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NOTES

ON

METEOROLOGICAL CORRECTIONS

FOR THE USE OF

GUNNERS.

BY

D. BRUNT, M.A., B.Sc., and J. DURWARD, M.A.

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By D. BRUNT, M.A., B.Sc., AND J. DURWARD, M.A.

The Range Tables used by the gunner give the ranges which can be attained under certain standard conditions of wind, pressure, temperature and humidity. In the first place it is assumed that the air is still, or that there is no wind. The pressure of the air at the ground is assumed to be equivalent to 30 inches of mercury in latitude 45° . Further, it is assumed that the temperature at the ground is 60°F. , and that the temperature above the ground falls off at the rate of about 2°F. for every 1,000 feet, while the relative humidity of the air at all points of the trajectory is taken as 50 per cent.

In practice these conditions are never attained. Air is never still through any considerable depth of the atmosphere, and it becomes necessary to consider the effect of a wind upon the path of a projectile. A following wind will increase the range without affecting the line, while a cross wind will change the line without materially affecting the range.

The other factors enumerated above, pressure, temperature and humidity, affect the range of the projectile mainly through the changes which they produce in the density of the atmosphere.

The gunner who would obtain accurate shooting must therefore have, in addition to his range tables, information as to the variation from normal conditions based upon accurate measurements of the speed and direction of the wind, the temperature, and humidity at all points of the trajectory, as well as the barometric pressure at the ground.

In the following pages some attempt is made to give a brief description of the methods of observing these meteorological factors and of the methods of reducing these observations to a form suitable for applying the correction of computed ranges of guns.

Wind.

3

Wind.

Wind near the ground may be measured by means of an anemometer. Several types of instrument are available for the purpose. The Dines pressure-tube anemometer, whose vane is fixed on the top of a high mast, gives a very accurate register of the variations of the wind both in magnitude and direction. The mast of this instrument has to be firmly mounted, and a hut is required at the base to shelter the registering portions so that the instrument lacks portability. When the wind at, say, 5 feet above the ground is required, a small portable windmill anemometer (airmeter), which can be contained in a small cubical box whose edge is about 6 inches, can be relied upon to give good results. A third form of instrument is the electrical cup anemometer, which consists of four hemispherical cups fixed at the ends of horizontal arms, so arranged that an electric circuit is completed once for every 25 revolutions of the cups. A bell or lamp arranged in the circuit will give a record of each 25 revolutions, and it is then only necessary to note the time between successive signals. The corresponding speed of the wind is obtained by referring to a table supplied with the instrument. The instrument can be fixed on top of a mast in any suitable position, and the electric bell and bell push, etc., can be arranged in any suitable place at any distance from the anemometer.

Winds at considerable heights above the ground are usually observed by means of pilot balloons. These are indiarubber balloons whose circumferences when fully inflated vary from 70 to 90 inches. The rate of ascent of such balloons is sensibly constant, and can be calculated from the weight of the balloon itself and the weight it can lift when fully inflated. It is found convenient to arrange that the balloon shall rise 500 feet per minute. The balloon is followed by means of a theodolite, and readings of its elevation and azimuth are taken every minute or half-minute, and from these readings, the assumed height being known from the assumed rate of ascent, the wind at different heights is easily derived.

It is found that on an average the wind tends to veer through 2 or 3 points in the first 2,000 feet, while the velocity increases steadily. Beyond that height there is a slight increase, but no general change in direction. These results, however, are to be regarded as averages only. On a particular day the changes of wind with height usually deviate very considerably from the average case, so that the rule stated above has no practical value for the gunner. For instance, fig. 1 shows the variation of velocity with height of a West wind (curve (a)) increasing from 5 ft./s. at the ground to 58 ft./s. at 10,000 feet, and of an East wind (curve (b)), increasing from 5 ft./s. at the ground to 27 ft./s. at 2,000 feet, and then decreasing to 7 ft./s. at 10,000 feet. These two cases illustrate clearly the danger of trying to calculate the upper wind from the wind at the ground. The surface wind

is 5 ft./s. in both cases, but the total effect of the upper winds in the two cases on a trajectory reaching say 10,000 feet would differ very considerably.

