THE PHYSICAL PROCESSES OF WEATHER

THERE is a curious similarity between meteorology and medicine which was expressed perhaps in past times by the astrological ideas of the relation of the macrocosm, the order of the universe, to the microcosm, the order of the human body. In more recent times the analogy finds recognition in various ways. V. Bjerknes, a natural philosopher, writes of the study of the meteorological situation as "diagnosis," and the precalculation of future states (of the atmosphere) as "prognosis." Mr Rudyard Kipling made some play with the astrological method of treating diseases in a copyright speech at a dinner of the Royal Society of Medicine. With the affectation of omniscience which sits so charmingly on the shoulders of a successful writer of fiction Mr Arnold Bennett[1] accentuates the analogy between meteorology and medicine in a periodical which has much larger circulation than that of meteorological discoveries. Both medicine and meteorology are of personal interest to everybody; the natural consequence of this universal interest is a gradation of the contributions which are offered for the presentation of either subject, in almost insensible steps between treatment on the most rigorous scientific lines and compositions which amount to sheer quackery, whether conscious or unconscious. These common characteristics of the two sciences are incidental to a similarity which is of greater scientific interest. The meteorologist, as we have already pointed out, must take his facts as he finds them in the life-history of weather, and endeavour by co-ordination and analysis to bring them into relation with the laws of nature which physicists and chemists have elaborated; and, in like manner, the student of medicine must take the facts and functions of the human body as he finds them in the life-history of man, and bring them into relation with the same laws of nature. In both sciences the facts are subject to the control of physical laws; in either, cases of similarity may occur; but in neither can any occurrence be repeated, no matter how frequently similarity may be observed.

In that lies the essential difference between the observational and the experimental sciences. That part of the science of medicine which concerns itself with the physics, chemistry and dynamics of the human body is called physiology, and thereby is introduced a subtle distinction between the physics of a living organism and the experimental physics of a laboratory.

Aerology is the special name, if any, for the part of the science of meteorology that deals with the control exercised over weather by the laws of physics, chemistry and dynamics; and it is well to keep in mind the essential difference between the sciences which are concerned entirely with experiment under

[1] "Men of science know no more about so-called inorganic matter and the mysterious antics thereof than doctors know about the human body. The merit of the best of them, like the merit of the best doctors, is that they know they don't know. A few know they never will know; which is an even greater merit."

the personal control of the operator, and those in which experiment can be used only to illustrate and account for observation.

We might indeed have profited by the analogy to which we have drawn attention by giving to this volume the title "The Physiology of Weather" as defining the attitude which meteorologists have to adopt towards experimental physics. We have felt however that to do so might convey the impression that we were proposing to regard weather as the expression of a living organism. Although the weather has many characteristics that are suggestive of vitality we have thought it best to avoid that impression.

As far as may be, we desire to give an insight into the physical processes that are operative in the control of weather. Our purpose is in fact to call the attention of the reader to the processes which can be recognised as physical, in the hope that he will be sufficiently interested to seek for any additional guidance that he may find necessary in the recognised treatises on the different parts of the subject. The achievement of that purpose implies the selection of a number of subjects from the recognised text-books of physics. Our presentation may be incomplete and disjointed; and for that reason a suggestion was made to define the scope of the volume with the title "Miscellanea physica," but that was found to be more recondite than wise.

WAVE-MOTION

The exposition of the subjection of the phenomena of weather to the control of physical laws begins conveniently with the consideration of wave-motion. Starting from the tidal wave which gets round the earth in about twenty-five hours, a maximum speed at the equator of 38,000 kilometres per day, and the visible waves of water which may travel with a speed of some 1500 kilometres per day and are indeed a natural demonstration of the mechanical energy of weather, we pass on to the suggestions of wave-motion of the same character in air, to the travel of sound and then to the reception and disposal of the vast amounts of energy in waves received from the sun which form the basis of all the various aspects of the Science of Meteorology.

