patches sometimes move in a remarkable way, and probably under forces other than those of the winds.

Having for purposes of classification divided the wind structure of the atmosphere into different classes, I must now attempt to put them together, and to show that some of the types that seem very different are in reality closely connected.

Following on inquiries made by Mr. W. H. Dines on the correlation between the surface pressure and various meteorological elements at a height of 9 kilometers, it was suggested by Dr. W. N. Shaw, F. R. S., that the changes of pressure to which our changes of weather are due, have their origin, not near the surface of the earth as hitherto supposed by many meteorologists, but just below the level of the stratosphere at a height of 9 kilometers or so above the surface. This view is in accordance with the observed facts of the wind distribution in the different layers of the atmosphere.

Supposing that on a certain day there is a pressure distribution just below the stratosphere, which at that level produces a westerly wind of a certain strength; this pressure distribution will be transmitted through all the lower layers of the atmosphere, and unless modified by other conditions will produce a west wind at the surface; the velocity of this wind will, however, be only about one-third of that at the 9-kilometer level owing to the greater density of the air near the surface. If, however, the air to the north at every height were at a lower temperature than the air at a corresponding height over the place of observation, there would be at all levels a tendency for easterly winds. This will have the effect of reducing the westerly wind as we descend through the atmosphere, and when the surface is reached the west wind will have a much lower value than it would have had were it only for the increased density of the air. If the wind at the 9-kilometer level is not very strong, or if the tendency to produce an easterly wind is strong, as would be the case if the air to the north were very cold we may get a calm at the surface, or the calm may even be reached at some distance above the surface, in which case the tendency for easterly winds may actually produce such a wind which will increase in velocity as we descend toward the surface under the layer of calm and be strongest a little above the surface of the earth at a point where surface friction begins to cause a diminution of velocity.

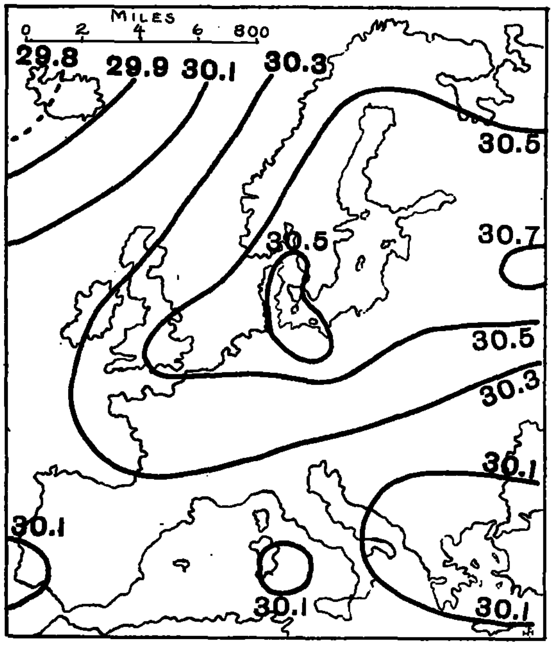

FIG. 5.—Isobars at sea level 1909, February 22, 6 p. m.

If again at the 9-kilometer level there is a pressure distribution producing an easterly wind cold air to the north will produce a tendency for an increase of easterly wind as we descend through the atmosphere; but the greater density of the air at the lower levels will produce a decrease of wind velocity from whatever direction the wind may be coming; the two tendencies may neutralize one another in which case we get a solid current of east wind between the stratosphere and the ground level.

If there is no wind at the 9-kilometer level cold air to the north will produce easterly winds in the lower levels in which case we should find easterly winds increasing in velocity as the surface is approached.

These considerations give some idea of the mechanism by which the different types of vertical wind structure may be produced. The wind increasing with height, the solid current, the wind decreasing with height, are seen to fall into their places. The reversal, with an east wind near the surface and a west wind higher up, is only an extreme case of the slackening of the westerly wind near the surface; and the point of reversal, far from marking a point of discontinuity in the atmosphere, is seen to be merely the result of forces extending right through the lower part of the atmosphere, between the stratosphere and the earth.