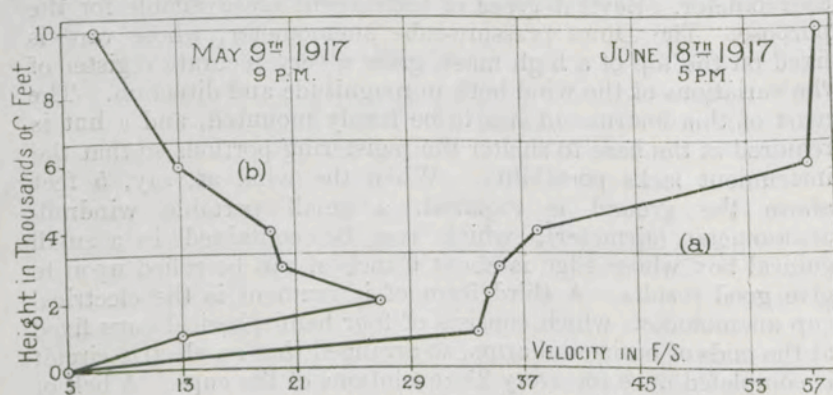


FIG. 1.—Curves illustrating the Variation of Wind Velocity with Height (a) of a West Wind (b) of an East Wind.

The variation of the wind during the day is also of importance. The surface wind is stronger by day than by night, while the reverse usually holds for winds at 1,000 feet and above. There is normally a well defined change in the surface wind at sunrise and sunset. At sunrise it increases and veers through several points, and at sunset it decreases and backs, often dropping to a calm which lasts the greater part of the night. These changes are reversed at 1,000 feet, where the wind decreases and backs by day, and increases and veers by night. Figure 2 shows the daily variation of wind speed at the base and at the top of the Eiffel Tower in Paris.

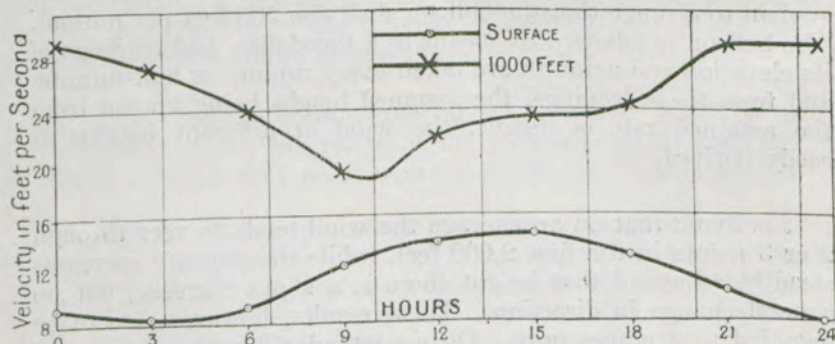


FIG. 2.—Diurnal Variation of Wind Velocity at the Base and the Top of the Eiffel Tower.

The task of computing the wind at any height from observations of wind at the surface being impossible frequent measurements of the wind at different heights are necessary. Fortunately the winds in the upper layer of the atmosphere are much more steady than those which prevail in the lower layers, where

the turbulence due to obstacles on the ground upsets the steady state. The observations are usually carried out by the pilot balloon method briefly sketched above, but there are several other methods in use. A variant of this method, in which the balloon is followed with two theodolites, placed at the ends of a base line of known length and orientation, gives results which are independent of any assumption as to the rate of ascent of the balloon. The single theodolite method is usually accurate enough for firing under service conditions, but for application to accurate experimental work such as Range and Accuracy trials, the two theodolite method is necessary. A third method of measuring the wind at given heights is by observation of the drift of smoke from shells timed to burst at the given heights. The drift of the smoke from the burst is followed by one or two mirrors, the two mirror method being somewhat more satisfactory. During the War the French Meteorological Service developed a fourth method, consisting in sending up small balloons with charges timed to burst approximately at a given height, the bursts being located by the sound ranging method. This method is very useful in cloudy or foggy weather, but as it demands the use of considerable personnel, transport and material, it has not come into common use.

When it is not possible to obtain direct measurements of the upper winds, a trained meteorologist who has before him a complete synoptic chart, can form a reliable estimate of the upper winds from the distribution of pressure and temperature.

The Equivalent Constant Wind.