Among the common features of the atmosphere which can be cited as illustrations of the laws and principles of physics few, if any, are more striking or more likely to excite curiosity than those which are concerned with light and sound. The blue sky, the red sunset and sunrise with their transient green ray, the lowering cloud with its silver lining, the sun drawing water, the fleecy cloud with its patch of iridescent colour, the mysterious halo, the mock sun, the distortion of the enormous orbs of the sun and moon at rising and setting, the crepuscular bands across the sky, and before all the rainbow with its message of hope for fine weather, the flash of lightning, the mysterious roll of thunder, the roar of the rushing wind and the fickleness of distant sounds are every man's experience and the subjects of every man's inquiry.

All these are regarded, by those who know, as belonging in some form or other to wave-motion. In the introductory portion of volume II we have displayed a diagram of the fundamental properties of waves, their wave-length or their frequency and the rate of travel. In that diagram very small space indeed was allotted to the waves which are held to account for the behaviour of light and a space fifty times as large to other waves—electric waves, which must be regarded as indistinguishable from light-waves except for the fact that the mechanism of our eyes is not adjusted to use them for seeing. All the waves enumerated in that diagram are regarded as being waves in the "aether," a medium which has been invented to account for the transmission of waves, to provide, as the late Lord Salisbury said, a nominative case for the verb "to undulate." Whether the aether has in fact a real existence or is a figment of scientific imagination it is certain that the behaviour of light, which is illustrated by the atmospheric phenomena that we have mentioned, has been explained more clearly than by any other method as the behaviour of waves travelling with an absolute velocity of nearly 200,000 miles a second, or 26,000,000,000 kilometres a day through an imponderable aether pervading space. We shall ask the reader to regard all the phenomena represented by that diagram as depending upon wave-motion.

If we confine our attention to optical phenomena, the waves are all-important and we do not have to consider anything else, hence we can be content with an undulatory theory: if we study the electrical properties we are concerned with the energy and may be content with a corpuscular one, where attention is concentrated on the carriers of the energy. (Sir J. J. Thomson, *Beyond the Electron*, C.U. Press, 1928, p. 25.)

Sound, too, is definitely proved to travel as wave-motion, not in the imponderable aether but in the real atmosphere. It is not quite the same kind of wave-motion as that which is invoked to explain the behaviour of light. The record of sound received and preserved in the gramophone is a mechanical effect whereas the record of light which is preserved on a photographic plate is a chemical effect. The actual properties of the motion which constitutes sound have been subject to more thorough investigation than the supposed motion of the aether; and in consequence physicists are able to say with confidence that the travel of sound through the atmosphere is accounted for by the "elasticity of the air," which provides facilities fôr oscillation of the particles affected, backwards and forwards alternately, in the line of travel. While it is travelling, the sound consists of a succession of phases of alternate compression and rarefaction of the air, producing waves which have been made visible, at least photographically, by special contrivance. They travel at a speed which is proportional to the square root of the ratio of the elasticity of the air under very sudden compression to its density. The elasticity in those circumstances is represented by the familiar meteorological quantity pressure multiplied by a factor γ which is the ratio of the two specific heats of air (at constant pressure and constant volume respectively) and is equal to 1·40.

The velocity of travel of sound is in consequence proportional to the square root of the temperature of the air traversed. At the ordinary temperature of the air 290tt, it has the value of 342 m/sec, 1122 feet per second, 30,000 kilometres per day.

Wave-motion offers the most mysterious examples of the transmission of energy from one region of the earth or of the universe to another. By some process at present imperfectly understood a "train of waves" is set up in the transmitting medium, seismological waves in the earth, tidal waves or gravity waves or compression waves in water or air, capillary waves in water, electric waves including light waves and other waves of similar character in the hypothetical medium of transmission called the aether as set out in the diagram of waves, fig. ii of vol. II.

By a train of waves we understand a succession of similar waves following each other in rhythmical order with definite velocity along the surface of the earth or through its thickness, along the surface of water, along a surface of discontinuity in the atmosphere, through the atmosphere or through space. The "shape" of the wave travels along its medium with an appropriate velocity, while any particle that has taken part and is taking part in the transmission describes an "orbit" which it repeats as the successive waves of the train affect it. Where the medium is uniform in all directions the transmission is in straight lines, where the medium is varied a bend takes place, continuous variation in the medium means curvature in the line of transmission. A surface of discontinuity involves transmission along the surface, perhaps all round the earth. No energy is spent in the transmitting medium when the train is once established except that which is represented by the effect of internal friction (viscosity) of the medium, if any. The energy of the wave is passed on from particle to particle in a manner which is quite easily described but by no means easily explained.

