The Inclination of Winds to the Isobars.—The vorticose motion of the winds in a cyclone towards and in upon the centre has been already pointed out. One of the more important practical problems of meteorology is the determination of the angle of inclination of the winds to the isobars in the different segments of the cyclone, not only from the application of the results of the inquiry to the theory of storms but also to practical navigation. The first real contribution to the subject, based on accurate measurements, was made by Clement Ley in 1873.[1] From the observations made at fifteen places in north-west Europe examined by him he showed that the winds incline from districts of higher towards those of lower pressure at a mean angle of 20° 51′; that the inclination is much greater at inland than at well-exposed stations on the coast, the respective angles being 28° 53′ and 12° 49′; and that the greatest inclinations are with S.E. winds. Then follow S.W., N.E., and N.W. winds, the last showing the least inclination. Whipple has recently compared the winds at Kew with the barometric gradients for the five years ending 1879, with the result that the greatest inclination is 63° with S.E. winds, the least 35° with N.E. winds, and the mean for all winds 52°.

As regards the open sea, Captain Toynbee has shown, from a careful investigation of the great Atlantic storm of August 24, 1873, that the mean angle of inclination calculated from one hundred and eight observations was 29°, the mean at the three selected epochs examined varying from 25° to 31°.

Barometric Gradient and Velocity of the Wind.—In inquiring into the relation of the velocity of the wind to the barometric gradient, it is necessary to have some definite information as to the increase of the velocity with height above the ground. Stevenson recently made observations on this point on winds varying from 2 to 44 miles an hour from the surface up to a height of 50 feet, from which he has drawn the following conclusions:—(1) the spaces passed over in the same time by the wind increase with height above the ground; (2) the curves traced out by these variations of velocity from 15 to 50 feet high coincide most nearly with parabolas (fig. 20) having their vertices in a horizontal line 72 feet below the surface; (3) between 15 feet and the ground there is great disturbance of the currents, so that the symmetry of the curves is destroyed; (4) the parameters of these parabolas increase directly in the ratio of the squares of the velocities of the different gales. If x be the velocity of the wind at height H above the ground, the parameter of the corresponding parabola is $x^2/(H+72)$; and as x varies the parameter will vary as x^2 or as the square of the velocity of the gale. It follows that, to render wind observations comparable, it is necessary that anemometers be placed at one uniform height above the ground, and that standard height not lower than 15 feet above the surface. It is very desirable that the inquiry were prosecuted up to a height of 100 feet; and it is of the utmost importance that the variation in the diurnal velocity be at the same time determined at different heights from 15 feet upwards.

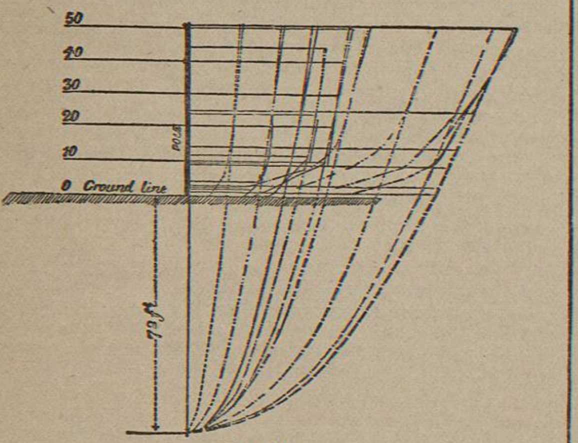

Fig. 20.

Stevenson also made wind observations on the Calton Hill, Arthur's Seat, and the Pentland Hills, in the vicinity of Edinburgh, up to a height of 1600 feet above sea-level. It is from observations made at stations on knolls and peaks at different heights above the sea, and at different heights above the surfaces of their summits, that the problem of the variation of the wind's velocity at different heights with the same barometric gradient can be ascertained. In carrying the inquiry to considerable heights, the results cease to be comparable with those obtained at lower levels, unless in those cases where neighbouring heights are available for data from which the barometric gradient at the observed height can be calculated. The results of observations as to the velocity of atmospheric currents at very great elevations in the atmosphere deduced from the apparent movements of the higher clouds are altogether incomparable with the winds near the surface of the earth, for these among other reasons:—the heights of the clouds can be at best but imperfectly ascertained; the motion of the clouds, particularly the higher clouds, may be only apparent, it being sometimes difficult to distinguish between the formation and dissolution of clouds and their motion; and above all, since the higher clouds are usually the accompaniments of the greater weather changes, their movements are the result of barometric gradients towards a knowledge of which we are absolutely powerless to take a single step.

As regards surface winds, Clement Ley in 1881, and Whipple more recently and with greater fulness, have calculated the mean wind velocities for twelve gradients,—the gradients being derived from the daily weather charts of the Meteorological Office for the five years 1875 to 1879 at 8 A.M., and the corresponding wind data being obtained from the hourly readings of the Kew anemograph. The barometric gradient is for 15 nautical miles, and the following are the velocities for the twelve gradients on the mean of the year:—

Gradient. inch.	Velocity. miles.	Gradient. inch.	Velocity miles.
0·002	5·0	0·017	15·0
0·005	7·0	0·020	16·5
0·007	7·5	0·022	19·1
0·010	9·2	0·025	22·0
0·012	11·6	0·027	22·0
0·015	12·6	0·030	25·5

The influence of season is very strongly marked. The velocities for the same gradients in order are—October to December, 12·5 miles; July to September, 12·6 miles; January to March, 14·8 miles, and April to June, 17·2 miles. From those observations of Whipple it follows that during the six months when the temperature is falling the velocity for the same gradients is least, while the velocity is greatest during the six months when the temperature is rising, and absolutely greatest during the three months ending June, when the greater part of the annual increase of temperature occurs. It is evident that the observed increase in the velocity of the wind for the same gradients is to be referred to the same cause that brings about the diurnal increase in the wind's velocity, viz., the wind blowing over a warmer surface than itself.