The variation of wind with height is allowed for in the following manner. The trajectory of the projectile in still air under standard conditions is known from a small arc computation. The height of the trajectory is divided into a number of layers of equal thickness, as in fig. 3, where for convenience five layers only are taken. The points A, B, C, &c., are the points at which

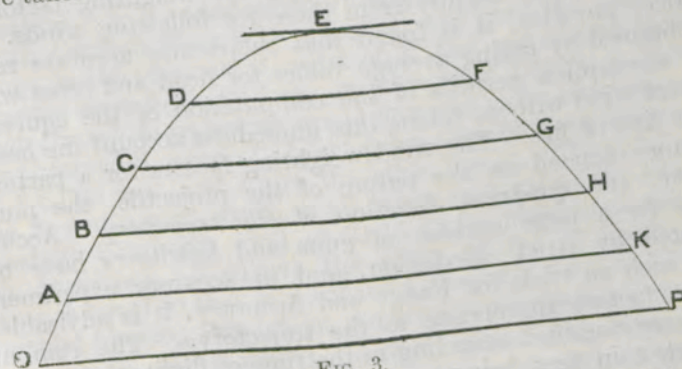


FIG. 3.

the trajectory enters or leaves successive layers. By a laborious but quite straightforward computation it is possible to calculate the effect upon the range, of a wind of 1 foot per second which

starts to affect the projectile at any of the points O to K, and continues to the end of trajectory. Consider first the effect of a following wind. It may be noted in passing that a head wind has for all practical purposes exactly the opposite effect to an equal following wind. Let the increase of range due to a following wind of 1 foot per second along the whole of the trajectory be r , and let the increase of range due to a following wind starting at any one of the points A, B, . . . K, and continuing to the end of the trajectory, be $a, b, . . . k$. Then the increase of range due to a following wind of 1 foot per second blowing only during the part OA of the trajectory is $r - a$, the increase of range due to a wind of 1 foot per second blowing only during the part AB of the trajectory is $a - b$, &c. The increase of range due to a wind of 1 foot per second blowing in the layer ABHK is $(a - b) + (h - k)$. This quantity is expressed as a fraction of the increase of range r , produced by a wind of 1 foot per second blowing during the whole trajectory. The fraction $\frac{a - b + h - k}{r}$

is called the *weighting factor* for the layer considered (the second layer in this particular case). A following wind of 1 foot per second blowing only in the second layer has the same effect upon range as a wind of $\frac{a - b + h - k}{r}$ feet per second blowing during

the whole trajectory. The weighting factors for the other layers are evaluated in the same way. The weighting factors so evaluated give a measure of the relative effects upon range of winds in different layers of the trajectory. If the wind observed in each layer be multiplied by the corresponding weighting factor, the sum of the products so obtained is the wind which, blowing during the whole trajectory, would produce the same effect on range as the observed winds. This fictitious constant wind is called the *equivalent constant wind*.

The weighting factors for cross winds are evaluated by a similar process. It is found that in general the weighting factors for cross winds differ slightly from those for following winds. In practice, however, it is found that sufficiently accurate results are obtained by taking average values for head and cross winds. This assumption permits of the computation of the equivalent constant wind without taking into immediate account the bearing of the line of fire. The wind weighting factors for a particular trajectory depend on the nature of the projectile, the muzzle velocity, and quadrant elevation of the trajectory. Accurate factors for a large number of guns and howitzers have been evaluated by strict calculation, and in accurate experimental work, such as trials for Range and Accuracy, it is advisable to use the factors appropriate to the trajectory. The computed factors are classified according to the time of flight, the height of the vertex in feet being assumed to be given with sufficient accuracy by $4t^2$, where t is the time of flight in seconds. Mean values of the weighting factors for times of flight 7, 10, 20, 30, 40, and 50 seconds have been evaluated from the computed

factors, and in the field these average factors are used for computing the equivalent constant wind. Usually the layers are taken to have a thickness of 2,000 feet.

The method of computation of the equivalent constant wind can be most easily explained by an example. The following table gives the computation of the equivalent constant wind for a 50 sec. trajectory, from the observations represented in Fig. 1a for June 18th, 1917, at 5 p.m.

Layers.	Observed Speed.	Wind Direction.	West Component.	South Component.	Weighting Factors.	W. Component of e.c.w.	S. Component of e.c.w.
8-10,000 ...	57	230°	44	37	·43	18·92	15·91
6-8,000 ...	58	225°	41	41	·18	7·38	7·38
4-6,000 ...	47	226°	34	33	·15	5·10	4·95
2-4,000 ...	30	244°	27	13	·13	3·31	1·69
0-2,000 ...	28	247°	26	11	·11	2·86	1·21
					1·00	37·57	31·14

Equivalent constant wind is 49 ft./s. from 230° (40° S. of W.).