The orbit of a particle which is taking part in the transmission may be simple or complicated. The simplest orbit is that of waves of sound through air of uniform composition and temperature. In that case the particle affected oscillates backwards and forwards along the straight line of transmission—the waves are then called longitudinal. Longitudinal waves occur in other "elastic" media, such as earth or water; a separate law of transmission applies to each kind of elasticity, longitudinal or transverse. Light waves also exhibit phenomena corresponding with simple linear oscillation but transverse to the line of transmission instead of being along the line. The motion of the particles in light is regarded as analysable into component oscillations at right angles to each other and to the direction of motion of the wave. The orbit may therefore be rectilinear, when the two components have the same phase, or it may be circular or elliptic, when the phases of the component oscillations are not identical.

Polarisation

Some substances like tourmaline or Nicol prisms have the remarkable property of "polarising" light, i.e. of being transparent in one position and quite opaque in another position for light which has passed already through one plate or prism. Allowing that in ordinary light the "particles" of the incident beam have an elliptical orbit, this astonishing property is explained by supposing the first plate to be transparent to the component along one line and opaque to the component at right angles thereto, so that what falls upon the second plate is already in rectilinear vibration. Light which is transmitted by particles in rectilinear vibration is said to be "plane polarised"—a name that sticks, though linear polarisation would probably express the idea better; but light with components at right angles may be elliptically polarised, circularly polarised or plane polarised, the motion being in every case confined to a plane at right angles to the line of transmission. Ordinary light may be regarded as consisting of a discontinuous succession of trains of waves representing successive quanta of energy, each train being separately unrestricted as to the orbits of its particles. Polarisation is exhibited only by light waves after they have been passed through some filtering medium that absorbs all the energy except that corresponding with the linear oscillation which the filtering medium can transmit.

The particles of gravity-waves in water or air may also have elliptical orbits but in that case one of the components is longitudinal, i.e. in the direction of motion, and the other vertical.

Rectilinear transmission of energy by waves and the law of inverse square

One of the most striking features of wave-motion is the transmission of the energy in straight lines. The shadows formed by opaque objects in a beam of sunlight are the most familiar example. In fact in accordance with modern views a straight line might be defined as the path of a beam of light, although there are cases in which the unsophisticated reader may have some difficulty in reconciling it with what he understands by the shortest distance between two points. From that principle, assuming that the medium of transmission is perfectly uniform, we may easily understand that the energy of any form of wave-motion originating in a point will spread out into a sphere with the point as centre and with a radius which increases with the velocity of transmission, just as though the energy belonged to a limited number of material particles projected in all directions from the point with the velocity appropriate to wave-motion in the medium. Thus the intensity of the energy per unit of area at any distance is like the force of gravity inversely proportional to the square of the distance from the point of origin.

That such a distribution is possible with energy that is expressed as wave-motion can be inferred by watching the spread of waves which originate from the point of disturbance of water caused by dropping a stone in an undisturbed surface. In order that the experiment may properly illustrate the principle there must be no obstacle in the path of any part of the advancing wave. An obstacle in the way spoils the regularity of the advance in its immediate neighbourhood and part of the energy is devoted to disturbing the medium behind the obstacle.

A proper undulatory theory takes account of such secondary disturbances;

they are included under the name of diffraction; the theory claims that the front of the wave can be regarded as made up of an infinite number of independent elements of disturbance each distributing its energy in independent wavelets, and is able to show that if the energy sent out by any element, at any angle θ from the normal to the wave-front, is related to the energy sent out along the normal by the factor $\cos\theta$, the combined effect of all the elements of the complete wave-front is the same as if the energy were all transmitted in straight lines with the inverse square law. The proposition of the rectilinear propagation of wave-motion is an essential part of the undulatory theory of light. The setting out of the proposition will be found in any account of the undulatory theory; reference may be made to Glazebrook's *Physical Optics*[1]. The proposition is not limited to light but applies to wave-motion in general. Any form of wave-motion will furnish illustrations of the rectilinear propagation of energy and the diffraction caused by obstacles.