If the winds are resolved into components at right angles to each other, that is north-south, and west-east components, it is found that in most cases the west-east component decreases below the stratosphere and is a minimum near the surface, an east wind in this case being considered as a negative west wind. This is what should be the case if the ideas I have been considering are correct, for the air to the north is generally colder than the air over this country. In the case of the north-south component we find no such general rule, but this also is as it should be, for the air to the east and west may be either of the same temperature, or warmer, or colder than the air over the station, in other words, there is a normal north to south temperature gradient but not a normal west to east gradient, in our islands.

The supposed cases mentioned are of course simple types, and it can be readily understood how varying conditions of pressure and temperature may in similar ways produce varieties of vertical wind distribution. In considering the pressure distribution just below the stratosphere as the regulator of the winds and the weather in the lower part of the atmosphere, I fear I have nothing to add concerning the laws governing these pressure distributions: the idea is a new one and has yet to be worked out in its details, and to stand the test of criticism and fuller investigation.

METEOROLOGY AS AN EXACT SCIENCE.[1]

By Prof. Dr. VILHELM BJERKNES.

[Delivered at the University of Leipzig, Jan. 8, 1913.]

It is a time honored custom that the newly appointed professor in his inaugural address should devote a few words to his predecessors by way of commemoration. I can not follow this example; therefore, ought I to be so much the more grateful for the honor of having been

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[1] Die Meteorologie als exakte Wissenschaft. Antrittsvorlesung gehalten am 8. Januar 1913 in der Aula der Universität Leipzig. Braunschweig. 1913. 16 p. 8°.

chosen as the first occupant in this university, of the new chair of geophysics.

Just as the earth is a part of the entire cosmos, so geophysics can be conceived as a part of cosmical physics. It is divided into three branches: Physics of the atmosphere, Physics of the hydrosphere and Physics of the rigid earth; and has thus an extraordinarily extensive scope. It will not be easy to succeed in treating satisfactorily at one time all the branches, and I believe it to be consistent with the conditions of my call to this chair, if I direct my personal field of action as investigator and teacher to the first two branches particularly. These two are closely related to each other, and I can elucidate the points of view which I desire to place in the foreground in this lecture on the first branch, that is, the Physics of the atmosphere.

The physics of the atmosphere treats of the same subjects as meteorology. For this very reason, however, these two sciences must not be confounded with each other. The distinction is marked for the reason that physics ranks among the so called exact sciences, while one may be tempted to cite meteorology as an example of a radically inexact science. Meteorology becomes exact to the extent that it develops into a physics of the atmosphere. I shall consider this development in the present lecture.

Man has always entertained a keen interest in the weather and in atmospheric phenomena. Even in the infancy of scientific research, he made this a hobby of speculation. We see this equally in the serious writings of Aristotle, and in the romping comedies of Aristophanes. The beginnings of a meteorology already existed among the ancients. They were able very exactly to define not only their own weather phenomena, but also the peculiarities of the grand, impressive, strictly scientific phenomena of the Tropics such as the Indian monsoon. They also possessed a not inconsiderable knowledge of physics. Archimedes had founded a rigorous system of hydrostatics; and the expansion of air by the application of heat was also known. Upon the latter were based various of the famous juggleries of Hero. Not one of the ancients, however, dared to combine this varied knowledge in order to explain, for example, the cause of the monsoon or any wind in fact. Consequently we can not well discuss the physics of the atmosphere, or more generally speaking, geophysics among the ancients.

In the age of the great geographical discoveries, meteorological information also expanded particularly with respect to the weather conditions of the Tropics. Still more steadily than the monsoon, blow the trade winds which Columbus discovered on his first voyage. Upon further exploration, the trade winds were found in the southern hemisphere, and the knowledge of the monsoon was reinforced.

Contemporaneously physics began to develop into a systematic science. In the later Renaissance dynamics was founded, the principles of hydrostatics rediscovered, and the effect of applying heat to bodies more minutely inquired into. This prepared the way for some investigating spirit to perceive, sooner or later, the relationship between the winds of the Tropics and an unstable equilibrium produced by heat. The first one to express this happy idea was Newton's friend and pupil Halley, when he returned in 1686 from a two-year voyage through the Tropics. His conclusion was that heated air is lighter than cold air and must therefore rise, being displaced by inflowing currents from below and round about. Thus over the thermal equator an ascending current forms, fed by two currents of air blowing longitudinally over the earth toward the equator, i. e., the trade winds of the Northern and Southern Hemispheres. The Indian monsoon originates in like manner. Here the warmest place, over which the ascending air current rises, is the Asiatic Continent or the Indian Ocean, according to the season. Hence the seasonal change of the monsoon.