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[1] *Journal Scottish Meteorological Society*, vol. iv. p. 66.

Whipple has also sorted the winds according to the eight points of the compass, with results of the greatest interest. If N.W., N., N.E., and E. winds be grouped together as polar, and S.E., S., S.W., and W. winds as equatorial winds, the mean hourly velocity of the polar winds, for the same gradients, is 1·1 miles in excess of the equatorial winds. Now, since polar winds pass into lower latitudes, the surface of the earth over which they blow is warmer, whereas the surface is colder than the equatorial winds which blow over it. It follows that the increased velocity of polar winds is referable to the same conditions which result in the diurnal increase in the wind's velocity and the greater velocity for the same gradients of winds when the annual temperature is rising, since in all these cases the winds blow over a surface of a higher temperature than their own.

It is evident from these considerations that for the development of the law of the relation of the wind's velocity to the barometric gradient with an exactness sufficient to warrant us in expressing that relation in a general mathematical formula much yet remains to be done. In truth, as regards the various formulæ submitted by Ferrel, Mohn, Hann, Everett, and others, we have no choice but to allow the justness of Strachan's criticism (*Modern Meteorology*, p. 98) that the theoretical values furnished by the formulæ do not accord with the actual values, and that therefore a satisfactory formula is yet to be found. Ere such a formula need be looked for, the conditions must be fulfilled for the preliminary work of supplying the observational data required. The "Challenger" observations prove that, with gradients substantially the same, the velocity of the wind is greater on the open sea than near land; and we have seen that the velocity varies with the hour of the day, and generally is increased as the temperature of the surface rises above that of the air blowing over it, and diminished as the temperature of the surface falls below that of the air. It is evident that observations on the open sea will afford data for the simplest solution of the problem; but on land the diurnal, seasonal, and non-periodic changes of temperature greatly complicate the problem, and render necessary for its solution observations specially designed for the purpose. It is not easy to see how these can be obtained but by carrying out the plan proposed in 1875 by Stevenson of establishing strings of well-equipped meteorological stations planted sufficiently close that the barometric gradients may be determined within the limits of accuracy required. Observations made twelve times daily for a year, at stations so arranged, would supply the observational data for the solution of this fundamental problem in meteorology. Till some such proposal be carried out, the problem remains unsolved, for barometric gradients based on the widely separated existing stations are too uncertain and rough and the wind observations are wanting in that comparability which alone can satisfy the inquiry.

Weather and Weather Maps.—Weather is the state of the air at any time as respects heat, moisture, wind, rain, cloud, and electricity; and a change of weather implies a change in one or more of these conditions. Of these changes the most important as regards human interests are those which refer to temperature, wind, and rain; and, as these are intimately bound up with the distribution of atmospheric pressure, the latter truly furnishes the key to weather changes.

These relations are well shown by the International Monthly Weather Maps issued by the United States Signal Service. Of these that for December 1878 is a striking example. This month was characterized over the globe by unusually abnormal weather. A line drawn from Texas to Newfoundland, across the Atlantic, the north of France, and Germany, thence round to south-east, through the Black Sea, the Caucasus, India, the East India Islands, and Australia to the South Island of New Zealand, passes through a broad and extended region where pressure was throughout considerably below the mean of December, and this low pressure was still further deepened in various regions along the line. Another line passing from Australia, through the Philippine Islands, Japan, Manchuria, Behring's Strait, and Alaska, also marks out an extensive region where pressure was uninterruptedly below the mean.

On the other hand, pressure was above the average, and generally largely so, over the United States to west of longitude 90°, over Greenland, Iceland, the Faroes, Shetland, and a large portion of the Old Continent bounded by a line drawn from Lapland round by Lake Balkhash, Canton, Peking, to the upper reaches of the Lena. Another area of high pressure extended from Syria, through Egypt and East Africa, to the Cape; and part of a third area of high pressure appeared in the North Island of New Zealand. As regards North America, the greatest excess of pressure, 0·196 inch above the mean, occurred in the Columbia Valley, from which it gradually fell on proceeding eastward to a defect from the average of 0·146 inch near Lake Champlain and to northward, rising again to near the mean on the north of Nova Scotia. To the north and north-east exceedingly high pressures for these regions and the season prevailed, being 0·635 inch above the mean in Iceland, 0·500 in the south of Greenland, and at the three stations in West Greenland, proceeding northward, 0·445, 0·402, and 0·346 inch.