The reconciliation of the undulatory theory and diffraction with the transmission of light in straight lines and orderly reflexion and refraction is a step of far-reaching importance towards the apprehension of the physical nature of the universe. It justifies us in associating together the breakers on Land's End, the crimson glow of a cloud in the evening sky and the invisible waves which, without any leave asked or given, pass through our homes and our bodies and by licence of the postmaster-general convey to us the prospects of to-morrow's weather—it enables us to treat all these things either as bundles of rays suggestive of corpuscular travel or as the effect of a train of wave-fronts with all the incidental consequences of diffraction, and we can, if we are so disposed, pursue the idea to the ramification of the tidal wave in an estuary a hundred miles from the sea. In the wave-motion last mentioned it is the energy conveyed by the travel of material that arrests our attention and reminds us that at both ends of the scale beyond the range of the ordinary sea-wave at one end and beyond the electron at the other the transference of energy is corpuscular, but in the open medium the motion is undulatory.

The most typical representation of wave-motion is the sine-curve in which ordinates at successive equal intervals from the starting-point correspond with the sines of angles with equal increment; the full angle of 360° corresponding with the length of the wave. We have already indicated in chap. XIII of vol. I the importance of the sine-curve in the analysis of the sequence of events, and there is no department of the science of meteorology for which the comprehension of a sine-curve is not required.

The sine-curve is the best illustration of the regular transmission of a *shape* as wave-motion: the shape transmitted in that case is the curve representing the fundamental component in harmonic analysis and is related to the horizontal or vertical displacement of a particle which describes a circle with uniform angular velocity. But the shape transmitted need not be and indeed seldom is a simple sine-curve. Harmonic analysis on Fourier's theorem enables us to resolve into a series of sine-curves of related periods, any shape whatever

[1] *Text-books of Science*, Longmans, Green and Co., London, 1883, chap. II.

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Excerpt
More information

that is repeated after a definite interval. The shape need not even be expressed by any finite number of harmonics. An almost infinite variety of shapes can be transmitted as wave-motion in a beam of sunlight in which the separate periods can be identified by suitable apparatus. When therefore we talk about a train of waves as represented by a sine-curve it should be understood that we are using the simplest form not because that is the most frequent or the most likely but because it presents the least difficulty in algebraical computation.

While we are thinking of changes which are represented by wave-motion and their laws we may take the opportunity of reminding the reader of the other type of change which is to be found all over the universe, namely, exponential change, the basis of the law of compound interest. For example, in the atmosphere when the temperature is uniform, pressure is proportional to $e^{-gz/Rtt}$, where z is the height, and to $e^{-E/R}$, where E is the entropy, and in similar conditions specific volume is proportional to $e^{E/R}$.

Between this logarithmic change with its perpetually increasing or diminishing value and cyclical change represented by the variations in the sine and cosine there is a curious association which is represented algebraically by the effect of the mysterious symbol $\sqrt{-1}$.

Thus as t increases e^t is a continuously increasing quantity and e^{-t} is a continuously decreasing quantity, $e^t + e^{-t}$ is the sum of two quantities one of which increases and the other decreases, but $e^{t\sqrt{-1}} + e^{-t\sqrt{-1}}$ is a periodic quantity, namely $2 \cos t$, and $(e^{t\sqrt{-1}} - e^{-t\sqrt{-1}})/\sqrt{-1}$ is also a periodic quantity, namely $2 \sin t$.

We can take the reader a step farther and combine the two expressions without much effort. $Ae^t(e^{t\sqrt{-1}} - e^{-t\sqrt{-1}})/2\sqrt{-1}$ will represent the "plane polarised" motion of a particle in the path of a train of waves when the amplitude of vibration Ae^t is gradually increasing beyond any possible limit, and $Ae^{-t}(e^{t\sqrt{-1}} - e^{-t\sqrt{-1}})/2\sqrt{-1}$ represents the same kind of motion which is gradually fading or decreasing in amplitude though it will take an infinity of time to reduce it actually to zero. So $A(e^t - e^{-t})(e^{t\sqrt{-1}} - e^{-t\sqrt{-1}})/2\sqrt{-1}$ represents two trains of waves in opposite phase passing the affected particle in the same direction, one increasing in amplitude without limit and the other fading. Increasing without limit is not a common occurrence but fading in periodic motion is common enough. The e^{-t} indicates what is called a coefficient of damping because the quantity affected by it is fading all the time. Curiously enough in all these calculations e is a number which cannot be expressed by a finite number of figures in the ordinary decimal notation, though it is indispensable for the construction of a table of logarithms. To the third place of decimals it is 2·718.