Halley's explanation of the origin of the trade winds and the monsoon has held true for all time. On the other hand, he incorrectly explains the phenomenon that the trade wind has a component in the direction of the equator instead of flowing perpendicularly to it. This point in his theory was corrected and completed about 50 years later by Hadley, another English astronomer. By means of a well-known elementary consideration, which is frequently presented even in geographical text-books, he demonstrates that the wind is not actually deflected but only appears to be so to the observer who is traveling with the rotating earth.

Through the efforts of these two English astronomers, so similar in name, the relationship between the two sciences of meteorology and physics first came to be recognized, and the first step was taken toward the development of a physics of the atmosphere. We may here advantageously compare the great revolution in astronomy which just preceded this advance. Newton had applied dynamics, which had sprung from other than astronomical sources, to the phenomena of the heavens, and had thereby been able to explain the stellar motions. Halley and Hadley had applied a knowledge of the theory of heat, hydrostatics, and dynamics, derived from other than meteorological sources, to the phenomena of the atmosphere and had thereby explained the great movements of the atmosphere. The results of both these advances were similar. The subsequent discoveries in the motions of the solar system were without exception based upon Newton's laws; and those concerning the motions of the atmosphere were all traceable to the fundamental principles established by Halley and by Hadley. All the latter were directly or indirectly due to heating, and all, excepting the cases of purely local winds, show the influence of Hadley's theory of deflection. The essential difference, however, between meteorology and astronomy was that atmospheric motions could only be studied qualitatively, whereas stellar motions might also be studied quantitatively and indeed so accurately that, from the known position of a star at one time, its position could be successfully predicted for a remote date. Consequently by that one stroke astronomy became an exact science, while meteorology had taken only its first step in that direction.

It is self-evident that there should be this difference. Astronomical observations yielded all the data necessary for predicting the positions of the stars. On the other hand, at that time meteorological observations were quite unable to furnish suitable fundamental data for predicting atmospheric conditions. In mathematical calculations, the heavenly bodies may be regarded as individual points which move in the simplest manner under mutual influences. Newton's Mechanics was designed for precisely such conditions, and not for the handling of the motions of a continuous medium, such as the air. The quantitative laws governing the interchange of mechanical and thermal processes had not yet been discovered. The transformation of meteorology into an exact science necessarily called for the extensive further development of physics, on the one hand, and of observational meteorology, on the other.

It would take too much time to delineate in detail the parallel development of the two sciences. I must limit myself to a few essential points.

Galileo and his pupils constructed the first thermometer; Torricelli made the first barometer. These instruments lent to observational meteorology a precision it had previously lacked. As time went on it became evident that the study of simultaneous observations would be extremely fruitful, and several students laboriously collected these and began to present the results by means of synoptic charts. The work of H. W. Brandes published at Leipzig in 1820 and 1826, the latter date being that of his University Dissertation, are among the most important of those to be mentioned in this connection, though they did not immediately meet with the appreciation that they merited. At about this same time Redfield in America began to draw his synoptic charts.

At last the storm of November 14, 1854, over the Black Sea caused so much damage to the fleets of the combined Western Powers that it gave the needed impetus toward a speedier development of the science. The eminent astronomer Leverrier received an official order to study conditions of that storm with a view to the possibility of foreseeing such occurrences and the establishing of a storm-warning service. Upon this foundation rose the present organized international telegraphic weather service.

Great as was this advance, still the resulting Weather Service could not meet the very great expectations that it originally excited. Quite properly, one sought the true ground for such disappointments in the observational scheme. All the observations available came from the lower limit of the atmosphere. Almost no information was available concerning the conditions in the free air. It is true that after the balloon was invented, occasional ascents had been undertaken with the object of securing meteorological observations. The ascensions by Glaisher in England are especially noteworthy, although they were attempted with an instrumental equipment that was still inadequate to the task. A more accurate method for securing meteorological observations under these new conditions was first developed by Assmann in the course of that splendid series of Berlin ascensions executed during the last decennium of the last century. Shortly thereafter methods were devised for securing observations in the free air without necessitating the ascent of the investigator himself.

