MANUAL OF METEOROLOGY

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VOLUME II

COMPARATIVE METEOROLOGY

BY

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TO

THE DIRECTOR OF THE METEOROLOGICAL OFFICE

Sir George Simpson, K.C.B., F.R.S.

this volume is gratefully inscribed

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PREFACE TO THE FIRST EDITION

FROM the study of Meteorology in History as set out in the introductory volume of this Manual the conclusion was arrived at that the primary need of the science was a sufficient knowledge of the facts about the atmosphere in its length and breadth and thickness to furnish a satisfactory representation of the general circulation and its changes. The present volume is intended to provide the reader with the means of making himself acquainted with the nature and extent of the material which is available for satisfying that need. In the first place the normal general circulation and its seasonal changes are represented by maps, tables and diagrams, with references to the original sources for further details. Next the transitory changes are dealt with, first by considering the results of the purely arithmetical methods of chronology, periodicity and correlation, and secondly by the results of the graphic methods of the weather-map in combination with the autographic records of the meteorological observatory. Incidentally we should like to call attention to remarkable evidence of the effectiveness of the maps in the case of pressure, notwithstanding their small size. It will be found on p. 213.

The tables and diagrams which are added to supplement the information contained in the maps are only samples of many possible compilations. Their number and extent are necessarily limited by the considerations which control the size of the volume. In so far as those tables and diagrams are successful they will recall the suggestion of the preface to the first volume, of an encyclopaedia or dictionary which would embody information of that character for all parts of the world. If each year a part were brought up to date the whole would constitute a permanent work of reference to which a student could turn for information now accessible only to the few privileged persons who live within easy access of a meteorological library. The advantage of some provision of that kind will be apparent to the reader who notices the discontinuous and unceremonious introduction of certain information in the form of supplementary tables. At the last moment they seemed indispensable as additions to material which had already been included in the text, and room had to be found for them.

The maps of normal distribution, which form the original foundation of the whole work, are reproduced from blocks prepared by the Cambridge Press under the supervision of the late Mr J. B. Peace. The original drawings were made for me in the Meteorological Office during the years 1919 and 1920 by the late Mr Charles Harding and Dr C. E. P. Brooks.

The incorporation of these charts into the body of what is intended to serve as a text-book would not have been possible without the initiative enterprise of Mr Peace and the skilful management of the material by his successor, Mr Lewis, and the staff of the University Press.

For further help of various kinds in relation to the illustrations I make the following grateful acknowledgment:

To His Majesty's Stationery Office for permission to reproduce Figs. 4 (inset), 5, 6 Ice in the N. Atlantic and in the Southern Ocean, 55 Curves of normal conditions in the upper air of England, 156, 161–2 Wind-roses of the equatorial belt, 181 Diurnal variation of wind at St Helena, 184 One hundred years' rainfall over London, 198 Waterspouts (Capt. J. Allan Mordue), 205 Isanakatabars (Solar Physics Observatory), 207 and 213 Meteorograms of British observatories, 208 Meteorogram for July 27, 1900, and 209 Embroidery of the barogram August 14–15, 1914. Fig. 216 Early life-history of a secondary, and the entablatures of pp. 244 and 246 are redrawn from the *Life History of Surface Air-Currents* and Fig. 217 from *The Weather Map*.

To the Lords Commissioners of the Admiralty and the Astronomer Royal for the charts of magnetic elements Figs. 9 and 10.

To the Meteorological Office for the original copy for Fig. 3 Influence of orographic features on weather, 12 and 13 Thunderstorms, 15 Weekly weather, 182 Wind-velocity at the Eiffel Tower and the Bureau Central, 185–8 Quarterly weather, 217 Weather in relation to the centres of cyclones, also blocks for Fig. i Temperature scales, and Fig. 60 Glass models of temperature July 27 and 29, 1908.

To Professor H. H. Turner and Mr J. J. Shaw for permission to reproduce Fig. 7, Earthquakes.

To Dr S. Fujiwhara for details of the distribution of Japanese volcanoes incorporated in Fig. 8.

To Dr W. J. S. Lockyer for the original unpublished charts from which Figs. 204 and 206 have been prepared.

To the Royal Meteorological Society for Figs. 61, 62, 210, 211, 212 and 214.

To the Scottish Geographical Society for the block of Fig. 163.

To the Royal Society for permission to reproduce Colonel Gold's article on "Forecasting," from the Catalogue of theSociety's exhibit in the British Empire Exhibition 1924, and to Colonel Gold for his concurrence in that permission. Also, with the permission of the Society, we have made use of the diagram of Electro-magnetic-waves in *Phases of Modern Science*.

To the Royal Astronomical Society and to Mr J. H. Reynolds for photographs of Jupiter, pp. 169–171.

To Dr J. Bjerknes for the stereo-photograph of his model of the circulation of a cyclone (Fig. 219).

Other borrowings are acknowledged in the text with equal gratitude; and foremost among my obligations I must regard that to the authors of *Les Bases de la Météorologie dynamique* from which I have ventured to take several illustrations.

The maps of the distribution of pressure over the Northern and Southern Hemispheres for February 14, 1923 (Figs. 189, 190), were prepared for the International Commission for the Exploration of the Upper Air. In a different form they have appeared in a folio of charts of the distribution of pressure over the globe on the international days of the year 1923 for the illustration of a specimen volume of the results of the observations of the upper air of that year. Thirty-six days are represented in the volume which was presented to a meeting of the Commission held at Leipzig at the end of August 1927 with the title *Comptes rendus des jours internationaux*, 1923. The maps are believed to be the first examples of synchronous charts of pressure for the whole globe.

I am again indebted to Captain D. Brunt and Commander L. G. Garbett, R.N., for the reading of the proof-sheets and for valuable suggestions of various kinds.

Finally I am indebted to the Meteorological Office for Miss Elaine Austin's continued assistance.

Prefixed to the text of this volume is a collection of definitions of quantities and ideas which are often employed or referred to in meteorological literature and may be wanted in the reading of this book.

The volume concludes as the previous volume did with a summary chapter on the atmosphere, but in a form which may be unfamiliar to the reader. Certain assumptions, principles and conclusions are set out in very definite wording, and in the scholastic manner, so that they may challenge assent or dissent. The chapter forms, in fact, the brass plate, bell-pull and knocker of the house which is to be represented by the remaining volumes.

