air speed of the machine to be 100 m h p , and the distance from the destination after flying for a pre-arranged time would be just over 2½ miles

A third aspect of the subject is in relation to the selection of the best height for flying, with a view to effecting an economy of fuel and time If time alone has to be taken into account, the problem is relatively simple, for assuming that the machine can maintain a given air speed at any height, the only factor to be considered is the loss of time in climbing to the selected height and in descending again But in deciding the best height to fly from the point of view of fuel economy, the problem is more complicated and requires more data for its solution than the meteorologist has, at present, in his possession There are, of course, frequent outstanding cases in which the solution is obvious An example is to be found on October 16th, 1926 The synoptic chart and upper wind data for that day (Fig 4)

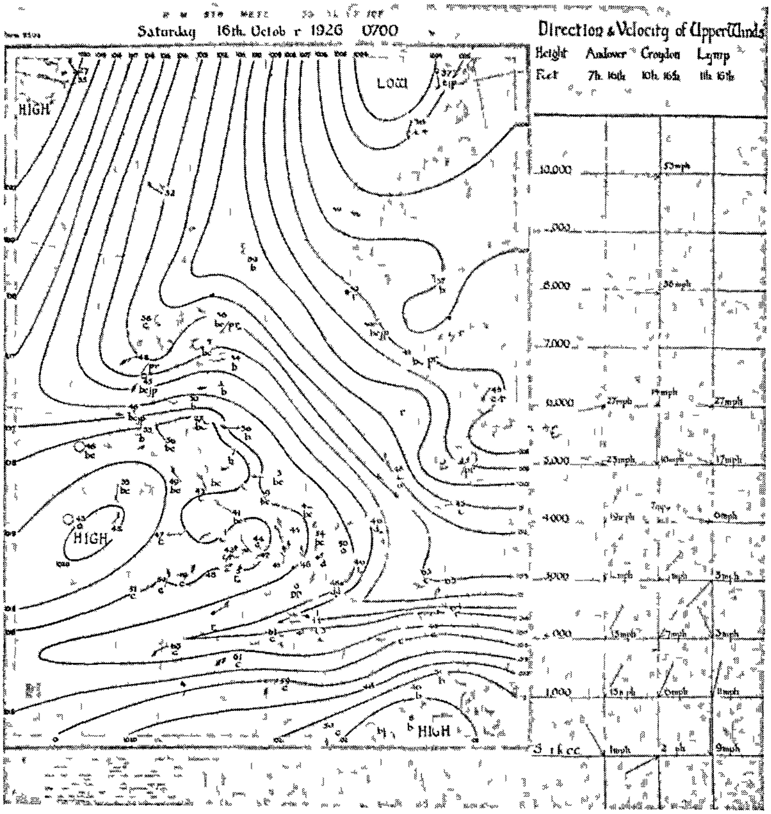

FIG 4

show that in the lower layers the wind was light from the N E or N , while above 5,000 feet there was a definite westerly current It is clear that on that day it would have paid to fly high on a west to east route, and low on an east to west route But on other days the problem is not so simple, and requires for its solution a knowledge of the performance of each type of machine for which the information has to be given, in addition to a knowledge of the wind distribution The question clearly points to the need for co-operation between the experts on the aeronautical and meteorological sides It should be possible to prepare statistical data on machine performance in such a form that the meteorologist can use it in conjunction with the information about the wind already in his possession, in order to give definite advice regarding the best height to fly on a particular day without an elaborate calculation

In discussing the subject of wind structure, no reference has been made to vertical currents which are produced by hills or mountains and, more generally, by instability in the atmosphere These and other phenomena such as squalls and thunderstorms have an important bearing on practical aviation For adequate treatment, however, this branch of the subject would require more space than it is possible to devote to it here Further, it does not come strictly within the scope of the present discussion

DISCUSSION

MR COWLEY (CHAIRMAN) It has been noticed that in several full scale tests of machines there is a marked tendency during the summer months to get a slightly lower rate of climb at low standard heights than on an average day during the winter months This has been attributed to vertical currents

It is rather mysterious that currents should continuously descend during the summer over a very large area, and I should like to ask the lecturer whether he has any information which will support the theory that such variations in machine performance are due to up currents in winter and down currents in summer

In some recent investigations I have made on economy in air transport, I was surprised at the importance of the wind factor For example, it was thought that it would greatly add to the economy of freight-carrying machines if they were designed for a much lower speed, say 60 m p h At low speeds less energy is called upon and petrol saved thus increasing the machine's carrying capacity In designing machines we must take the wind into account however, and naturally we must not only consider the speed of the wind over a long period, but also the maximum conditions which the machine will have to overcome I found the effect of this to be that the most economical speed for freight-carrying machines was somewhere in the neighbourhood of 100 m p h I think that, neglecting the factor of the wind, you would find the optimum speed to be in the neighbourhood of 50 m p h

CAPTAIN SAYERS I should like to ask to what extent the figures given for the changes in velocity direction, etc of wind, are to be regarded as accurate ?