Wave-motion introduces us to the transference of energy and in that connexion we shall ask the reader's attention also to the logarithmic laws when we come to the relation of physical quantities to one another and their common relation to entropy which is of fundamental importance in the consideration of the energy of atmospheric changes.

THE PHYSICS OF THE ATMOSPHERE

Thus by the study of wave-motion in its simplicity or its complexity we are brought into quantitative relation with the general physical problem of the atmosphere, and the tracing of the transformations of energy in the sequence of the phenomena of weather. For that we require a working acquaintance with the application of the laws of thermodynamics to the various conditions of the atmosphere. We have taken the opportunity to put together the relations of the physical properties of the atmosphere to entropy and temperature in a form which enables us to set out the liability of the atmosphere at any time in respect of energy as disclosed by the results obtained from soundings by balloon.

We shall claim that the physical processes of weather are fairly well understood and from that point of view our knowledge of the physics of the atmosphere is generally sufficient for meteorological purposes. Having explored that province we shall take the opportunity of pointing out, as the conclusion of this volume, the bearing of some of our knowledge on the still unsolved problem of the general circulation. We are obliged to confess that our knowledge of the dynamics of the atmosphere is imperfect, singularly unaesthetic in its form and inadequate in its scope. The subject is really waiting for a novum organum.

There will remain for us therefore the examination of the methods for expressing the dynamical processes that are operative under the physical laws which this volume brings to account.

Some of the results of dynamical reasoning to which we have to call attention are already included in the volume which was published ten years ago as Part IV. Some prefatory chapters on the dynamical methods and some additional matter on the results of current dynamical theory in a new issue of that part as vol. IV will complete our representation of the subject.

*** The compilation of a volume so miscellaneous as the present one necessarily levies contributions from many authors. A large amount of information is naturally derived from the past issues of the recognised meteorological journals, the *Meteorologische Zeitschrift*, the *Journal of the Royal Meteorological Society*, the *Monthly Weather Review* and the *Meteorological Magazine*; and to these we must add the *Smithsonian Physical Tables* and the *Annals of the Astrophysical Observatory* of that Institution, the *Meteorological Glossary* and the *Dictionary of Applied Physics*. The principle upon which the structure rests is that it is best, so far as possible, to give an original author's own words and references to the source from which they have been derived. It is hoped that the references will not only be accepted as an acknowledgment by the author of his obligations for contributions to our common stock of knowledge, but also serve as an invitation to the reader to satisfy the natural desire for further information.

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In addition to these obligations the author gladly acknowledges the assistance which he has received from friends who have read the work in proof; Sir Richard Glazebrook and Mr Sidney Skinner, colleagues for many years in the teaching of practical physics at Cambridge; Mr R. G. K. Lempfert, the first of a series of personal assistants at the Meteorological Office; Mr D. Brunt and Commander L. G. Garbett, R.N., associates in a later effort at the Imperial College of Science and Technology to represent for a class of students the application of physical laws and principles in the atmosphere.

In the suggestions which have arisen in the discussion of the text with one or other of these friends there has emerged a feeling of uncertainty as to the class of readers to whom this volume is offered. It is not a text-book of physics, nor yet a text-book of meteorology which assumes all physics and its auxiliary mathematics as the common possession of author and readers. Some things which cannot be regarded as easy are assumed and some that are not difficult are expounded.

