C. J. P. CAVE

The Structure of the Atmosphere in Clear Weather

A Study of Soundings with Pilot Balloons

THE STRUCTURE OF THE ATMOSPHERE IN CLEAR WEATHER

A STUDY OF SOUNDINGS WITH PILOT BALLOONS

BY

C. J. P. CAVE, M.A.

Nonne vides etiam diversis nubila ventis
Diversas ire in partis inferna supernis?

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INTRODUCTION

THE investigation of the wind currents of the air above the surface layers is one of the greatest importance in the study of meteorology; one reason for the slow advance made by this science in the last fifty years is to be found in the fact that until quite recently meteorologists only took note of that part of the atmosphere that was close to the surface of the earth, and beyond some cloud observations and a few isolated records, such as those obtained by Glaisher, nothing was known of the conditions existing in the free air. The recent rise of aviation and its probable extension in the near future make it more than ever necessary to investigate the nature of the currents in the free air above the surface of the earth.

During the last few years the conditions of temperature, humidity, and wind have been investigated by means of kites carrying self-recording instruments to very considerable heights. Free balloons carrying lighter instruments have continued these records to still higher regions, heights of 25 kilometres and more having been reached. The motion of such a balloon if accurately observed gives a record of the wind currents traversed by it in its ascent through the atmosphere. Such records may also be obtained by small balloons that carry no instrument when they are followed by means of a theodolite during their ascent. The following pages give some account of the investigation of the upper air by means of such observations, some of the records having been obtained from balloons carrying instruments and others from small free balloons carrying nothing beyond a stamped label to be posted if the burst balloon should be found after it reaches the earth. An account is given in the first chapter of the general types of structure disclosed by the observations, and figures are given of models prepared to show the sequence of wind velocities and directions met with during the ascents on occasions when the different types of structure were found. An account follows of the methods of observing the balloons and of the theodolites employed for this purpose, together with an account of how the observations are worked up to give the horizontal trajectory of the balloon, and the method of measuring the wind velocity and direction at different heights from the trajectory. In Chapter III will be found a discussion of the accuracy of the methods employed, and a comparison of the trajectory determined by the observations of two theodolites at opposite ends of a base line with that determined by the observations of one theodolite only, and the assumption that the balloon ascends with a uniform or at any rate with a known velocity. Following on this is a discussion of the rate of ascent of rubber balloons which it is of great importance to determine as accurately as possible; in this connection the results of observations and of theoretical considerations by investigators in this country and on the Continent are given. The relation of surface air currents to the configuration of the ground is also touched on; this is a point of great importance for aviators and it is one that should be gone into more fully with balloons that ascend more slowly than those that have been used in these investigations.

A general summary of the results obtained is given in Chapter V in which certain types of structure in the atmosphere are recognised, and the different types are considered in their relation to the wind at the surface, the gradient wind, and the general distribution of pressure and temperature in the region. Five types are described: (*a*) wind in the upper air steady with no increase in velocity with height; (*b*) wind in the upper air increasing, sometimes to several times the gradient value, but remaining more or less steady in direction; (*c*) wind in the upper air decreasing in velocity; (*d*) reversals or great changes in wind direction in the upper air; (*e*) wind in the upper air blowing away from centres of low pressure. In the types represented by these five classes the wind in the upper air has been compared with that on the surface. A consideration of the higher ascents has shown that the strongest current is as a rule to be found in the region just below the stratosphere. This rapidly moving current must be associated with a corresponding pressure distribution in that region. Recent researches[1] have tended to show that it is there that changes of pressure originate, and from this point of view the layer just below the stratosphere must be regarded as controlling the conditions throughout the atmosphere beneath. The transference of the supposed seat of action from the surface to the region of nine kilometres suggests that variations in the currents in the layers beneath might with advantage be referred to the conditions prevailing at the time at the nine kilometre level instead of to those at the surface. This method of looking at the results of the ascents was suggested to me by Dr W. N. Shaw when this book was already in type. An examination of the cases which are represented by diagrams at the end of the volume shows that the method would greatly simplify the systematic representation of the atmospheric stratum between the surface and the region in question. Starting with a strong Westerly wind under the stratosphere we find almost without exception that the Westerly wind falls off in the lower levels, and the falling off may proceed continuously to such an extent that the direction