They must be based on some sort of average pressure gradient and rate of movement of the system as a whole Therefore presumably they may indicate under normal conditions what may normally be expected to happen, but do not do more than that, and still leave us a long way from arriving at a reliable forecast under any abnormal conditions

CAPTAIN TYMMS Good wine needs no bush, but probably no one outside the Meteorological Office is in a better position than I am to judge of the immense amount of work that Captain Entwistle has done to place the science meteorology, and particularly climatology, at the service of pilots, who at the present time are making a very great deal of use of the Department of which Captain Entwistle is the head

As to the paper itself, I do not feel very well qualified to discuss it The one point I want to refer to is one the lecturer omitted from the reading of his paper In one paragraph he refers to the use of wind data in air survey It is obvious that wind structure is of very great importance in the problem of air survey photography, where the problem is to fly with absolute accuracy, and any variation in the wind is going to affect the result, but I do not quite agree that it can be dealt with in the way he suggests He has suggested that you should collect a great deal of data as to the actual winds over the area which you are going to photograph, and that from this data you should form an accurate estimate of the probable changes over that area

I do not think any pilot engaged in air survey could rely on an assumption from observations which had been made prior to his flight It is quite clear that the observations would be approximately correct, but the forecast from this data would be less correct The pilot flying for air survey has his own method of allowing for the wind which is blowing, and that is by the use of a drift indicator, This problem is receiving a great deal of attention by the air survey people, and they are working towards an improvement in the design of the aircraft itself, so that they can use a different and simplified type of sight, which will allow for the wind without actually determining its velocity

The pilot will steer by means of the landmarks of the country ahead , it is hardly necessary to remark that in photographic flying he can always see the ground

In another way wind structure does affect the problem greatly In Professor Melvill Jones's book, "Aerial Survey by Rapid Methods," there is a very interesting account of how he carried out flights with the object of determining what errors would occur in the track in a flight of fifty miles During these flights he took photographs in order to record his track, and on examining the results he discovered a few funny kinks in one or two flights The pilot had steered a constant compass course, so he got his photographs and from them deduced the height of the machine over that part of the track in which those kinks occurred He found that the machine had changed height by 100 or 200 feet, and he traced the kinks in his track to these changes in height which had taken the aircraft into a different wind strata I think this is rather an interesting illustration of the importance of this particular paper

In conclusion I should like to express my thanks and appreciation of the opportunity of being here to listen to Capt Entwistle's very interesting paper

CAPTAIN ENTWISTLE'S REPLY TO THE DISCUSSION

Replying to the Chairman's remarks, I cannot, for the moment, offer any explanation of the phenomenon which he describes I understand that it could not be due to the seasonal variation in temperature, because the discrepancy was still evident after the figures had been corrected for density

I was interested in the remarks concerning an economy estimate for flying in the case of a freight machine, and I personally wish that the Chairman had given us a little more information on that subject, because it is one on which I was afraid to venture very deeply, as it is rather a question for the aeronautical engineer than for the meteorologist It is, however, a matter upon which meteorologists who have to cater for the needs of aviation, require information in order that they can arrive at the meteorological data which is necessary for the solution of the problem

Replying to Captain Sayers, the figures to which he refers certainly indicate that the changes over short distances are ordinarily very small They are only intended to be used in cases where more accurate data are not available

Replying to his question regarding the formula for computing geostrophic wind, this is a general formula, and assumes, naturally, that in applying it to a particular case, the units which are used are consistent

I was interested in Captain Tymms's account of the method of correcting for drift in the case of an aircraft engaged on a survey flight, and have no doubt that that method would be more accurate than a method by which data obtained before the flight are corrected approximately from observations taken during the flight

In taking an air survey flight as an example, I wished merely to refer to a flight in which it is necessary to steer an accurate course For ordinary navigation the method which I have described would be sufficiently accurate, and would normally enable the pilot to hit his objective very closely

A very hearty vote of thanks to Capt Entwistle for his interesting paper brought the meeting to a close