The second and third columns give the speed and direction of the wind, the latter being specified by the bearing from North, measured clockwise, of the direction from which the wind blows. The next two columns give the components of the winds in each layer resolved along the West-East, and South-North line. The 6th column gives the weighting factors. The 4th and 5th columns are multiplied by the weighting factors, and the results written in columns 7 and 8. The equivalent constant wind has therefore components 37 feet per second from West, and 31 feet per second from South, and the resultant of these is 49 feet per second from 230°, or 40° S. of W.

The separate items in the last two columns admit of simple explanation. A S. wind of 15·91 feet per second affecting the projectile through the whole trajectory will have the same effect on range as the observed S. wind of 37 feet per second blowing only in the layer 8-10,000 feet. A S. wind of 7·38 ft./s. blowing through the whole trajectory would have the same effect on range as the observed S. wind of 41 feet per second blowing only in the layer 6-8,000 feet, and so for the other layers. The total effect of the S. component winds in all layers is equal to the effect of a constant Southerly wind of 31·14 ft./s. blowing during the whole trajectory. Similarly the effect of the Westerly components is equal to that of a constant Westerly wind of 37·6 feet per second blowing throughout the whole trajectory.

It is to be noted that in the example given in the above table the weighting factor for the top layer is much greater than for any other layer. This is a universal rule for wind weighting factors, which are least for the lowest layer and greatest for the top layer.

It may be added that if it is desired to compute the effect of wind upon the time of flight of a projectile, the weighting factors to be used would differ from those for following or cross winds.

Density.

The resistance of the air to the motion of a shell is directly proportional to the density, or the mass per unit volume of the air. It is not practicable to obtain direct measurements of the density, but it is easily determined by means of the factors on which it depends; namely, pressure, temperature and humidity. The effect of the last of these is very small in comparison with the other two, so we shall limit ourselves in the first place, to the consideration of pressure and temperature only. If we refer to any range tables, we find a column which gives (a) the effect of 10° variation from normal of the temperature of the air, and a column which gives (b) the effect of 1 inch variation in barometric reading. The density correction is thus done in two apparently independent steps, and it is of some importance to see that the separation into two steps is reasonable and sufficient.

Consider a unit mass of gas, whose pressure is p_0 , absolute temperature T_0 , and density ρ_0 under standard conditions. Let pressure be p_1 , temperature T_1 , and density ρ_1 under any other conditions. The change from the set of conditions p_0 , T_0 , ρ_0 to the set of conditions p_1 , T_1 , ρ_1 may be satisfactorily represented as taking place in two stages.

(a) Let the pressure change from p_0 to p_1 , while the temperature remains constant. The density ρ_0 is changed to ρ' , where by Boyle's Law

$$\frac{p_0}{\rho_0} = \frac{p_1}{\rho'} \text{ or } \rho' = \rho_0 \frac{p_1}{p_0} \dots\dots\dots A$$

This equation is simply a statement that, so long as the temperature remains constant, the density is proportional to the pressure.

(b) The second stage consists in keeping the pressure constant at p_1 , while the temperature changes from T_0 to T_1 , and the density changes from ρ' to ρ_1 . So long as the pressure is unchanged, the volume of a given mass of gas is proportional to its absolute temperature, and therefore its density is inversely proportional to the absolute temperature.

$$\begin{aligned} \text{i.e., } \frac{\rho'}{\rho_1} &= \frac{T_1}{T_0} \\ \text{or } \rho_1 &= \rho' \frac{T_0}{T_1} \dots\dots\dots B \end{aligned}$$

The method of correcting for density by means of the appropriate columns for barometer and temperature in the range tables really consists in the application of formulæ A and B in turn. It must here be emphasized that the variations in ρ , p and T are never more than small fractions of the quantities themselves. The temperature T is measured on the absolute Fahrenheit scale, i.e., 60°F. is 519.4° absolute F.