[1] See W. H. Dines, F.R.S., "Statical Changes of Pressure and Temperature in a Column of Air that accompany Changes of Pressure at the bottom," *Quart. Journ. Royal Meteorological Society*, vol. XXXVIII. p. 41; and letters in *Nature*, vol. LXXXVIII. p. 141 by Dr W. N. Shaw, F.R.S., and p. 175 by Mr W. H. Dines.

of motion is reversed at some point in the intermediate layers, so that near the surface an Easterly wind is shown instead of the Westerly one of the upper regions. Even if the intermediate layers themselves provided no variation in the distribution of pressure that would affect the velocity we should expect the strength of the current to be diminished in the lower layers because the density there is greater than in the higher regions, and the velocity corresponding to the pressure gradient transmitted from above would be less in the inverse proportion of the density; on this ground alone the wind velocity near the surface would be reduced to about one-third of the velocity at nine kilometres. But in the cases considered it will be evident that the diminution in the Westerly wind is at a greater rate than the increase of density, and the additional decrease must be due to pressure distribution accruing in the lower layers. Actual reversals are accounted for by representing the additional decrease as a superposed Easterly wind originating from pressure distribution in the lower layers which is sometimes so great as to show a wind at the surface in a reversed direction. The gradual modification of the gradient with increasing depth below the nine kilometre layer could easily be accounted for by a distribution of temperature in the layers underneath such that the air to the North is always colder than the air to the South, that is to say by assuming a distribution of temperature that corresponds with the latitude. The more rapid reversals on special occasions would thus be accounted for by a fall of temperature from South to North greater than the average. It will be seen that from this point of view the reversal of the air current implies no discontinuity in the atmosphere below the nine kilometre level, the change from West to East taking place gradually throughout the whole thickness.

This result is of general application in all the high ascents either as a decrease of the Westerly wind as described, or in some cases as an absence of decrease of an Easterly wind if such should exist at the nine kilometre level, when the decrease of velocity due to the density as the surface is approached is balanced by the increase due to the pressure distribution in the lower layers. This effect of the lower atmosphere in producing an Easterly component of the wind which is stronger the nearer to the surface is quite in accord with the calculations of M. Teisserenc de Bort of an average Westerly circulation in the four kilometre level modified as regards the lower layers by the distribution of temperature.

Similarly regularity is not apparent as regards the winds from North and South, and the recognition of this fact has led, on Dr Shaw's suggestion, to an examination of a number of the ascents by the analysis of the wind at each level into a West-East component and a South-North component. This process has simplified the classification of the ascents in a remarkable manner. It appears that the structure of the atmosphere as disclosed by all the high ascents can be represented as regards the West-East component by the gradual development of an East-West component increasing continuously as the surface is approached, and doubtless due to the temperature distribution in latitude. As regards the South-North component the effect of the lower layers is to alter the velocity by the continuous addition of a component which may be from the North or from the South according to circumstances. The South-North component shows a decrease of intensity as the surface is approached but there is no differentiation between the effect of the lower layers such as that shown by the West-East component. Thus the variation in the Northerly and Southerly winds depends on meteorological conditions which may show effects in opposite directions on different occasions. The effect of the layers beneath the nine kilometre level may be seen in the ascent for Nov. 6th, 1908, when the West-East component at nine kilometres was 11 metres per second; the effect of the superposed East-West component due to the lower layers was to reduce the velocity fairly regularly till at 3·5 kilometres the West-East component was balanced by the East-West component; at lower layers there was a reversal and at one kilometre above sea level the East-West component was 13 metres per second, or perhaps it is clearer to say that the West-East component was − 13 metres per second. At the same time the South-North component had increased from − 5 to + 9 metres per second. On Oct. 1st, 1908, the West-East component decreased from + 11 metres per second at 9 kilometres to − 1 at 4 kilometres, below which however the decrease was not maintained; the South-North component decreased from 18 to 13 metres per second, the decrease continuing down to the ground level. One more example may be given, Sept. 15th, 1911, an ascent not elsewhere discussed in this book; the West-East component decreased from + 32 metres per second at 9 kilometres to − 8 at 1 kilometre while the South-North component decreased from + 12 to − 10 metres per second.