NAPIER SHAW

November 4, 1927

PREFACE TO THE SECOND EDITION

In the eight years that have elapsed since the completion of the original volume many notable additions have been made to the information available for a meteorological gazetteer of the world. On the table adjoining that on which I am writing is a collection of data for the upper air which covers 196 pages for 1923, 185 for 1924, 1058 for 1925, 1228 for 1926, 1674 for 1927 with a volume of 140 pages for one country for 1932.

A complete revision of the presentation of meteorological data from the point of view of 1935 instead of that of 1927 is not possible. The effort has been limited to correcting errors and omissions, substituting new figures in place of Nos. 43–4, 57–9, 72, 184–8, 192, and, at the end of the volume, a chapter of notes in place of the "New Views about Cyclones and Anticyclones" and the forty-five articles of the syllogistic summary of conditions of the middle atmosphere.

For additional information as to matters to be added in the supplement we are indebted to many colleagues, to Col. Gold, Dr Whipple, Mr R. Corless, Prof. Brunt, Capt. Garbett, Dr Brooks and Miss L. D. Sawyer, to Dr C. W. B. Normand and his colleagues of the Indian Meteorological Department, to Mr D. C. Archibald of the Canadian Service and to Prof. F. Eredia of the Italian Aeronautical Department.

And to the Director of the Meteorological Office for Miss Austin's assistance in the revision of the volume.

NAPIER SHAW

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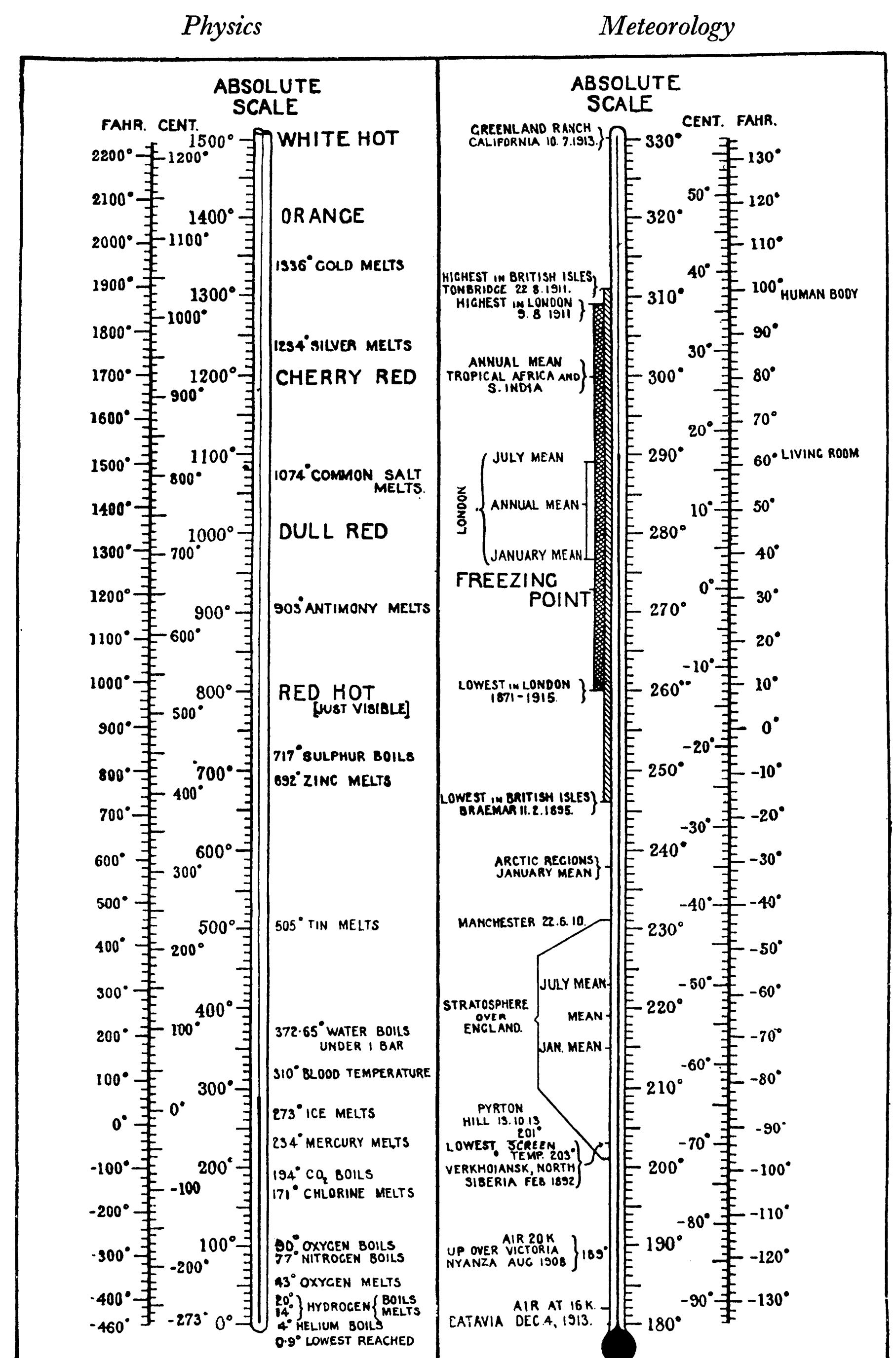


Fig. i. Comparison of the absolute scale of temperature with the Fahrenheit and Centigrade scales. Extreme and mean air-temperatures, and a selection of physical thermometrical constants. From *The Weather of the British Coasts*, M.O. 230, London, 1918. The "lowest reached" at Leiden is now ·08 (July 1933).

DEFINITIONS AND EXPLANATIONS OF CERTAIN TECHNICAL TERMS

Absolute: a word that is frequently used with respect to temperature to indicate the graduation of a scale of temperature which is independent of the nature of the "thermometric substance." Thermometers based upon the expansion of solids or of liquids or gases in glass enclosures are not expected to agree exactly all over their scales although they may be constructed to agree at any two fixed points. An absolute scale can be made out in various ways as, for example, by the saturation pressure of vapour of a liquid of known composition; but a better known way of arriving at an absolute temperature is an indirect one based upon the thermodynamic principles of the relation between heat and work. A gas-thermometer of constant volume gives a very close approximation to the absolute scale; and a thermometer with a perfect gas as thermometric substance, agreeing with the absolute scale at two points, would agree throughout the range. Hence a hydrogen-gas-thermometer is the medium by which a practical realisation of the absolute scale is arrived at. If the freezing-point of water be taken as 273 on the absolute scale, and the boiling-point of water under standard pressure as 373, the position of the absolute zero is found to be 273·1 below the freezing-point of water.