Combining equations A and B we find

$$\begin{aligned} \rho_1 &= \rho_0 \frac{p_1}{p_0} \frac{T_0}{T_1} = \rho_0 \frac{1 + \frac{p_1 - p_0}{p_0}}{1 + \frac{T_1 - T_0}{T_0}} \\ &= \rho_0 \left(1 + \frac{p_1 - p_0}{p_0} - \frac{T_1 - T_0}{T_0} \right) \end{aligned}$$

approximately, since $p_1 - p_0$ is only a small fraction of p_0 , and $T_1 - T_0$ a small fraction of T_0 .

$$\therefore \rho_1 - \rho_0 = \rho_0 \left(\frac{p_1 - p_0}{p_0} - \frac{T_1 - T_0}{T_0} \right) \dots\dots\dots C$$

This equation again shows the corrections for pressure and temperature separately.

A change of 1 inch in pressure, while temperature remains constant, gives a change $\frac{\rho_0}{30}$ in ρ_0 and a change of temperature of 10°F. while pressure remains constant, gives a change of $\rho_0 \frac{10}{519}$, or $\frac{\rho_0}{52}$ in ρ_0 . Thus the effect on density of a change of 1 inch in pressure is $\frac{52}{30}$ or 1.73 times the effect of a change of 10°F. in temperature.

It will, in fact, be found that the figures in the column in the range tables headed "One inch variation in the barometric reading," are about 1.73 times the figures in the column headed "10 degrees variation in temperature of air."

The two corrections can also be related quite simply to the column headed "effect of 10 per cent. change in ballistic coefficient," which is included in some range tables. The rate of loss of velocity of a shell moving in air, due to resistance is directly proportional to the density, and inversely proportional to the ballistic coefficient. The effect of 10 per cent. increase of density is therefore the same, approximately, as 10 per cent. decrease of ballistic coefficient. Thus the effect of a change of

1 inch in pressure, which is equivalent to a change of $\frac{1}{30}$ in density, is equivalent to a change of 3.3 per cent. in ballistic coefficient. It will be found on reference to any set of range tables that the figures in the column giving the effect of a change of 1 inch in barometer are $\frac{1}{3}$ of those in the column giving the effect of a 10 per cent. change of ballistic coefficient.

Before considering the treatment of deviation of the temperature and pressure from standard, it is desirable to define clearly the standard conditions. The average densities actually observed at different heights are found to agree very closely with the formula.

$$\log \frac{\rho_0}{\rho} = \frac{.141h}{10,000} \dots\dots\dots K$$

where ρ_0 is the density at the ground, ρ the density at height h , and h the height in feet. The density defined by this formula is taken as the standard density at all heights. The standard

pressure at the ground being 30 inches, and the standard temperature being 60°F., we can apply this formula to compute directly the density, and from the density, by the use of a formula not given above, we deduce the standard pressure and temperature. The following table gives the standard pressure and temperature at different heights:—

Height.	Pres- sure.	Temp.	Height.	Pres- sure.	Temp.	Height.	Pres- sure.	Temp.
5,000	25.02	50.4	16,000	16.54	23.0	—	—	—
4,000	25.95	52.4	14,000	17.86	28.8	35,000	7.46	-56.5
3,000	26.92	54.5	12,000	19.28	34.1	30,000	9.31	-30.5
2,000	27.92	56.4	10,000	20.78	39.0	25,000	11.54	-8.5
1,000	28.93	58.3	8,000	22.40	43.8	20,000	14.14	10.2
0	30.00	60.0	6,000	24.12	48.3	18,000	15.30	16.7

This table shows that the standard conditions of temperature are 60°F. at the ground, with a decrease of approximately 2.1°F. per 1,000 feet of elevation. It is convenient to be able to refer to this rate of decrease with height as the standard rate of decrease with height.

Pressure.

The pressure of the atmosphere near the ground is measured by means of the barometer. Two types of barometer are in general use: (a) the mercury barometer, and (b) the aneroid barometer. In the mercury barometer it is the height of the column of mercury held up by the air pressure which is measured. For artillery purposes it is usual to measure this column in inches. The observed height usually requires a small correction for expansion or contraction of the various parts of the instrument, due to temperature changes.