The gradual increases which are here described may be distinguished from the occasional increases of velocity locally at different times at various levels which appear as protruberances on the curve of relation of velocity of the several components with height. With these localised disturbances may probably be grouped the remarkably rapid variations with velocity shown in the lower layers on some of the occasions when the balloon was lost to sight on account of clouds at a comparatively low level. For these disturbances no explanation is offered for the present.

The foregoing considerations which did not suggest themselves till this book was already in type should be born in mind in Chapter IX which deals with the relation of vertical wind distribution to the distribution of pressure at the surface.

The subject of the wind in the stratosphere forms the subject of a separate chapter. It is quite clear that when a balloon enters this region it meets with winds of much smaller intensity than those traversed below this level. With Westerly, Northerly, and Southerly winds the stratosphere wind as far as has been observed remains more or less the same in direction as the winds in the lower strata, though with greatly decreased velocity; but when Easterly winds are found in the layers immediately below the stratosphere the wind in that region exhibits curious fluctuations; the balloon trajectory traces out loops as though spiral motions were met with. Since the observations dealt with in this book were concluded several more balloons have been observed till they were well within the stratosphere, and these observations fully bear out what is herein recorded.

When the balloon enters the stratosphere the West-East component decreases, as also however do the South-North or North-South components; a decrease in the West-East component would be occasioned if the air at this level were colder to the South than to the North, that is if there were a temperature gradient in latitude in the reverse direction to that at the surface; this is probably the case; observations in low latitudes by M. Teisserenc de Bort and Professor A. Lawrence Rotch have shown that at heights above nine or ten kilometres the temperatures in the low latitudes are lower than the temperatures at corresponding heights in higher latitudes.

At the end of the book will be found two tables; the first gives a list of the 200 ascents in order of date with the greatest height to which the observations were carried in each instance, to what class each ascent belongs, and the distance of the point of fall where this is known. The second table commencing on page 84 gives the wind velocity and direction for each ascent for every half kilometre of height, and at the beginning of each ascent will be found the gradient velocity and direction in all cases when the gradient was sufficiently definite for this to be calculated. I have to thank Mr R. Corless and Mr R. G. K. Lempfert, members of the staff of the Meteorological Office, for kindly giving me the necessary information about the gradient wind at the times of the balloon ascents.

After the tables will be found 24 diagrams giving the wind velocity and direction plotted against the height for certain typical or interesting ascents, together with weather maps showing the isobars and the velocity and direction of the wind at the surface, information which was taken from the Weekly Weather Report of the Meteorological Office. Diagrams showing the variation of the wind with height have been prepared for all of the 200 ascents, but it was not found practicable to reproduce more than those that appear at the end of this book.

Throughout the work metres and kilometres are employed for heights and distances, and metres per second for wind velocities. The direction of the wind is given in degrees from the North point, so that an East wind is 90°, a South wind 180° and so on. The use of metric units has been adopted because they are used by the International Commission for Scientific Aeronautics, it being of great importance that observers in different countries should use the same units. In the case of atmospheric pressure the English unit of inches of mercury has been retained because the information concerning the pressure distribution at the times of the ascents has been taken from the publications of the Meteorological Office.

The investigation of the upper air by means of pilot balloons is a somewhat lengthy process, and involves a considerable amount of tedious calculation, which can however be much lightened by the use of the slide rule and mechanical calculators. Apart from all other work the plotting of the trajectories of the 200 ascents has involved the solution of some 8000 triangles.