West Greenland being thus on the west side of the region of high pressure which occupied the northern part of the Atlantic, and on the north-east side of the area of low pressure in the States and Canada, strong south winds set in over that coast, and the temperature at the four Greenland stations, proceeding from south to north, rose to 1°·1, 8°·8, 12°·1, and 14°·4 above the means. As the centre of lowest pressure was in the valley of the St Lawrence about Montreal, strong northerly and westerly winds predominated to westward and southward, where consequently temperature was below the average, the deficiency at Chicago and St Louis being 9°·5; and, winds being easterly and northerly in California, the temperature there was also under the mean. On the other hand, in the New England States, the greater part of the Dominion of Canada, and West Greenland temperature was above the average. Pressure was much higher at St Michael's, Alaska, than to south-westward at St Paul's, Behring's Strait, and hence, while temperature at St Paul's was 2°·9 below the normal, it was 12°·0 above it at St Michael's, where strongly southerly winds ruled. With these strong contrasts of pressure, America presented contrasts at least as striking in the distribution of the temperature. Along the south of Lake Michigan the November temperature was 13°·7 above the normal, whilst the December temperature was 9°·5 below it, the difference there between the two consecutive months being thus 23°·2.

As regards Europe, Iceland was on the east side of the patch of high pressure which overspread the north of the Atlantic, and hence northerly winds prevailed there and temperature fell 7°·2 below the mean, presenting thus a marked contrast to the high temperature of West Greenland at the time. In Europe, the area of lowest pressure occupied the southern shores of the North Sea, extending thence, though in a less pronounced form, to south-eastward. Hence over the whole of western Europe winds were N.E., N., and in the south-west of Europe W.; and hence everywhere from the North Cape to the north of Italy temperature was below the normal, in some places greatly so, the deficiency being 10°·4 in the south of Norway and 12°·2 in the south of Scotland. On the other hand, on the east side of this area of low pressure winds were southerly and temperature consequently high. In some localities in Russia the excess above the mean was 15°·0, and over a large proportion of European Russia the excess was not less than 9°·0. This region of high temperature extended eastward into Siberia as far as the Irtish, being coterminous with the western half of the anticyclonic region of high pressure which overspread central Siberia. But over the eastern portion of the anticyclone northerly winds prevailed, with the inevitable accompaniment of low temperatures over the whole of Eastern Asia, the deficiency at Nertchinsk on the upper Amur being 6°·8. Here again, just as in America, Greenland, and Iceland, places with atmospheric pressure equally high presented the strongest contrasts of temperature. Thus at Bogoslovsk, on the Ural Mountains, pressure was 0·211 inch and at Nertchinsk 0·154 inch above the normals, but Bogoslovsk on the west side of the high pressure area had a temperature 15°·0 above, whilst at Nertchinsk it was 6°·8 below the average.

At this time of the year the mean pressure falls to the minimum in Australia, but during December 1878 the usually low pressure was still further diminished. Pressure at this season also falls to the annual minimum in the North Pacific and North Atlantic, and it has been seen that the low pressure of these regions was likewise still further diminished. But in the case of the Atlantic it was attended with a most important difference. The centre of lowest pressure, usually located to the south-west of Iceland, was removed some hundreds of miles to the south-east, and an unwonted development of extraordinarily high pressure appeared to the northward, overspreading the extensive region of Baffin's Bay, Greenland, Iceland, Faroes, and Shetland. It was to this region of high pressure, particularly in its relations to the low-pressure region to the south-east of it, that the extreme severity of the weather in the British Islands at the time was due. Now this high-pressure region was intimately connected with, and doubtless occasioned directly by, upper atmospheric currents from the widely extended region of low pressure to southward, with its large centres of still lower pressure in the North Sea, mid-Atlantic, and United States, where pressures were respectively 0·307, 0·322, and 0·146 inch under the normals. Thus, with the single exception of the high-pressure area about Greenland, the meteorological peculiarities which render December 1878 so memorable over nearly the whole globe arose out of a distribution of the earth's atmosphere essentially the same that obtains at that time of the year, but the usual irregularities in the distribution of the pressure appeared in more pronounced characters.

Taking the all-important bearings of these areas of high and low pressure on weather and climate into consideration, along with the abnormal concentration of aqueous vapour over extensive regions which they imply, it is evident that, when the meteorologist will be in a position to forecast, on scientific grounds, the weather of the coming season for the British Islands, it is to the Atlantic he will require to look for the data on which the forecast is based.

These questions, which the International Weather Maps of the United States enable us to discuss, are of the first importance in meteorology, whether we consider the amplitude of the atmospheric changes they disclose (these being often so vast as to embrace four continents at one time, besides being profoundly interesting from their direct bearings on the food supplies and commercial intercourse of nations) or regard the larger problems they present, with hints towards their solution, which underlie physical geography, climatology, and other branches of atmospheric physics. The discussion presents the great atmospheric changes as influenced by oceans and continents, including the subordinate but important parts played by mountain ranges, extensive plateaus, and physically well-defined river basins in determining the development, course, and termination of these changes.