We owe the first step[1] in the development of this "aerological" method of observing to an American, the late A. Lawrence Rotch. By means of kites he sent up self-recording instruments from his observatory at Blue Hill, near Boston. Later, L. Teisserenc de Bort, in France, sent up similar instruments attached to small unmanned balloons, which descended to earth somewhere after completing their trip; most of these were subsequently picked up and returned to him. Assmann replaced Teisserenc de Bort's paper balloons with closed rubber balloons which burst when high up in the air, after which the instruments descend with a parachute. In this way the journey is performed quicker and there are greater chances of recovering the instruments. In addition to kites and registering balloons, small captive balloons are also employed. Further, small free balloons without any attached instruments, so-called pilot balloons, are employed to observe only the atmospheric motions; these are observed by means of a theodolite.

To-day a large number of aerological observatories are at work with these auxiliaries, the largest one being the Royal Prussian Aeronautical Observatory, founded by Assmann, at Lindenberg. Moreover, and mainly through Hergesell's initiative, there exists an organized international cooperation among the aerological observatories; moreover, a series of occasionally contributing institutes has also been developed. On certain prearranged days an extensive region of the free atmosphere is investigated. This region extends from the west coast of Europe across central Europe far into Russia; each year sees it expanded and more thickly studded with aerological stations. The atmosphere over this territory is sounded to heights of 15 or even 20 kilometers or more. Since at these altitudes the atmospheric pressure is reduced to but one-tenth to one-twentieth of that at sea level, it is obvious that as much as nine-tenths or more of the mass of the superincumbent air of this extensive territory is now being explored. This investigation includes directly, or indirectly, all the meteorological elements that define the condition of the atmosphere, seven quantities in all: the three velocity components, also the pressure, temperature, density, and humidity of the air. On the days of international observation the values of all these elements are determined, first at the various observing stations and then by suitable methods of interpolation they are deduced for all points of the territory. Thus observational meteorology has practically completed and perfected her task, no matter what future advances may yet be made in instruments and in organization.

Parallel with this development of meteorology has been the extensive advance in experimental and theoretical physics since the Renaissance. I can mention here only the principal milestones that are the most important for our subject.

Analytical mechanics has developed on the foundations laid by Galileo and Newton. About the middle of the eighteenth century Clairaut established the equations of hydrostatics, and Euler did the same for those of hydrodynamics. About 1820 Navier supplemented these equations by adding those terms that represent the effect of internal friction. In 1835, exactly 100 years after the true pioneer Hadley, Coriolus presented his well-known theorem in dynamics, now generally used in dynamic problems to express the effect of the earth's motion.

After the invention of the barometer and the thermometer it was possible, by their aid, to investigate the laws of gases, and we gradually came to the complete Boyle-Gay-Lussac law. We learned to discriminate between the idea of temperature and the idea of quantity of heat, and established the laws of melting and freezing, evaporation and condensation. In continuation of this development and guided by the new fundamental ideas of Sadi Carnot and Robert Mayer, the early years of the nineteenth century saw the growth of the modern theory of thermodynamics for whose development and completion we are indebted to von Helmholtz, Kelvin, and Clausius.

In like manner physics has rendered the service that was demanded of it. I have already mentioned the seven variables which we call "meteorological elements." As a result of the progress that I have outlined, physics is now able to formulate the seven corresponding equations, viz, the three hydrodynamic equations of motion, the equation that expresses the principle of the conservation of mass (the so-called "equation of continuity"), the equa-

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[1] See, however, this issue of this Review, p. 39.—EDITOR.

tion of condition for gases, and the two equations that result from the two fundamental theorems of thermodynamics. By means of these equations together with the necessary boundary conditions and the data relative to external influences, the problems of dynamic meteorology become definite formulated problems from a mathematical point of view. Theoretically speaking, they can now be attacked both qualitatively and quantitatively with some hopes of success.

The theoretical treatment of meteorological problems has kept pace with the development of observational meteorology and theoretical physics. At first idealized phenomena were discussed. By making appropriate assumptions, one or more variables may be eliminated, and thus one may devise problems of a purely dynamic or of a purely thermodynamic character. By still further simplifying assumptions we obtain corresponding simple integrable systems of equations whose solutions are essential to the comprehension of various meteorological phenomena. Ferrel, Guldberg and Mohn, Helmholtz, Hertz, Von Bezold, and others have given us valuable works of this character. To a certain extent Hann's theoretical works are also related to this class, since they aim at more precise general elementary explanations of meteorological phenomena.