The investigations were undertaken and this book was written at the suggestion of Dr W. N. Shaw, F.R.S., to whom my grateful thanks are due for introducing me to a most interesting field of study and for his invaluable help both in the course of the investigations and in the writing of this volume. He also kindly supplied me with the diagrams of surface pressure in Figures 32, 33, 35, 37, 39, and 40. I must also express my indebtedness to Mr W. H. Dines, F.R.S., who has helped me in a number of ways; without his unfailing assistance I should hardly have begun researches on the upper atmosphere. For the preparation of the diagrams that appear at the end of the volume I have to thank Miss Humphreys, a member of the staff of the Meteorological Office.

C. J. P. C.

DITCHAM PARK,
PETERSFIELD.
2 *April*, 1912.

CONTENTS

LIST OF ILLUSTRATIONS

CHAPTER I

The Structure of the Atmosphere as disclosed by the Observations of Pilot Balloons at Ditcham

This book gives the results of 200 observations of pilot balloons or ballons sondes. The process of observation consists in watching the progress of small balloons as they rise through the air and are carried along by the winds. The majority of the observations were made at Ditcham in Hampshire, on the southern slopes of the South Downs. Fourteen ascents in May, 1907, were made at Totland Bay in the Isle of Wight, and two, on July 1st, 1907, at Chobham Common.

From the observations the height and horizontal distance of the balloon are computed, generally from minute to minute, by methods which will be described and discussed.

The purpose of the investigation is to determine whether the wind in the upper air is the same in direction or velocity as that at the surface, and to form a numerical estimate of the deviations that are observed. If we regard the air as composed of a series of horizontal layers or strata each with its own special wind velocity and direction at the time of observation, it is evident that the balloon rising with approximately steady upward motion will be carried along first by the surface current, and subsequently by the currents in the successive layers. We may suppose without inaccuracy that very little time is lost in adjusting the velocity of the balloon to the flow of the air current in which it happens to find itself at any moment, because the whole mass of the balloon is quite trifling compared with the forces that would be required to hold it against a flowing current of air; and we are therefore justified in assuming that the horizontal distance traversed in any minute represents the average velocity of the layer passed through by the balloon in its journey aloft during that minute. Thus the horizontal velocities of the air in successive layers may be regarded as given by the observations. The thickness of the layers traversed in successive minutes depends upon the rate at which the balloon is ascending. In many cases this has been assumed to be uniform, and reasons will be given for considering that this assumption is sufficiently nearly justified for the results to be relied upon as giving at least a general representation of the true motion of the atmosphere in successive layers.

For the sake of uniformity the heights in the atmosphere will be given in kilometres, and for general purposes we shall consider the atmosphere as made up of a pile of layers each a kilometre in thickness. The highest of the observations deal with a pile of 18 such kilometre layers, which took 80 minutes or more to observe, but the large majority were much less thick. In some ascents only one or two kilometre layers were traversed, but a large number included five kilometre layers.

On each occasion the balloon was watched until one or other of the following events happened; either the balloon became invisible because it entered the clouds, or it was seen to burst and begin a precipitate descent, or it became so small that the observer was no longer able to identify the speck in the telescope. Sometimes this last event happened in consequence of the gradual diminution of the speck beyond the power of the eye to identify it, and on other occasions the observer after taking his eye from the telescope could not again find the speck. Sometimes in hazy weather the balloon was lost to sight when, had it been clear, its diameter would have been easily discernible.

A large number of the ascents were made in the evening, as at that time the convection movements due to the heating of the ground by the sun's rays no longer interfere much with the uniform ascent of the balloon; moreover the haze, which was found to interfere with the observations during cloudless days, was less at that time than at an earlier hour; it was also found that near the time of sunset, when the sky was becoming less bright, the balloon illuminated by the sun's rays became very easy to see at long distances; in some cases a balloon was watched for many minutes after the sun had set on the earth's surface, the balloon shining brightly and looking like a planet seen through a telescope; on one occasion a balloon was seen to burst under such circumstances at a horizontal distance of about 40 miles. The time of sunset was also convenient because it corresponded nearly with one of the hours of observation for the Daily Weather Report of the Meteorological Office.

The heights reached, and in many cases the immediate cause of the termination of the experiment, are given in the general table of results.