At the absolute zero the hydrogen of a gas-thermometer would have no pressure, water or any other liquid would have no vapour-pressure, and the limit of conversion of heat into work would have been reached. It has therefore been regarded hitherto as unattainable; and from the point of view of measurements is theoretical, though temperature has been carried down to ·08 absolute, 273·02t below the freezing-point.

The readings of a well-made mercury thermometer, such as those used at meteorological stations, differ little throughout the range of meteorological measurements from the absolute scale of temperature counting 273 as the freezing-point of water and 373 as the boiling-point. Consequently it is customary to convert the meteorological centigrade measurements of temperature into "absolute" temperature by adding 273. That does not give, strictly speaking, the absolute temperature, though it is near enough for meteorological purposes. In this work we avoid the inaccuracy by calling the centigrade reading increased by 273, the tercentesimal temperature, with the symbol tt; but we use the resulting figure in formulae based upon absolute temperature, generally without correction, because the difference is too small to be of importance.

Adiabatic: a compound Greek word meaning "no road" or "impassable." It is applied to a gas or liquid which being enclosed in a cylinder or other environment (q.v.) is subject to changes of pressure and consequent changes of temperature when the environment is such that no heat can pass either way across the boundary between the substance operated upon and its surroundings.

In a laboratory under ordinary experimental conditions adiabatic changes cannot be examined because there the thermal isolation of the substance operated on is far from complete. Heat flows more or less freely between the substance and its environment to make up for any loss or gain of temperature due to rarefaction or compression; and the conditions approximate more nearly to those known as isothermal (i.e. of the same temperature) than to the adiabatic (i.e. no heat transference). In order to approximate to adiabatic conditions the operations must be within the limits of the protected enclosure of a vacuum flask, or the changes must be very rapid and the observations correspondingly quick.

But in the free air when a very large volume of air is undergoing change of pressure the exchange of heat across the boundary is small and has no immediate effect upon any part of the mass except that quite close to the boundary. The only way in which the internal mass of free air can lose heat or gain it is by radiation from or to those of its constituents which are capable of emitting or receiving radiation: this effect is so small that it is customary to regard even slow changes of pressure in the free atmosphere as operating under adiabatic conditions.

The word "adiabatic" is also used as an abbreviation for adiabatic curve which shows the relation between the pressure and temperature of a mass of air when the adiabatic condition is rigorously maintained. The curves are derived by computation from other known properties of air, not (up to the present) from direct observation. Two sets of adiabatics have been computed, namely dry adiabatics, applicable to those changes which do not cause the air operated upon to pass below its point of saturation, or dew-point, and saturation adiabatics that are appropriate to air which is always saturated, any changes of pressure being associated with evaporation (if the air is compressed) or condensation (if the air is expanded) so that the condition of saturation is always maintained.

Such curves are often called **isentropic** because what is called the "entropy" of the substance cannot change when the conditions are adiabatic. Isentropic is contrasted with isothermal as representing essentially different conditions connected with the transformation of heat into mechanical energy. If a gas is working against its environment under isothermal conditions the energy which is transformed is derived from, or carried to, the environment; but if the conditions are isentropic the energy transformed is derived entirely from the heat-store of the working substance itself, at the sacrifice of its temperature. If atmospheric air were homogeneous the word "isentropic" would be as applicable as adiabatic; but, in consequence of the peculiar properties of water-vapour and the latent heat which it contains, saturated air can make use of the latent heat of water-vapour to carry out its work instead of drawing entirely upon its own supply; it saves thereby some of the loss of temperature which would be inevitable if the air were not saturated. Adiabatic, as expressing the condition with reference to environment, is in consequence a more useful term than isentropic; the latter refers to the substance under operation, which can change its composition during the operation.

Aerology: a word that has been introduced to denote the modern study of the atmosphere, which includes the upper air as well as the more conventional studies which have been connoted by the older word "meteorology." Sometimes it is used as limiting the study to the upper air. In like manner **Aerography** is a modern word for the record of the structure of the atmosphere and its changes.

Altimeter: an aneroid barometer which is graduated to read "heights" instead of barometric pressure in millibars or inches or millimetres of mercury. The word height in this case is necessarily used in a conventional sense because the instrument is actuated by pressure alone (with possibly some influence of temperature and mechanical lag) and the height is not determinable by observing change of pressure alone, but requires also a knowledge of the density of the air between the ground-level and point of observation.

There is a good deal of laxity about the use of the word height, of the same kind as that of the aeronauts who graduate a pressure-instrument to read what they call height. For example, V. Bjerknes and others would express the height of a point in the atmosphere by the geopotential at the point, calling the quantity expressed the dynamic height. We reproduce an extract from the *Avant Propos* of the *Comptes rendus des jours internationaux*, 1923.

"The relation of the geopotential Γ at any position to the geometric height of that position h and the gravitational acceleration g is $\Gamma = \int g dh$. The value is governed accordingly by the local value of gravity depending on the attraction of gravitation and the rotation of the earth; but not to any appreciable extent upon the condition of the atmosphere at the time of observation. We will refer to this measure for the time being as the geodynamic height. The dimension of its measure in the absolute system of units is l^2/t^2 and the special unit employed by Bjerknes is represented by 10 m²/sec².

"There are, however, other ideas in meteorological practice which may be associated with the word *height* and which are useful in their several ways, although they depend upon the state of the atmosphere. They refer to the pressure, specific volume of air, and entropy of unit mass of air (potential temperature or megatemperature[1]) respectively. The association of these ideas with height is based upon the fact that the atmosphere cannot be in equilibrium unless the rate of change of pressure with height is negative, the rate of change of specific volume with height is positive and the rate of change of entropy or potential temperature or megatemperature is positive.

"We may consider these several ideas of height in turn.

1. *Surfaces of equal pressure, isobaric levels expressed by the equation* $p_0 - p = \int g\rho \, dh$.

It is in this manner, by universal practice, that altimeters are graduated for determining the height attained by aircraft. What is actually indicated on the instrument is pressure but it is read as height. The height expressed in this manner is also 'dynamic' and might by analogy be called the *barodynamic height*; its dimensions are mass divided by length and the square of time and its unit on the C.G.S. system is gramme/(centimetre second²).