All these works antedate the founding of modern aerology. But now that complete observations from an extensive portion of the free air are being published in a regular series, a mighty problem looms before us and we can no longer disregard it. We must apply the equations of theoretical physics not to ideal cases only, but to the actual existing atmospheric conditions as they are revealed by modern observations. These equations contain the laws according to which subsequent atmospheric conditions develop from those that precede them. It is for us to discover a method of practically utilizing the knowledge contained in the equations. From the conditions revealed by the observations we must learn to compute those that will follow. The problem of accurate pre-calculation that was solved for astronomy centuries ago must now be attacked in all earnest for meteorology.

The problem is of huge dimensions. Its solution can only be the result of long development. An individual investigator will not advance very far, even with his greatest exertions. However, I am convinced that it is not too soon to consider this problem as the objective of our researches. One does not always aim only at what he expects soon to attain. The effort to steer straight toward a distant, possibly unattainable point, serves, nevertheless, to fix one's course. So, in the present case, the far-distant goal will give an invaluable plan of work and research.

Here I may be permitted to draw an illustration from my personal experience. For many years I had already occupied myself with the application of the laws of hydrodynamics to the motions of the atmosphere, and had come to many interesting results. But the question kept recurring to me: What is it that I really seek? Whither am I steering? I could not free myself from the thought that "There is after all but one problem worth attacking, viz, the precalculation of future conditions."

As I had been able to find enthusiastic young colaborers who had the courage to follow me, I determined to always steer directly toward this distant goal.

We have never regretted it. To be sure the work we have already accomplished seems but to emphasize how far removed our goal really is. Yet our work has always been fruitful. Precisely because we have always kept the end clearly before us, we have been able to clearly formulate a whole series of preparatory individual problems, and to solve them one after the other. I can not go into details here. I will give but one example.

Obviously the usual mathematical methods will not be adapted to a problem of this sort. There can be no thought of an analytical presentation of the observational results with a subsequent analytical integration of the equations. As the observations are presented by means of charts, therefore all mathematical computations must be recast into graphical operations by means of maps. In this way we have developed for ourselves the rudiments of a graphical mathematics by means of which we derive one map from the other, just as one usually derives one equation from another by calculation. The steady development of the methods, which the novelty of our problem makes necessary, gives the work a peculiar charm which we would not forego. I hope that during my work here in Leipzig I may interest many younger colaborers in the abundant problems we meet with in this work.

Before closing I must touch upon an objection which is brought against our work. Our problem is, of course, essentially that of predicting future weather. "But," says our critic, "How can this be of any use? The calculations must require a preposterously long time. Under the most favorable conditions it will take the learned gentlemen perhaps three months to calculate the weather that nature will bring about in three hours. What satisfaction is there in being able to calculate to-morrow's weather if it takes us a year to do it?"

To this I can only reply: I hardly hope to advance even so far as this. I shall be more than happy if I can carry on the work so far that I am able to predict the weather from day to day after many years of calculation. If only the calculation shall agree with the facts, the scientific victory will be won. Meteorology would then have become an exact science, a true physics of the atmosphere. When that point is reached, *then* the practical results will soon develop.

It may require many years to bore a tunnel through a mountain. Many a laborer may not live to see the cut finished. Nevertheless this will not prevent later comers from riding through the tunnel at express-train speed.

PECULIARITIES OF THE CALIFORNIA CLIMATE.

EXPLAINED ON THE BASIS OF GENERAL PRINCIPLES OF ATMOSPHERIC AND OCEANIC CIRCULATION.

By GEORGE F. McEWEN,

Oceanographer of the Scripps Institution for Biological Research.

[Dated January 5, 1914.]

INTRODUCTION.

In the report on the scientific results of the Challenger Expedition, Buchan (1) concluded his discussion of atmospheric circulation with the following statement:

> The isobaric maps show, in the clearest and most conclusive manner, that the distribution of the pressure of the earth's atmosphere is determined by the geographical distribution of land and water in their relation to the varying heat of the sun through the months of the year; and since the relative pressure determines the direction and force of the prevailing winds, and these in turn the temperature, moisture, rainfall, and in a very great degree the surface currents of the ocean, it is evident that there is here a principle applicable not merely to the present state of the earth, but also to different distributions of land and water in past times.

In the present paper an attempt is made to show the effect of the difference in temperature between land and