It will be understood from this description of the mode of procedure that from each ascent one can form a mental picture of the successive currents of air traversed by the balloon in its journey. It is true that the geographical position of the balloon will be different for each minute, but these differences are so small compared with the extent of the atmospheric current that the variation in position may be disregarded; and as a general rule we may regard the position of the successive currents as applicable to the atmosphere immediately above the observer at the time of the commencement of the ascent.

The mental pictures thus obtained of the succession of air currents which constitute the structure of the atmosphere over the observing station are of the most varied and sometimes of the most complicated character. In order to enable the reader to carry with him an idea of the sort of structure which may be disclosed by the observations of a pilot balloon the various features have been classified according to some prominent characteristic which is easily recognised in the diagrams representing the results of the ascents.

A further note must be made before proceeding to consider the different types of structure which have been disclosed by the observations. The wind close to the surface is influenced by the shape of the ground and other obstacles from which the upper layers are free. Hence the variations close to the surface are often of a specially complicated character having little relation to the structure of the atmosphere as a whole. Generally speaking the wind increases from its surface value in direct proportion to the height above sea level (see Chapter IX), with some little veer in direction until a height of between half a kilometre and a kilometre is reached. Thereafter the effect of the surface may be regarded as no longer applicable. The surface wind is accordingly a very unsatisfactory datum to which to refer the variations in the upper air. Generally speaking the wind gradually approximates to that computed as the "gradient wind" (see page 32) from the distribution of pressure at the surface. In many ways the gradient wind is a better datum than the observed surface wind and it has been noted in the tables and marked on the diagrams whenever a reasonably satisfactory computation could be made. In some cases however the distribution of pressure in the neighbourhood of the station is too irregular and too ill-defined for a satisfactory computation of the gradient wind to be made.

With this explanation we proceed to refer to some of the principal types of structure of the atmosphere which a study of the diagrams has disclosed. It must be remembered that they are necessarily limited to the occasions when balloons can be followed with a telescope. These are generally occasions of clear weather. During rain, or when there is fog or low cloud, observations are not possible.

The figures that follow are taken from cardboard models prepared to show the distribution of wind direction and velocity with height. Each card shows by its direction and length the wind direction and velocity at each kilometre of height[1]. In general the light coloured cards represent winds from between 300° (W.N.W.) through North to 120° (E.S.E), that may be supposed to come from polar regions; the dark cards winds from 120° through South to 300°, that may be supposed to come from equatorial regions. This classification is only approximate, since it is evident that, for example, a Northerly wind at the station may be a current of air that has been drawn from an equatorial region, but has curved round and passes over the station from a Northerly direction.