2. *Surfaces of equal specific volume: the isosteric surfaces of Bjerknes* (*or of equal density: isopycnic surfaces*). The expression of height by means of this measurement might be called the *elastic height*, the dimension of its measure on the absolute system is length³/mass and the unit in the C.G.S. system is cm³/gramme. These surfaces form the correlative of the isobaric surfaces in the dynamic representation of the atmosphere.

3. *Surfaces of equal entropy or potential temperature.* These surfaces are determined by the temperature of the air and its pressure (as the surfaces of equal specific volume are) but the measure is arrived at by expressing the temperature which would be attained if the pressure were increased from its local value to a standard pressure. As a standard pressure the estimated mean pressure at sea-level, 760 mm of standard mercury, has often been used and is sometimes so defined. Our instructions in the règlement of the Commission are to use a pressure of 1000 millibars as the standard and we therefore need a special name for the potential temperature with that pressure as standard. We have adopted 'megatemperature' as a suitable name because the measurement is given as temperature with a megadyne per square centimetre as standard pressure; the name will, therefore, automatically remind the user of the standard employed. The 'height' connoted in this manner may be called the 'thermodynamic height'; it is related to the other quantities by the equation

$$T = \int_p^{p_0} \partial t/\partial p \; (\phi \text{ const.}) \, dp = \int_p^{p_0} \frac{\gamma - 1}{\gamma} \frac{t}{p} \, dp.$$

We use this conception of height in the diagrams which are referred to as tephigrams. In the form of entropy (which is proportional to the logarithm of potential temperature) the dimensions of thermodynamic height are (mass × velocity²)/temperature, and its unit on the C.G.S. system is gramme × (cm/sec)² per degree of absolute or tercentesimal scale.

"The idea of height is implicit in the values of p and t. Thus, while the use of the word height without qualification must always be understood to mean the geometrical or geographic height, we could, without much straining of language, speak of the 'geodynamic height,' the 'barodynamic height,' the 'elastic height' or the 'thermodynamic height' of a particular portion of the atmosphere if we wished to lay stress upon the general idea of height which is inherent in the several measures employed."

Amplitude: the extent of the excursion (on either side) of the value of a quantity which is subject to periodic change. (See **Phase**.)

[1] We have learned to prefer megadyne temperature.

Anabatic (ἀνά up, βαίνω I go). A word used to describe the character of a wind which is found flowing up a hill-side in consequence of the warming of the slope by the sun's rays or otherwise: more generally the travel of air upward through its environment. It need not be regarded as related to the distribution of pressure.

"Atmospheric." See **Stray**.

Atmospheric shells. A word is required to denote a layer of atmosphere between two surfaces having some defined characteristic on the analogy of a number of other words, to indicate different and more or less independent layers of the earth's structure: the solid earth is called the *lithosphere*, the water lying upon it the *hydrosphere*, the whole body of air lying upon the two the *atmosphere*, though by derivation the word refers to water-vapour rather than to air. The atmosphere is divided into the *stratosphere* in which convection is not possible and the *troposphere* which is permeated by convection when circumstances are favourable thereto. When circumstances are not favourable and we have a layer of atmosphere which has stability and consequent identity we may call the bounding surfaces thermodynamic surfaces, and the shell a thermodynamic shell; on the other hand, the shell between two surfaces of equal geopotential may be called a geodynamic shell. The *tropopause* is the name given to the boundary between the stratosphere and troposphere; it is not a thermodynamic surface nor a geodynamic surface. A thermodynamic shell which cuts across the tropopause is much thinner in the portion within the stratosphere than in the portion within the troposphere.

Autoconvection: the readjustment of equilibrium in a column of fluid when the density of a lower layer is less than that above it in consequence of the warming of the base or of differences of dynamical cooling (W. J. Humphreys). See **Stability**.

Azimuth (Bearing): a convenient but rather uncouth Arabic word used to indicate the horizontal angular deviation of a more or less distant object from the true North and South line. Bearing is a nautical term which means the same thing, when the bearing is described as "true." In practice the bearing is often given as referred to magnetic North and South. Moreover, bearing may be given in compass points, WSW, N, E, or whatever the point of the compass may be; but azimuth is almost invariably given in "degrees from true North," going round "clockwise." An azimuth of 221°, for example, is 41° past the true South line.

Boiling: a familiar process with water and some other liquids when heated. As temperature rises, by the heating of the vessel which contains the liquid, bubbles of vapour are formed, first at the hottest part of the container. They break away and float upwards to the surface carrying away part of the liquid as vapour. So far as meteorology is concerned the word is sometimes used metaphorically to describe the commotion of the atmosphere which is apparent when celestial objects are seen through a telescope; more frequently perhaps in relation to "boiling-point," by which we are reminded that the temperature at which any liquid boils depends on the pressure to which the surface is subjected by the atmosphere above it. So water boils at a lower temperature on a mountain than in the valley beneath because the pressure is less.

C.G.S.: the initials of Centimetre, Gramme, Second, the fundamental units selected, half a century ago, for the systematic expression of all physical quantities connected with electricity and magnetism, and consequently also all dynamical quantities such as velocity, acceleration, force, pressure, work, power.

The systematic nature of the practice is expressed by calling the series of units based upon the fundamentals centimetre, gramme, second, the C.G.S. *system*.

All the quantities which are used for meteorological measurements are included in the scheme of the C.G.S. system except temperature, and even that comes in when regarded from the thermodynamical point of view; and it would appear therefore that, in so far as the science is to be regarded as systematic, meteorology should come into line with other systematic sciences and join in a common and convenient "system of units."

It is hardly conceivable, but nevertheless true, that large numbers of people, including even scientific people of high distinction, are disposed to regard the use or otherwise of a system of units as a matter to be disposed of by personal habit and convenience, and in some quarters the idea of having to learn what is meant by a centimetre, a gramme and a second, is so appalling as to obliterate all other considerations, even the interests of future generations.

Still it seems probable that the millibar as a systematic unit for pressure will hold its own, and possibly the kilowatt per square dekametre as the unit of strength of sunshine; others may come in time.

Circulation: the displacement of air along lines forming closed curves.

When a solid body forces its way through a fluid medium such as air it has first to push the air in front of it out of the way, and the air at the back will travel after the departing mass to fill the space which would otherwise be left void. We may thus picture to ourselves a series of curves indicating the direction in which the air is moving, away from the body in front, towards it at the back and intermediately leading from the front round to the back.

When the body has a solid boundary and moves rapidly through the fluid the circulation which is set up is confined to the immediate neighbourhood of the moving body. The circulation produced by the passage of a motor-car is a familiar example. The study of such circulations is a part of the important question of the resistance which a fluid offers to a solid travelling through it.