Weather Forecasts and Storm Warnings.—It is in tropical and subtropical countries that an isolated observer may, with a close approximation to certainty, predict the approach of gales and hurricanes. In these regions atmospheric pressure and the other meteorological conditions are so constant from day to day that any deviation, even a slight one, from the average of the hour and season in respect of pressure, the direction and strength of the wind, and the direction and amount of cloud, implies the presence of a storm at no great distance. Dr Meldrum has practically worked out this problem at Mauritius with great success. At the Royal Alfred Observatory there the mean pressure at sea-level in January at 9 A.M. is 29·966 inches, from which it falls to 29·904 inches at 4 P.M., then rises to 29·980 inches at 10 P.M., and again falls to 29·927 at 4 A.M. The mean direction of the wind and the diurnal variation, both as regards direction and force, have been stated (p. 125). Suppose then that the barometer is observed to fall after 9 A.M. more rapidly than is due to the usual daily barometric tide, that in the afternoon it does not indicate the second maximum or that it continues to fall instead of rising,—or suppose, in short, any deviation from the mean daily march,—then it is certain that there is somewhere an atmospherical disturbance near enough to Mauritius to influence the pressure. The direction in which the disturbance is from Mauritius is readily known from the wind, and the distance of the storm closely approximated to by noting the rate and amount of the fall of the barometer, in connexion with the changes of the wind and the clouds,—the rate and progressive motion of the storm being known chiefly from the veerings of the wind. For a good many years past notifications have been sent to the daily newspapers when observations show that a storm is not far from the island, stating its position and probable course from day to day. The scheme of storm warnings at Mauritius has been entirely successful, and the result is of great value, since it shows what may be done at an isolated station in the ocean, or what may be done in ships at sea. In this connexion it is not possible to overestimate the importance to seamen of a knowledge of the hourly variations of the barometer and its mean monthly heights over the ocean tracks of commerce.

In passing from Mauritius to the British Islands we pass from a region where the forecasting of storms and weather is simplest and easiest to the region where it is most complex and difficult, particularly for the western districts of these islands. The great difficulty lies in the fact that the British Islands are immediately bounded by the Atlantic to westwards; and, since practically every storm and nearly all weather changes come from that direction, no telegraphic communication of their approach can be received. The Meteorological Office in London has therefore no choice but to base the forecasts on such of the observations telegraphed to the office as experience has shown to be the precursors of storms and other weather changes. The more important of these observations are the falling and rising of the barometer taken in connexion with changes in the direction and force of the wind. Since on the north side of the track of the centre of the storm winds are northerly and easterly and temperature low, and on the south side winds are southerly and westerly and temperature high, one of the most important points to be ascertained is the probable path the centre of the coming storm will take. Though a good deal remains to be accomplished in the development of this phase of storms, yet much has recently been done in this direction by close examination of the changes of pressure in the region of the anticyclone contiguous to the advancing storm and by the changing positions of the rain area near the centre of the cyclone.

As regards Europe, the facility of forecasting storms increases as distance from the west coasts is increased. Thus to the middle and eastern districts of the British Islands, were a day and night watch established in the west, forecasts of almost every storm could be issued, the exceptions being those small cyclones or satellite cyclones, as they are called, originating within the British Islands themselves, which are frequently characterized at once by their severity and by the rapidity of their onward course. In the United States, the system of weather forecasting is perhaps the best in temperate regions,—a result due to the admirable system organized and developed under the direction of the late General Myer, and adequately subsidized by the Government, but above all to the facilities to detect and track the storms in the region where nearly all of them have their origin, to west of the Mississippi, before they advance upon the more thickly peopled States.

Meteorology sustained a heavy loss by the death in 1877 of Leverrier, who was not only the keenest-sighted of physicists but also the prince of organizers of systems of meteorological observation. His last great service to the science was the establishment of a system of observation, by which the propagation of rain, hail, and other weather phenomena could be followed and recorded from commune to commune over France. This scheme for the investigation of the vitally important bearing on the meteorology of a country of a comprehensive observation of its rainfall, hail, and thunderstorms, through numerous observers possessing sound local information, is not only eminently just in science, but is calculated to be attended with the greatest benefits to agricultural and other public interests. The practical advantages of the scheme, it need scarcely

be added, can only be reaped after a very large expenditure of labour and money in organizing a comprehensive parochial scheme of observation, systematically and persistently carried through and discussed.

Further details regarding meteorological phenomena will be found in the articles ATMOSPHERE, BAROMETER, CLIMATE, HYGROMETRY OZONE, RAINGAUGE, SEA, and THERMOMETER. (A. B.)

TERRESTRIAL MAGNETISM.

1. In the preceding portion of this article some account has been given of the influence which the sun and moon exert upon the air, the earth, and the ocean, their strictly tidal effects being left to be separately dealt with. The discussion of the influence of these bodies on what may be termed the movables of the earth will not be complete, however, without embracing an account of the changes which they produce in the earth's magnetism. An account of the earlier magnetic observations has already been given under the heading MAGNETISM, and our task will now be to give in the first place a description of the best and most recent instruments by which the magnetic state of the earth is determined, embracing therein observatory instruments, those adapted for travellers whether by land or by sea, and differential magnetometers. We shall next give a short account of the magnetic system of the earth and of its secular variation; and we shall then investigate the changes connected with terrestrial magnetism depending on the sun and moon. In performing this task we shall be led to conclude that the sun's power is variable, and we shall therefore examine whether this conclusion is likewise borne out by strictly meteorological observations. Finally, we shall venture on remarks embodying a provisional working hypothesis, and our object will be gained if this should be found to suggest certain lines of thought to those interested in the subject which may lead them to examine and discuss the very great mass of observations at present existing.

INSTRUMENTS FOR DETERMINING THE MAGNETIC STATE OF THE EARTH.

(α) *Observatory Instruments.*

2. *Declinometer.*—It is that end of the needle which points to the north magnetic pole of the earth of which the position is invariably noted even when the observation is made in the southern hemisphere. The difference of this position from true geographical north denotes what is called the variation or declination (east or west) of the needle. East is often reckoned negative and west positive. The instrument by which this information is obtained is called the declinometer. The unifilar magnetometer, which is the form of declinometer now used, is described and figured in MAGNETISM, vol. xv p. 238.