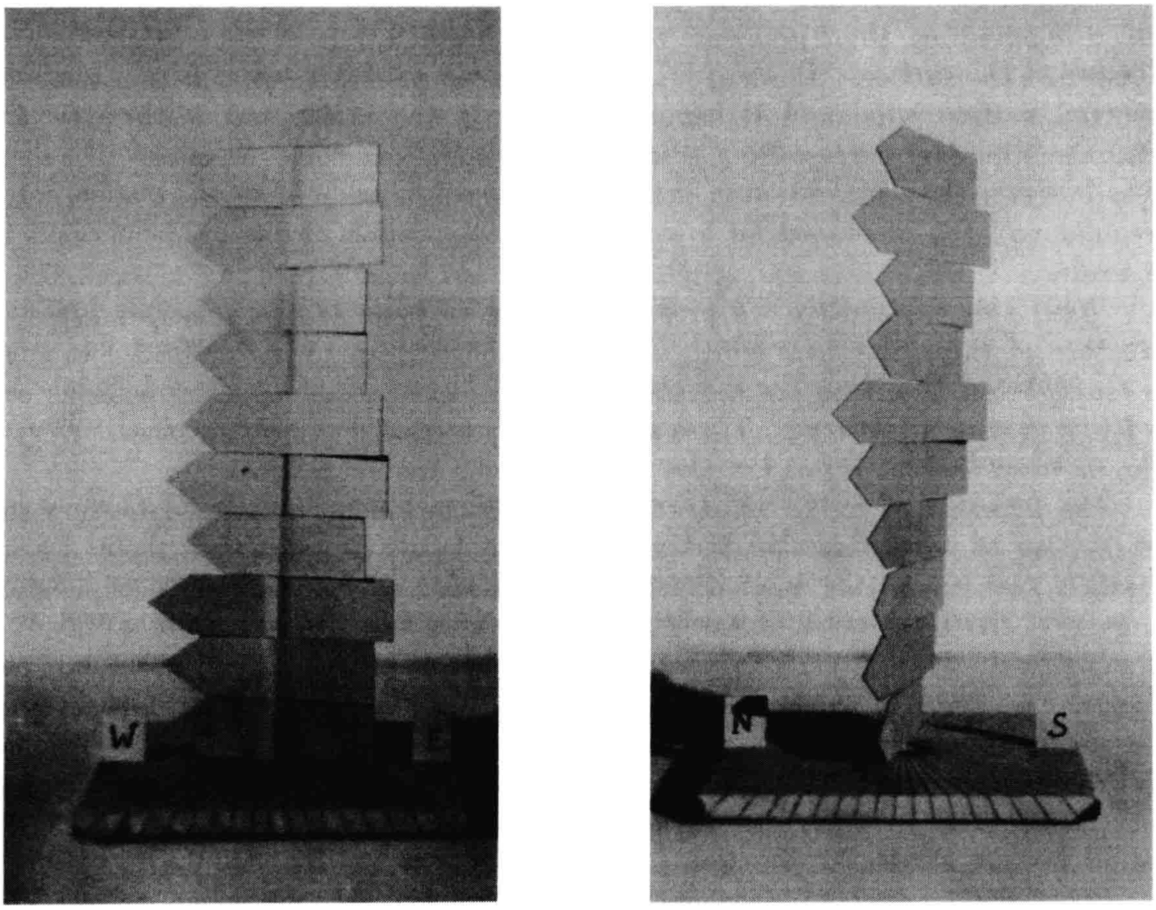
(*a*) "*Solid*" *current*. The first characteristic type is that which we may call the "solid" current, that is to say that after the interference of the surface has been passed, and the gradient velocity approximately reached the wind remains steady both in direction and velocity in the upper layers. This case is illustrated by the diagram representing the result of the ascent on May 5th, 1909 (Fig. 1).

(*b*) Continued increase of velocity beyond that of the gradient wind. In some cases it is possible to explain the increase of wind velocity by the change in the distribution of pressure in the upper layers without any discontinuous change in the air supply by reference to the distribution of pressure and temperature on the surface. Often however no such explanation is evident. These cases are illustrated by the results of ascents on Sept. 1st, 1907 and Oct. 1st, 1908 (Figs. 2 and 3).

[1] The arrow-head flies with the wind.

(*c*) Decrease of velocity in the upper layers. In this case after the gradient velocity has been reached the velocity falls off showing that the regime indicated by the surface pressure is over, and a new distribution commences, arising so far as we know from causes unrelated to the surface conditions. Sometimes the new regime is itself indicated by the observations at higher levels; not infrequently the observations had come to an end before the conditions in the higher levels were disclosed. This class is illustrated by the result of the ascent on May 7th, 1909 (Fig. 4).

(*d*) Reversals, or great changes of direction in the upper layers. Reversals of



a *b*

Fig. 1. Model representing the vertical wind distribution on May 5, 1909, 6.43 p.m. Class (*a*).
a. From South side. *b*. From West side.

direction are nearly always preceded by the falling off of the velocity to a light air. These cases may therefore perhaps be regarded as a continuation of ascents similar to those of class (*c*) if it had been possible to continue the observations. In these cases we see the superposition of distinct systems of currents without any specific relation between them that can be accounted for by a knowledge of surface conditions. This class is illustrated by the result of the ascent of Nov. 6th, 1908 (Fig. 5).

(*e*) Upper wind blowing out from distant low pressure centre; frequent reversals in the lower layers. A number of cases present themselves in which the