When the moving body is part of the air itself the circulation may be very complicated and may require a very wide range for its completion. A horizontal circulation may extend all round the earth and a vertical circulation may be localised in its ascending part and distributed over a very large area in the descending part that is required to complete it, but it must always be completed and all motion of air through the air must be treated as circulation, not as the motion of a body projected through empty space.

Convection: a Latin word which means simply "conveying" or "carrying": applied to the redistribution of heat in a gas or liquid, it implies that the different parts of the fluid, when readjusting their relative positions, carry their own heat with them.

Thermal convection is the redistribution of heat by the redistribution of mass consequent upon difference of temperature of adjacent masses. In the atmosphere the physical process of convection is complicated by the inevitable fact that the temperature of air varies automatically with its pressure. The law of thermal convection as stated in *Principia Atmospherica* runs as follows: "In the atmosphere convection is the descent of colder air in contiguity with air relatively warmer." The statement is generally appropriate because the motive power is derived from the greater density of the colder air, and the most typical example of convection is the flow of air down the slope of a hill where there is spontaneous cooling by radiation. But by convection meteorologists often have in mind the opposite aspect of the process, viz. the ascent of the warmer air pushed upward, it is true, by the descent of the colder but appearing to rise by its own levity instead of by the gravity of its environment. The ascent of warm air by thermal convection in this way is complicated not only by the automatic response of temperature to change of pressure, which takes place in dry air too, but also by the secondary effects due to the condensation of water-vapour when the pressure is reduced sufficiently.

Ordinarily the relative displacement of warm air in juxtaposition with cold air or *vice versa* is very limited in consequence of the automatic changes of temperature with pressure; but if the rising air becomes saturated the condensation of water-vapour may enable it to penetrate upward beyond the limit for dry air, and in the case of air going downward the journey can be prolonged if heat can be taken from the descending air by the cooled surface. In either of the cases we have examples of **penetrative convection** because a limited mass of air penetrates successive layers above or beneath, as distinguished from the ascent by mere accumulation of warm air in juxtaposition with colder air when the convection is said to be cumulative.

Convective equilibrium: the automatic variation of temperature of air with change of pressure introduces peculiar complications into the question of the equilibrium of successive layers of the atmosphere. A layer of air which is of uniform temperature throughout its depth is not like a layer of water in similar condition. The water is in "convective equilibrium," that is to say any portion may be exchanged for any other equal portion without any further adjustment. But in the layer of air a portion from the bottom transferred to the top would be too cold for its environment and the equal portion from the top brought down in exchange would be too warm. If, however, the successive layers are properly adjusted in temperature, being colder as one ascends by about 1t for 100 metres of height, a portion from any one layer can be exchanged for an equal portion of any other layer (provided the air is dry) without any adjustment. No change of temperature would be observable if the air were mixed up mechanically. The air is then said to be in convective equilibrium or in a "labile" state, provided the air remains unsaturated. Convective equilibrium has also a meaning when applied to saturated air, but it is a much more complicated one.

Corona: the name given to a coloured ring round the sun or moon, or indeed round any bright light, caused by the *diffraction* of the light by particles forming a cloud, if they are sufficiently regular in size. The best example of corona is that formed artificially by interposing in front of a bright light a plate of glass which has been dusted over with lycopodium grains. Each point of light gives its own corona, so that to get a good effect the source should be concentrated as nearly as possible in one point.

Débâcle: the name given to the resumption of summer conditions in rivers which are frozen in winter: a very important seasonal feature in continental countries. The ice gives way irregularly over a long stretch so that the flow of the river becomes blocked; in time the blocks give way suddenly and may produce floods and other disasters in the lower levels.

Diffraction: the secondary effect of large or small obstacles upon a beam of light. When a point of light throws a shadow of the straight edge of an obstacle the margin of the shadow will show colours. If a greasy finger be drawn across a plate of glass and the plate held up to the light there is a brilliant display of colours, like mother of pearl; iridescent clouds and coronas are phenomena of like nature. They are explained by supposing that the light spreads out from a point as a "wave front," and if the uniformity of the front is broken there is a formation of new wave fronts from the edge. A cloud of small particles may remake the front altogether.

Eddy: a word of unknown history. "The water that by some interruption in its course runs contrary to the direction of the tide or current (Adm. Smyth); a circular motion in water, a small whirlpool"—according to the *New English Dictionary*.

Eddies are formed in water whenever the water flows rapidly past an obstacle. Numbers of them can be seen as little whirling dimples or depressions on the surface close to the side of a ship which is moving through the water. In the atmosphere similar eddies on a larger scale are shown by the little whirls of dust and leaves sometimes formed at street corners and other places which present suitable obstacles. The peculiarity of these wind-eddies is that they seem to last for a little while with an independent existence of their own. They sometimes attain considerable dimensions and, in fact, they seemed to pass by insensible degrees from the corner-eddy to the whirlwind, the dust-storm, the waterspout, the tornado, the hurricane, and finally the cyclonic depression. It is not easy to draw the line and say where the mechanical effect of an obstacle has been lost, and the creation of a set of parallel circular isobars has begun, but it serves no useful purpose to class as identical phenomena the street-corner-eddy, twenty feet high and six feet wide, and the cyclonic depression, a thousand miles across and three or four miles high.

The special characteristic of every eddy is that it must have an axis to which the circular motion can be referred. The axis need not be straight nor need it be fixed in shape or position. The best example of an eddy is the vortex-ring or smoke-ring, which can be produced by suddenly projecting a puff of air, laden with smoke to make the motion visible, through a circular opening. In that case the axis of the eddy is ring-shaped; the circular motion is through the ring in the direction in which it is travelling and back again round the outside. The ring-eddy is very durable, but the condition of its durability is that the axis should form a ring. If the continuity of the ring is broken by some obstacle the eddy rapidly disappears in irregular motion.

It is on that account that the eddy-motion of the atmosphere is so difficult to deal with. When air flows past an obstacle a succession of incomplete eddies is periodically formed, detached, disintegrated and reformed. There is a pulsating formation of ill-defined eddies. The same kind of thing must occur when the wind blows on the face of a cliff, forming a cliff-eddy with an axis, roughly speaking, along the line of the cliff and the circular motion in a vertical plane.