3. *Dip Circle.*—The instrument by which the magnetic dip or inclination is observed contains a thin needle about 3 inches long, the centre of gravity of which coincides as accurately as possible with the axis of motion of the needle. The needle has two axles consisting of two very fine cylinders of hard steel standing at right angles to the plane of the needle, and great attention must be paid to keep these axles in a state of perfect polish and dryness. By means of these the needle can oscillate freely on two horizontal agate rounded edges, the one axle lying on the one edge and the other axle on the other. If the centre of gravity coincides exactly with the axis of motion, and if there be no adhesion or friction between the axles and the agate edges, the needle must settle into such a position that its magnetic axis lies in the true line of dip.

The position of the ends of the needle is read by means of two microscopes which move round on a cross piece carrying verniers. To view the position of the lower end of the needle we move round the lower microscope until the cross wire in its field of view (extending in the line between the two microscopes) symmetrically cuts the extremity of the needle. The lower vernier is then read. The same process is repeated for the upper vernier, and the mean of the two readings is taken. This mean will accurately denote the position of the needle if the circle is properly set.

The sources of error in a dip observation are—(1) a want of symmetry in mass, the centre of gravity of the needle not being coincident with the axis of motion; (2) the vertical circle being erroneously set; (3) a want of symmetry in magnetism, the magnetic axis not being coincident with the axis of figure; (4) excentricity, the axis of rotation of the needle not passing through the centre of the circle; (5) friction and adhesion of the axles as they rest on their agate supports. This last source of error is guarded against by taking great care of the axles, and by inserting them gently into a piece of cork before each observation; the agate supports ought also to be rubbed with cork. Then, again, when the needle has assumed its position, before reading it is gently raised by means of a lifter, the handle for turning which is shown in the figure towards the right. It is then gently lowered, and this process is repeated until no apparent change of position is produced by the operation.

4. We shall now describe a complete dip observation. The first point is to make the needle to swing in the plane of the magnetic meridian. In order to accomplish this, after levelling the instrument, the verniers are set for 90°, that is, for a vertical position of the needle. The whole instrument is now turned round its horizontal circle until the extremities of the needle are bisected by the wires of the two microscopes, and the position of the vernier of the horizontal circle is then read. The needle is next reversed so that the microscope shall view its other flat side; it is made vertical as before, and the position of the horizontal circle read once more. Next the face of the instrument is turned round 180°, and the same two operations repeated. We have thus four readings of the horizontal circle, and if we take the mean of these we shall have ascertained with sufficient accuracy the position of that plane for which the needle is vertical. Now this plane must be removed 90° from the magnetic meridian, for in such a plane the horizontal magnetic force of the earth would have no resolved portion acting in the plane of the needle's motion, so that the needle would practically be under the sole influence of the vertical magnetic force, and would therefore point in a vertical direction. By this means therefore we obtain the magnetic meridian, and thus know the plane in which we ought to swing the needle. The needle must now be read in the following positions:—(α) face of instrument east—face of needle to face of instrument; (β) face of instrument west—face of needle to face of instrument; (γ) face of instrument west—back of needle to face of instrument; (δ) face of instrument east—back of needle to face of instrument. Finally, the poles of the needle must be reversed, by rubbing them with powerful bar magnets in a direction opposite to that in which they were previously rubbed, and four observations taken corresponding to the above. The mean of the eight observations so obtained will give us the true dip.

The turning round of the face of the instrument from east to west is made to counteract any error due to erroneous setting of the vertical circle. The reversal of the face of the needle is made to counteract any error due to the centre of gravity of the needle not being quite coincident in the direction of the needle's breadth with its axis of motion, and likewise any error due to want of symmetry of the magnetic axis. The correction for excentricity is made by reading both ends of the needle. Finally, the reversing of the poles of the needle is intended to counteract any error due to the centre of gravity of the needle not being coincident in the direction of the needle's length with its axis of motion.

Dr Joule[1] has suggested a modification of the dip circle in which the needle is hung on fine threads on which it rolls instead of resting on agate supports.

5. *Horizontal Force Magnetometer.*—The theory of the instrument for determining the horizontal component of the earth's magnetic force has already been given in the article MAGNETISM, vol. xv. pp. 238 *sq.*, and the instrument is shown in two forms, *ibid.*, figs. 28 and 29. The corrections necessary for accurate results are explained in a paper by G. M. Whipple (*Proc. Roy. Soc.*, 1877).

(β) *Instruments adapted for Travellers by Land.*

6. *Declinometer.*—For travellers by land the unifilar instrument (§ 2), mounted on a tripod stand and duly levelled, is perhaps the most accurate kind of declinometer.

For this purpose it is furnished with a transit mirror by means of which an image of the sun may be thrown into the field of view of the telescope, and—the geographical position of the station as well as the apparent time of the observation being known—an azimuth thus determined. In order that such an observation may succeed, the following points must receive attention.