Acknowledging the impeachment the author would plead that his purpose in writing is not that of the text-book writer, which may be succinctly described as saving his readers as far as possible the trouble of thinking, by going through that process for them; but to suggest that, comprised within the almost unpronounceable name of meteorology, there are a large number of subjects that readers will find quite interesting and worth their while to think about, and to indicate to them at least where and how food for thought can be found. Within the last half-century the pursuit of meteorology as a science has been to some extent accepted as a responsibility of government, and the amateur has to the same extent been exonerated from supplying the material for the study of the atmosphere of the globe. As may be gathered from vol. II of this Manual, students of the subject have become aware of the gradual and orderly compilation of a vast multitude of data, but the opportunities of thinking about them have not been extended equally with the material to be thought about, and part at least of the responsibility of converting scientific data into science still remains for the amateur or the leisured hours of the official.

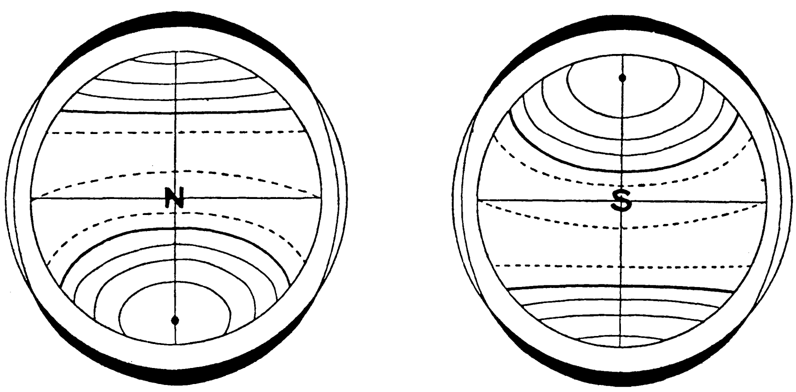
Nature as represented in weather is a little intolerant of organisation and classification and some parts of the subject, for example the stereography or the kinematography of clouds, belong to no official routine and offer an invitation to the enthusiastic amateur. There are many others which will suggest themselves to those who think about what has already been achieved, and this volume is in fact addressed to those who agree that "the books that help you most are those that make you think most."

CHAPTER I

GRAVITY-WAVES IN WATER AND AIR

The tides at this place [Funchal] flow at the full and change of the moon, north and south; the spring tides rise seven feet perpendicular, and the neap-tides four. (*The Voyages of Captain James Cook*, London, 1842.)

LUNAR TIDE ON THE EQUILIBRIUM THEORY



Northern hemisphere Southern hemisphere

Fig. 1. Adapted from fig. 29 of Sir G. H. Darwin's *Tides*, London, John Murray, 1898. The distribution of the displacement of the surface of a shell of deep water covering both hemispheres, computed for a tidal wave according to the equilibrium theory, adapted to the mode of circumpolar representation employed in this Manual for the distribution of temperature, pressure, etc.

Continuous curves indicate elevation of the water, interrupted curves depression.

The effect represented is the heaping up of water round a centre, marked by a dot in lat. 15° N immediately over which the influencing body (the moon) is supposed to be.

Counting as 2 the vertical elevation of the water at that point, concentric "small circles" round the central point show the positions of elevations measuring successively $1\frac{1}{2}$, 1, $\frac{1}{2}$, 0, four curves of continuous line. The last which marks the circle of no displacement is a thicker line. Beyond that, represented by interrupted lines, are successively the circles of depression of $\frac{1}{2}$ and 1 (the maximum depression) and again of $\frac{1}{2}$, a step towards another thick line for the second circle of no displacement. The incomplete curves of the one hemisphere are completed in the opposite hemisphere, the circles of elevation being centred at a point 15° S where the elevation is also 2, the antipodes of the first.

The profile of the wave (greatly exaggerated) along latitude 15° N is shown by the ovals surrounding the hemispheres—the elevated part is blackened. In order to realise the full effect of the displacement the oval curve with its protuberances must be thought of as rotated about its long axis.

For reasons which are explained in Sir G. Darwin's work the distribution of tidal water in this hypothetical wave does not agree with that of the observed tides in the open oceans.

The reader will find some interesting information on the subject of the equilibrium tide and its transformation into tidal waves on shore and in estuaries in a letter by A. Mallock, *Nature*, vol. CXXIII, 1929, p. 640, and in the works of G. I. Taylor or H. Jeffreys on tidal friction in shallow seas.