Whenever wind passes over the ground, even smooth ground, the air near the ground is full of partially formed, rapidly disintegrating eddies, and the motion is known as turbulent, to distinguish it from what is known as stream-line motion, in which there is no circular motion. The existence of these eddies is doubtless shown on an anemogram as gusts, but the axes of the eddies are so irregular that they have hitherto evaded classification. Irregular eddy-motion is of great importance in meteorology, because it represents the process by which the slow mixing of layers of air takes place, an essential feature of the production of thick layers of fog. Moreover, all movements due to convection must give rise to current and return current which at least simulates eddy-motion. (*Meteorological Glossary*, M.O. 225 ii, Fourth Issue, 1918, p. 90.)

Eddy-viscosity: every liquid or gas has a certain viscosity, or redistribution of momentum with dissipation of energy, in consequence of the relative motion of the fluid on the two sides of a surface of separation within it. If the surface of separation be horizontal, one effect of viscosity is that there is an exchange of molecules across the surface, even if the exchange requires molecules of a heavier fluid to ascend and those of a lighter fluid to descend. If the discontinuity of the motion is sufficiently marked to cause eddies, as it always is between a solid surface and the natural wind, there is an exchange of mass between the surface-layers and the layers above, which follows a law similar to that of molecular viscosity but is five hundred thousand times more effective in causing a redistribution of the mass. The process as thus enhanced is described as eddy-viscosity. The numerical magnitude is dependent upon many conditions such as vertical distribution of temperature, the nature of the surface, whether water or land, and so on.

Entropy: a term introduced by R. Clausius to be used with temperature to identify the thermal condition of a substance with regard to a transformation of its heat into some other form of energy. It involves one of the most difficult conceptions in the theory of heat, about which some confusion has arisen.

The transformation of heat into other forms of energy, in other words, the use of heat to do work, is necessarily connected with the expansion of the working substance under its own pressure, as in the cylinder of a gas engine, and the condition of a given quantity of the substance at any stage of its operations is completely specified by its volume and its pressure. Generally speaking (for example, in the atmosphere) changes of volume and pressure go on simultaneously, but for simplifying ideas and leading on to calculation it is useful to suppose the stages to be kept separate, so that when the substance is expanding the pressure is maintained constant by supplying, in fact, the necessary quantity of heat to keep it so; and, on the other hand, when the pressure is being varied the volume is kept constant; this again by the addition or subtraction of a suitable quantity of heat. While the change of pressure is in progress, and generally, also, while the change of volume is going on, the temperature is changing, and heat is passing into or out of the substance. The question arises whether the condition of the substance cannot be specified by the amount of heat that it has in store and the temperature that has been acquired, just as completely as by the pressure and volume.

To realise that idea it is necessary to regard the processes of supplying or removing heat and changing the temperature as separate and independent, and it is this step that makes the conception useful and at the same time difficult.

For we are accustomed to associate the warming of a substance, i.e. the raising of its temperature, with supplying it with heat. If we wish to warm anything we put it near a fire and let it get warmer by taking in heat, but in thermodynamics we separate the change of temperature from the supply of heat altogether by supposing the substance to be "working." Thus, when heat is supplied the temperature must not rise; the substance must do a suitable amount of work instead; and if heat is to be removed the temperature must be kept up by working upon the substance. The temperature can thus be kept constant while heat is supplied or removed. And, on the other hand, if the temperature is to be changed it must be changed dynamically, not thermally; that is to say, by work done or received, not by heat communicated or removed.

So we get two aspects of the process of the transformation of heat into another form of energy by working; first, alterations of pressure and volume, each independently, the adjustments being made by adding or removing heat as may be required, and secondly, alterations of heat and temperature independently, the adjustments being made by work done or received. Both represent the process of using heat to perform mechanical work or *vice versa*.

In the mechanical aspect of the process, when we are considering an alteration of volume at constant pressure, $p\,(v-v_0)$ is the work done; and in the thermal aspect of the process $H-H_0$ is the amount of heat disposed of. There is equality between the two.

But if we consider more closely what happens in this case we shall see that quantities of heat ought also to be regarded as a product, so that $H-H_0$ should be expressed as $T\,(\phi-\phi_0)$, where T is the absolute temperature and ϕ the entropy.

The reason for this will be clear if we consider what happens if a substance works under adiabatic conditions, as we may suppose an isolated mass of air to do if it rises automatically in the atmosphere into regions of lower pressure, or conversely if it sinks. In that case it neither loses nor gains any heat by simple transference across its boundary; but as it is working it is drawing upon its store of heat, and its temperature falls. If the process is arrested at any stage, part of the store of heat will have been lost through working, so in spite of the adiabatic isolation part of the heat has gone all the same. From the general thermodynamic properties of all substances, it is shown that it is not H, the store of heat, that remains the same in adiabatic changes, but H/T, the ratio of the store of heat to the temperature at which it entered. We call this ratio the *entropy*, and an adiabatic line which conditions thermal isolation and therefore equality of entropy is called an isentropic. If a new quantity of heat h is added at a temperature T the entropy is increased by h/T. If it is taken away again at a lower temperature T' the entropy is reduced by h/T'.

In the technical language of thermodynamics the mechanical work for an elementary cycle of changes is $\delta p\,.\,\delta v$ and the element of heat, $\delta T\,.\,\delta\phi$. The conversion of heat into some other form of energy by working is expressed by the equation

$$\delta T\,.\,\delta\phi=\delta p\,.\,\delta v$$

when heat is measured in dynamical units.

It is useful in meteorology to consider these aspects of the science of heat although they may seem to be far away from ordinary experience because, in certain respects, the problem of dynamical meteorology seems to be more closely associated with these strange ideas than those which we regard as common. For example, it may seem natural to suppose that if we could succeed in completely churning the atmosphere up to, say, 10 kilometres (6 miles) we should have got it uniform in temperature or isothermal throughout. That seems reasonable, because if we want to get a bath of liquid uniform in temperature throughout we stir it up; but it is not true. In the case of the atmosphere there is the difference in pressure to deal with, and, in consequence of that, complete mixing up would result, not in equality, but in a difference of temperature of about 100t between top and bottom, supposing the whole atmosphere dry. The resulting state would not, in fact, be isothermal; the temperature at any point would depend upon its level and there would be a temperature difference of 1t for every hundred metres. But it would be perfectly isentropic. The entropy would be the same everywhere throughout the whole mass. And its state would be very peculiar, for if one increased the entropy of any part of it by warming it slightly the warmed portion would go right to the top of the isentropic mass. It would find itself a little warmer, and therefore a little lighter specifically than its environment, all the way up. In this respect we may contrast the properties of an isentropic and an isothermal atmosphere. In an isentropic atmosphere each unit mass has the same entropy at all levels, but the temperatures are lower in the upper levels. In an isothermal atmosphere the temperature is the same at all levels, but the entropy is greater at the higher levels.