In the first place the axis of the mirror must be horizontal; the adjustment for this is made by means of a riding level. Secondly, the normal to the plane of the mirror must be perpendicular to the axis. The adjustment for this is made by a screw attached to the back of the mirror. Take some object sufficiently elevated and reflect it into the telescope, getting the object bisected by the wire of the telescope. Then reverse the mirror in its bearings. If the object remains still bisected by the wire no correction requires to be made, but if not the screw at the back of the mirror must be moved until the object is in precisely the same position in both observations. Thirdly, the line of collimation of the telescope must be perpendicular to the plane of the mirror. In order to obtain this there is a collimating eye-piece attached to the telescope by which the sun's light may be made to illuminate the cross wires. Now turn the transit mirror until the reflexion of the illuminated cross wires coincides with the wires themselves, in which case the line of collimation of the telescope must be perpendicular to the plane of the mirror. When this correction has been once made, note the circle reading of a small vernier which moves with the mirror and always set the mirror so as to give this reading.

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[1] *Proc. Lit. and Phil. Society, Manchester*, vol. viii. p. 171.

By these means an accurate reading of the sun's bearing may be made; and, the position of the place and the time of observation being known, there are tables which enable the azimuth to be at once determined.

7. *Lloyd's Method of Determining the Total Force.*—While the dip circle and the horizontal force magnetometer may be used by travellers in addition to their use as observatory instruments, the Rev. Dr Lloyd has devised a new method of determining the total force. The ordinary method of obtaining this is first to find the dip and the horizontal force, from which the total force can be at once determined by the equation,—total force = horizontal force × secant dip. This method is, however, open to objection in high magnetic latitudes where the horizontal force is very small and the dip approaches 90°. Now in Lloyd's method this objection is overcome. Another circumstance which renders his method peculiarly convenient for high magnetic latitudes, where a traveller's equipment must be kept as light as possible, is the fact that it only requires the addition of two needles to an ordinary dip circle in order to give the required determination. These needles must be carefully kept from contact with other magnets, and their poles never reversed.

Here as before we have two unknown quantities to determine, the one being the magnetic moment of the magnet and the other the total force of the earth. We must, therefore, obtain two results, the one embodying the product of the earth's total force into the magnetic moment of the needle, while the other gives the ratio between these two quantities.

8. In order to determine the former of these, let the needle have a grooved wheel of radius r attached to its axle as in fig. 21, and over this wheel let an accurately known weight W be suspended by means of a very fine silk thread. The best way of doing this is to have a thread with two hooks of precisely equal weight at each end and then attach the preponderating weight W to one of these hooks. When this is done a new position of equilibrium will be taken by the needle. If we suppose that m denotes the magnetic moment of the needle, that i is the angle of dip at the place, and that η denotes the angle which the needle in its deflected position makes with the horizon, the weighting being so made that η shall be less than i, then it is clear that the needle has been deflected out of its position of equilibrium through an angle $i-\eta$. If we call this angle u and designate by R the total force at the place, we obtain the following equation of equilibrium:—

$$m\mathrm{R}\sin u=\mathrm{W}r \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1),$$

on the supposition (which is very nearly but not strictly correct) that W denotes a constant force at all latitudes.

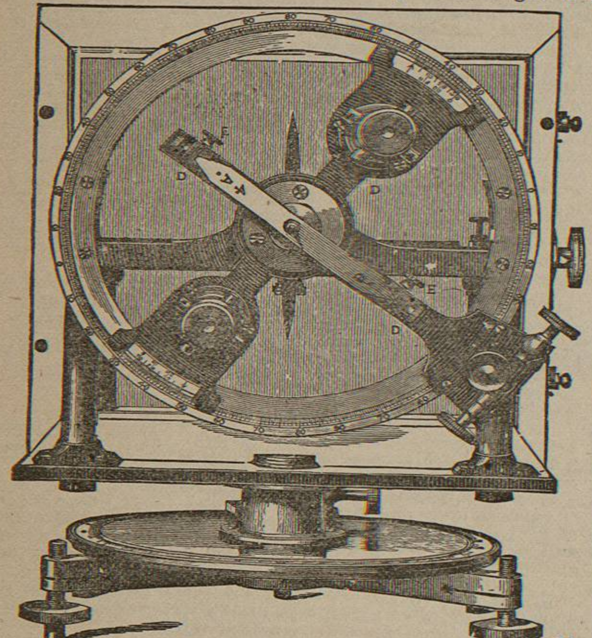

Fig. 21.—Dip Circle.

9. Next, in order to determine the ratio between this needle's force and that of the earth, let it be removed and employed to deflect another substituted in its place. When using it thus as a deflector it should be laid in a frame in an invariable position as in fig. 21. This frame is at right angles to the line between the two microscopes, and as both pieces move together the best plan is to turn the whole round until the deflected needle is visible in the centre of the field of the microscopes, in which position it is of course perpendicular to the deflecting needle. By always keeping to this arrangement we secure an invariable distance between the poles of the two needles. Suppose therefore that we have employed the needle as a deflector in the above manner, and that the deflected needle has thus been made to assume a position denoting an angle η' with the horizon. It has therefore been deflected from its position of equilibrium by an angle $i-\eta'$ (i denoting the dip as before); calling this angle of deflexion u', we obtain the following equation of equilibrium:—

$$\mathrm{R}\sin u'=m\mathrm{U} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2),$$

U being a function depending upon the distance of the needles and on the distribution of free magnetism in them.

10. If we multiply together equations (1) and (2), we obtain—

$$\mathrm{R}^2\sin u\sin u'=\mathrm{UW}r \quad . \quad . \quad . \quad . \quad . \quad . \quad (3),$$

in which u, u' are determined by observation, while W and r may be regarded as constants. U is, as we have said, a function depending upon the distance of the two needles and upon the distribution of free magnetism in them.

The magnetic moment of these needles is of course liable to alteration, but if they are carefully guarded from contact with magnets we may imagine that while their intensity alters, becoming weaker for instance, this nevertheless does not sensibly affect the distribution of the free magnetism within them, in which case the function U may be regarded as a constant quantity. The results obtained by this method of Lloyd's fully confirm this hypothesis regarding U; but it is essential that the two additional needles, the deflector and the deflected needle, should have their poles at no time either reversed or disturbed.

Assuming therefore the constancy of the quantity U, its value may be easily determined at any base station where the total force has been determined independently by the ordinary method.

11. Having thus determined the value of U, or at once of UWr (which we may call c), let us carry our instrument to a different station and make the requisite observations. We thus obtain

$$\mathrm{R}=\sqrt{\frac{c}{\sin u\sin u'}} \quad . \quad . \quad . \quad . \quad . \quad . \quad (4).$$

As this method is specially adapted for high latitudes, the dip circle employed (fig. 21) ought to be one for which the agate supports are horizontal, so as to admit of the needle being visible when the dip is nearly equal to 90°. It will also be noticed that, if the deflecting needle have the same temperature when it is used in equation (1) which it has when used in equation (2), then m in the one case is strictly equal to m in the other, and thus no temperature correction is rendered necessary.

12. A slight modification of the method now described is sometimes adopted. Instead of employing separate weights, which may be easily lost, two small holes are bored in the deflecting needle near each end. The one of these is filled with a suitably heavy brass peg when the observations are to be made in the higher magnetic latitudes of the northern hemisphere, and the other is filled in a similar manner when the observations are to be made near the southern pole. In this case therefore we must readjust the instrument as we pass from the one hemisphere to the other. A slight change must be made in the formula when this method is adopted, for it is clear that the weight will not now act always at the same constant leverage. If the weight be called W and its leverage when the needle is horizontal r, we shall have to modify equation (1) as follows:—

$$m\mathrm{R}\sin u=\mathrm{W}r\cos\eta \quad . \quad . \quad . \quad . \quad . \quad (5).$$

Equation (2) will, however, remain unaltered, and hence equation (3) will become

$$\mathrm{R}^2\sin u\sin u'=\mathrm{UW}r\cos\eta \quad . \quad . \quad . \quad . \quad . \quad . \quad (6).$$

If the quantity UWr be determined at the base station and called c', we shall have

$$\mathrm{R}=\sqrt{\frac{c'\cos\eta}{\sin u\sin u'}} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (7).$$

(γ) *Instruments adapted for Travellers by Sea.*

13. *Azimuth Compass.*—At sea the declination is generally observed by means of an azimuth compass invented by Kater. This is exhibited in fig. 22. It consists of a magnet with a graduated compass card attached to it. At the side of the instrument opposite the eye there is a frame which projects upwards from the plane of the instrument in a nearly vertical direction, and this frame contains a wide rectangular slit cut into two parts by a wire extending lengthwise. The eye-piece is opposite this frame, and the observer is supposed to point the instrument in such a manner that the wire above mentioned shall bisect the sun's visible disk. There is a totally reflecting glass prism which throws into the eye-piece an image of the scale of the graduated card, so that the observer, having first bisected the sun's disk by the wire, must next read the division of the scale which is in the middle of the field of view. He thus obtains a reading of the sun's position; let us call this 100°. From this, knowing the geographical position of his station and the time of the observation, he may deduce an azimuth; let us imagine that this is 70° W. Thus a reading of 100° corresponds to a position 70° W. Suppose next that the instrument is so adjusted that when the magnetic axis of the magnet is between the eye-piece and the wire the reading is 0°. It is thus clear that the magnetic meridian is 100° removed from the position 70° W. Let us imagine that the instrument is so graduated that this denotes a position 30° E. We have thus obtained the magnetic declination. If the vessel be at rest the plan generally adopted is to take the reading of the sun when rising and also when setting; a mean between the two will give that which corresponds to a geographical meridian.

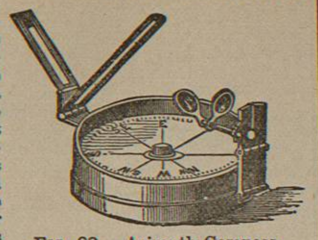

Fig. 22.—Azimuth Compass.

14. *Fox's Dip Circle.*—This instrument, contrived by Robert Were Fox, is more especially useful for observations at sea. In this case it must be placed on a gimball stand and duly levelled before commencing the observation. The following are the peculiarities of this instrument:—(1) the needles have two fine pivots or axles which are inserted into jewelled sockets; (2) in order to avoid parallax there are two graduated circles, the one farther from the eye than the other, and when reading the needle the eye is to be so placed that precisely the same reading shall be given by both circles,—the true position of the needle being thus obtained; (3) there is a rubber made of bone or ivory and roughened, the object of which is to rub a prolongation of the socket on the back of the instrument,—the friction which this rubbing causes enabling the needle to find its true position; (4) to avoid as much as possible all effects due to friction and adhesion, the entire socket arrangement may be turned round. The axles of the needle are thus compelled to be in contact with a different set of particles. Another way of varying the suspension is to use a magnetic deflecting arrangement attached to the back of the apparatus. Suppose that a reading of the position of the needle so deflected is now taken. Next reverse the position of the deflecting arrangement, which is done by turning a movable circle attached to this arrangement 180° round; let the position of the needle be again read. On the hypothesis that the needle is equally deflected on opposite sides of its true position in these two observations, the mean reading will give the true dip. The principle of the method of observing with this circle is precisely the same as that already described for observations on shore with an ordinary inclinometer.