An isothermal atmosphere represents great stability as regards vertical movements, any portion which is carried upward mechanically becomes colder than its surroundings and must sink again to its own place; but an isentropic atmosphere is in the curious state of neutral equilibrium which is called "labile." So long as it is not warmed or cooled it is immaterial to a particular specimen where it finds itself, but if it is warmed, ever so little, it must go to the top, or cooled, ever so little, to the bottom.

In the actual atmosphere above the level of ten kilometres (more or less) the state is not far from isothermal, below, in consequence of convection, it tends towards the isentropic state, but stops short of reaching it by a variable amount in different levels. The condition is completely defined at any level by the statement of its entropy and its temperature, together with its composition which depends on the amount of water-vapour contained in it.

Speaking in general terms the entropy increases, but only slightly, as we go upward from the surface through the troposphere until the stratosphere is reached, and from the boundary upwards the entropy increases rapidly.

If the atmosphere were free from the complications arising from the condensation of water-vapour the definition of the state of a sample of air at any time by its temperature and entropy would be comparatively simple. High entropy and high level go together; stability depends upon the air with the largest stock of entropy having found its level. In so far as the atmosphere approaches the isentropic state, results due to convection may be expected, but in so far as it approaches the isothermal state, and stability supervenes, convection becomes unlikely. (From the *Meteorological Glossary*, M.O. publication, no. 225 ii, H.M. Stationery Office.)

Environment: the material immediately surrounding a mass which is moving or undergoing other physical changes. When the behaviour and motion of a limited portion of air are under consideration the surrounding air forms its environment. There is always action and reaction between the limited mass and its environment which will affect its behaviour and its motion. The behaviour of the mass will therefore be controlled partly by its own condition and changes, and partly by the nature and condition of its environment.

Equiangular spiral: called also **Logarithmic spiral**: a curve described by a point which moves so that every step along its path is at a fixed angle to the straight line drawn from its position to a fixed point which is called the pole of the spiral. The equation of the spiral is $r = ae^{k\theta}$. A circle is a limiting case, being an equiangular spiral of ninety degrees. If the angle between the direction of motion and the radius passing outward is greater than ninety degrees, the point moves along the spiral towards the pole; if, on the other hand, the angle is less than ninety degrees the point goes outward with the radius and takes a widening sweep.

LENGTHS OF ELECTRO-MAGNETIC VIBRATIONS, VISIBLE AND INVISIBLE,

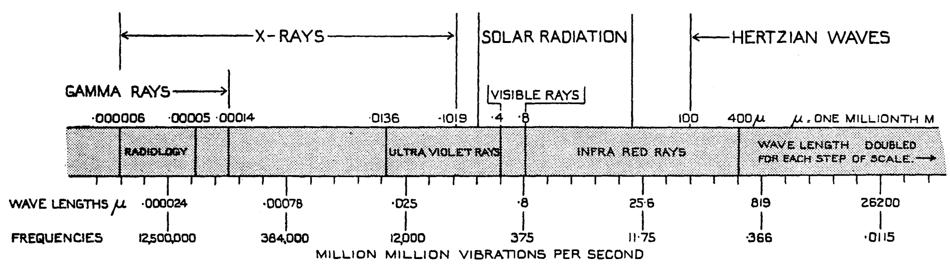


Fig. ii. Exhibiting the relation in respect of wave-length and of frequency of gamma rays, X-rays, ultra-violet rays, visible rays, infra-red rays, Hertzian waves (including

Frequency is employed in meteorology as a means of dealing statistically with non-instrumental observations as of winds from the several directions, gales, snow-storms, rain-days, fogs, etc. It is also extended to instrumental observations as a device for representing climate, for example, the frequency of occurrence of temperatures or relative humidities within specified limits. In this way curves of frequency can be constructed which are one of the implements of the statistical treatment of observations; the greatest ordinate of such a curve, representing the most frequent occurrence within the selected limits, identifies what is called the *mode* for the variation of that particular element.

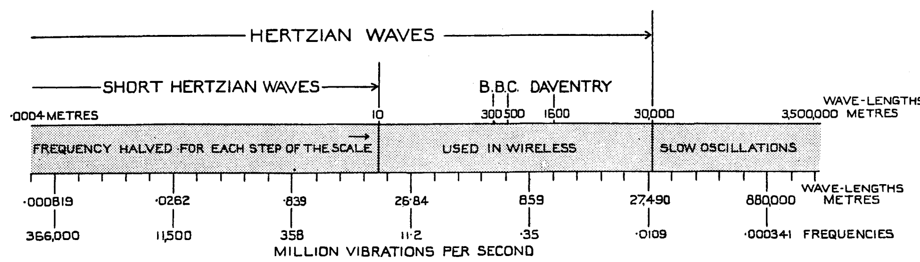
Frequency is also used to mean the number of complete oscillations in a second or other interval, as the correlative of period, with reference to oscillations or vibrations such as those of sound, light or the electrical vibrations of the ether. The period is the time of one complete oscillation; the wave-length the space travelled by the waves in one period. When the frequency is doubled and the period and consequently the wave-length halved the new vibration is said to be the octave of the first. The formula connecting wave-length λ, period of oscillation τ and velocity of transmission v is $v\tau=\lambda$. The methods of generation of the respective groups of waves and the means by which they are detected are enumerated in the diagram in *Phases of Modern Science* prepared by a Committee of the Royal Society for the British Empire Exhibition, 1925. Taking all kinds of vibration of the ether into account they range over sixty octaves. One of them covers the range of vibration of visible light; four cover the infra-red of solar radiation and one the ultra-violet. The rest are produced by electrical radia-

* * *

Friction is a difficult word to deal with from the point of view of meteorology. The idea is derived from the frictional force between two solid surfaces which are made to slide one over the other—a very complicated question in itself. It is extended to the frictional forces between air and the sea or land, and thence to the effect of obstacles on the surface of either, which is not entirely frictional, and also to the interaction of two masses of air moving relatively the one to the other. In the last case molecular diffusion between the two masses comes in under the name of molecular viscosity with accompanying eddy-motion, and that again is complicated by other physical differences such as those of temperature and humidity as between a cold surface-layer and warm upper layer or *vice versa*, which may alter the extent of the interchange so much that the general character is changed. Friction in the atmosphere is indeed a special subject of undoubted importance but of great complexity.