15. *Fox's Intensity Arrangement* is merely a modification of that introduced by Lloyd, and already described in § 7.[1]

(δ) *Differential Magnetometers and Self-Recording Magnetographs.*

16. In addition to determinations at fixed intervals of time, it is a point of much interest and importance to keep a continuous record of all the magnetic changes which take place at a few selected stations. This is accomplished by means of differential magnetometers. It is, however, necessary to continue to use absolute instruments side by side with differential magnetometers, because the latter (with the exception of the declination instrument) are badly fitted for recording changes of long period, such as the secular changes of the horizontal and the vertical force. The reason of this will presently be seen.

17. Early in the history of such instruments it was found that hourly observations were exceedingly laborious, and attempts were made to construct a set of self-recording magnetometers. The first set of such instruments which were brought into systematic operation were those devised and constructed by the late Charles Brooke, which have been at continuous work in the Greenwich Observatory since 1848. In 1857 John Welsh devised a fresh set of self-recording instruments, and introduced them into the Kew Observatory. These, with certain slight modifications, have formed the type of instruments supplied to a large number of magnetic observatories all over the globe.

18. As we cannot conveniently record changes of dip by a differential instrument, changes of vertical force are measured instead by a balance or vertical force magnetometer. We have thus in a differential system, whether adapted to eye observation or to continuous photographic registration, three instruments, namely, the declination, the horizontal force, and the vertical force magnetometers or magnetographs as the case may be. The most recently constructed instruments are adapted both for photographic registration and for eye observation through a telescope. The advantage of eye observations is that we see what is taking place at the very moment of its occurrence, whereas we only obtain the photographic record some time after the changes to which it relates have actually happened.

We shall therefore describe—(α) the three instruments of the Kew pattern as adapted to eye observations; (β) these instruments as adapted to continuous registration by photography; (γ) the method of determining their scale coefficients; (δ) the method of determining the temperature coefficients of the force instruments.

19. *Kew Instruments—Eye Observations.*—Fig. 23 shows us these instruments arranged in the relative positions recommended by Lloyd so as magnetically to interfere with one another as little as possible. We are supposed to be viewing the whole from the south. No. 1 to the right is the declination instrument, No. 2 that for the horizontal force, and No. 3 in the distance behind the central pillar (No. 4) the vertical force magnetometer. Figs. 24, 25, 26 give us the details of these three instruments in the same order as above. Connected with each instrument there is a circular mirror, or rather two semicircular mirrors, made of perfectly plane glass. One semicircular half of each mirror is attached to the magnet and moves with it, while the other half is firmly attached to the marble slab. Each magnet is enclosed in a gun-metal case with windows of perfectly plane glass; each gun-metal case is covered with a glass shade; and the whole is air-tight, and capable of exhaustion. Each magnet too is provided with a copper damper with the view of checking its oscillations. In fig. 23 will be seen two pillars of smaller size. The right-hand pillar carries a telescope, with a scale attached, to record the position of the declination magnet. The scale is reflected from the semicircular mirror moving with the magnet, and the position of this reflected scale as viewed in the telescope indicates the position of the magnet. The optical arrangement for the other instruments is similar, except that the vertical force mirror has a horizontal and not a vertical axis. The telescopes for viewing the force instruments are attached to the left-hand pillar of smaller size.

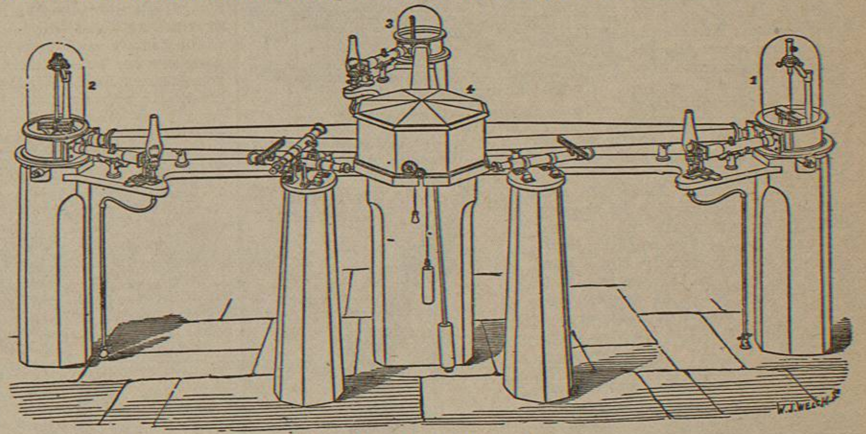

Fig. 23.—Kew Instruments.

20. The *Declinometer*[2] (fig. 24) consists of a magnet about 5 inches long suspended by a silk thread freed from torsion as completely as

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[1] A great deal of detailed information regarding instruments for absolute determination and the methods of observing with them is to be found in the *Admiralty Manual of Scientific Inquiry* in an article on "Terrestrial Magnetism," by Sabine and Welsh. A treatise on *Terrestrial and Cosmical Magnetism*, by E. Walker, may likewise be consulted with much advantage.

[2] For a detailed account of the Kew magnetographs, see *British Association Reports*. 1859.