Gale: a surface-wind exceeding force 7 on the Beaufort scale. When wind-velocities were measured exclusively by the Robinson anemometer, which smooths out the gustiness, the lower limit for a gale for the British coasts was set at 39 miles per hour, about 17·5 m/s; now that wind is recorded by anemometers which show the rapid fluctuations in the velocity of the wind, the word can only be used with much

WHICH CAN TRAVEL 30,000 MILLION CM PER SEC.—AND THEIR FREQUENCIES



wireless waves) and "slow" oscillations for wave-lengths exceeding 30,000 metres—less than 10 kilocycles, 10,000 oscillations per second.

tion of various kinds. The arrangement of the whole series is set out in fig. ii, which is adapted from the diagram of wave-lengths exhibited at the British Empire Exhibition in 1925. They show a range from ·000006μ (millionths of a metre) on the left-hand side, to 3,500,000 m on the right.

The band representing wave-lengths in the figure extends across the double page. A scale is shown at the bottom and has to be read in a peculiar manner. Each division of it represents the range of an "octave," by which is meant that the wave-length of the vibration at any division-line is double that of the vibration at the next line on the left, and one-half of the wave-length at the line next on the right. In that way the whole range of vibrations from 100 million billions per second on the extreme left to 85 per second on the extreme right can be brought within the limits of the double page.

The frequencies which are of importance in meteorology are primarily the solar radiation which has been recognised as including not only the visible rays but also the shorter waves known as ultra-violet and the longer waves of infra-red. The range in million million vibrations per second is from 1500 to 16. The infra-red rays of terrestrial radiation range from 375 to about 1 million million. There are besides the ionising waves of short wave-length which are related to aurora, and the Hertzian waves of wireless telegraphy which are often manifest in lightning flashes.

In recent practice of radio-telegraphy a complete vibration has become a "cycle" and the frequency is indicated by the number of "kilocycles" instead of by the wave-length in metres.

* * *

less confidence. On June 1, 1908, a solitary gust or squall which indicated a transient velocity of 27 m/s at Kew Observatory brought down part of the avenue of chestnuts in Bushey Park; it is excusable to call the catastrophe the result of a gale of wind; but on the basis of hourly velocity there was no gale.

Geopotential: the potential energy per unit mass at a point above the earth's surface consequent upon the separation of the mass from the earth under the influence of gravity and the rotation of the earth. It is expressed algebraically as $\int_0^H g\,dh$, where g represents the acceleration of gravity and is consequently variable with height and geographical position. The dimensions of geopotential on the C.G.S. system are cm^2/sec sec, a convenient practical unit is a square dekametre per second per second (10 m^2)/sec sec.

Surfaces of equal geopotential are "level surfaces" and are horizontal in the technical sense. The height of a point can therefore be expressed with advantage for scientific purposes in terms of the geopotential of the "level surface" which passes through the point.

The shapes of level surfaces of a homogeneous fluid like water or air can be calculated from the law of gravitation and the angular velocity of the earth's rotation.

The result is a surface of revolution round the polar axis with a polar diameter smaller than the equatorial diameter by about one-third of one per cent.

The "level surface" for the sea, or "sea-level," is the level to which all heights above or below are referred. The shape of the fundamental level surface is called the "geoid" (*see* C. F. Marvin, Washington, *Monthly Weather Review*, October 1920).

A table of the equivalents of geopotential in terms of geometric height is given on p. 260.

Geostrophic: a compound Greek word coined to carry a reference to the earth's spin; thus the geostrophic wind for a certain pressure-gradient is the wind as adjusted in direction and velocity to balance and therefore maintain the existing distribution of pressure by the aid of the earth's rotation in the absence of all external forces except gravity. The direction of the geostrophic wind is along the isobar and its velocity G is equal to $bb/(2\omega\rho \sin\phi)$, where bb is the gradient of pressure, ω the angular rotation of the earth, ρ the density of the air and ϕ the latitude of the place to which the gradient refers. A uniform system of units must be employed to give a proper numerical result. In latitude 50° the velocity in metres per second is 7·45 × pressure difference in millibars per 100 km.

For certain reasons it is supposed that the geostrophic wind is a very good representation of the actual wind when the isobars do not diverge appreciably from great circles on the earth's surface, and when the point of observation of wind and corresponding gradient of pressure is so high above the surface that the direct effect of the friction at the surface is inappreciable. The effect of friction, whether due to the earth or to air, is always to reduce the velocity and divert the wind from the line of the isobar towards the lower pressure.

Gradient (of pressure, temperature, etc.): the change in the pressure, temperature, etc. corresponding with a unit step along a horizontal surface. The unit step on the C.G.S. system is a centimetre and it is desirable to use that step in any formula that includes a considerable number of variables, but for some practical purposes in meteorology a unit step of 100 kilometres (10^7 cm) is more convenient.

Gradient wind: the wind tangential to the isobaric line and computed from the gradient bb by the formula $bb = 2\omega V\rho \sin\phi \pm \frac{V^2\rho}{E} \cot r$, where V is the velocity in C.G.S. units, ω the angular rotation of the earth, ρ the density of the air, ϕ the latitude, r the angular radius of curvature of the path of the air, and E the radius of the earth. The formula may be written $bb = bb\frac{V}{G} \pm \rho V^2 \cot r/E$, where G represents the geostrophic wind. The upper sign is to be used when the circulation is cyclonic and the lower sign when the circulation is anticyclonic.

Homogeneous as applied to a material or substance is generally understood to mean that every finite portion of the substance, however small, into which the substance may be supposed to be divided is composed of the same constituents in the same proportions by weight, thus every separate chemical substance is homogeneous. But in its particular application in the phrase "homogeneous atmosphere" we have to understand an atmosphere consisting of vertical columns of limited height each of which has the same density throughout its height as the air at its base and produces the same pressure at its base as the column of the actual atmosphere.

Horizontal: We have already explained in chapter XI of vol. I that the word must be understood as meaning perpendicular to the force of gravity, whence it follows that the surface of still water is horizontal. In the upper air the word must have the same meaning, a horizontal surface or level surface is everywhere perpendicular to the force of gravity. Successive horizontal or level surfaces are consequently not equidistant the one from the other over their whole extent, they are closer together at the poles than at the equator.