As this type of instrument is not suitable for transporting from place to place, it is customary to employ the second type, or aneroid barometer. The aneroid barometer consists of a metallic box from which all air has been exhausted. The effect of increasing pressure is to compress the box, and by means of a suitable arrangement of levers and a pulley this compression is indicated on a dial so graduated as to give the pressure in inches. Even with the most careful handling, this type of instrument tends to give readings deviating considerably from the true pressure, on account of imperfect elasticity of the metallic box. Rough handling, or the firing of heavy pieces near, are sufficient to produce changes in the readings of the aneroid. It is advisable to correct the aneroid by comparison with a mercury barometer at least once a month. In practice the height of the barometer for mean sea level is supplied in the "Meteor" telegrams. The M.S.L. reading has to be corrected for the height

of the battery. This is done with sufficient accuracy by subtracting from the reading supplied $\frac{1}{10}$ inch for each 100 feet of elevation of the battery above M.S.L.

Under standard conditions of temperature, the pressure falls off almost uniformly 1 inch for every 1,000 feet of elevation. Deviations from this rule can only be produced by deviations from the normal of temperature and humidity, and are implicitly taken into account in the computation of the "ballistic temperature," which is discussed later. The difference between the surface barometer reading and the standard value 30 inches can be taken to be a measure of the deviation of pressure from the normal at all points of a trajectory, since any change of pressure at the ground produces a proportionate change in the upper layers.

Temperature.

The temperature at the ground is obtained by reading a thermometer suspended in a properly ventilated screen. If no screen is available the thermometer can be hung in the shade of a tree. It is, however, important that it should be protected from the direct rays of the sun. A thermometer suspended in the sun does not give the air temperature, but gives an artificially high reading, due to the absorption of heat by the mercury.

The variations of temperature with height are much more complicated than variations of pressure, and it is necessary to obtain direct observations of temperature at different heights, up to the top of the trajectory. Such observations are made by means of thermometers or recording instruments carried by aeroplanes or kite balloons. These observations show that the deviation from standard of the surface temperature affords no indication whatsoever of the deviations from standard at different heights above the ground. For example the standard temperatures at the ground and at 10,000 feet are 60°F. and 39°F., but if on a particular occasion we observed a temperature of 50°F. at the ground, it would be highly dangerous to assume that the temperature at 10,000 feet was 29°F.

The problem we are now faced with is to find what is known as the "ballistic temperature." The ballistic temperature is closely analogous to the "equivalent constant wind." The range tables are drawn up for surface temperature 60°F., and the correction tables are made out for differences of ground temperature from 60°F., the rate of decrease of temperature with height being assumed to remain unchanged. On occasions when the rate of decrease with height differs from the standard rate, the observed surface temperature will require correction, and the corrected value is called the "ballistic temperature." This can be best illustrated by means of an example. We shall evaluate the ballistic temperature for a projectile reaching 10,000 feet (time of

flight 50 seconds). The trajectory is divided into 5 layers each 2,000 feet thick, and temperature observations are taken at the middle of each layer. At 10 a.m. on January 8th, 1920, the following observations of temperature in the upper air were made over S.E. England (Columns 2 and 3):—

—	Tempera- ture.	Standard Tempera- ture.	Difference from Standard.	Weighting Factor.	Product.
Feet.	°	°			
9,000 ...	30	42	— 12	·28	— 3·4
7,000 ...	36	46	— 10	·16	— 1·6
5,000 ...	41	50	— 9	·14	— 1·3
3,000 ...	43	55	— 12	·13	— 1·6
1,000 ...	26	58	— 32	·11	— 3·5
Surface ...	10	60	—	—	—11·4

In the 3rd column is given the standard temperature for each height and in the 4th column the difference of the observed temperature from the standard temperature for each height. As in each case the temperature was below the standard, the differences are negative. A given difference of temperature from the standard has a different effect in different layers of the atmosphere, and the "temperature weighting factors" given in the 5th column enable us to allow for the effects in the layers 0-2000 feet, 2-4, 4-6, 6-8, 8-10. In the last column are given the products of the 4th and 5th columns. The sum of the quantities in the last column, 11·4, gives the correction to the standard ground temperature 60°F., and the corrected ground temperature, which is called the "ballistic temperature," is therefore 48·6°F., or 49°F. to a sufficient degree of accuracy. Note that the temperature weighting factors differ from the wind weighting factors previously introduced.

This example shows very clearly the danger of using the observed surface temperature without any correction. The day referred to followed a night of clear sky, during which the ground and the air near the ground became very cold on account of radiation of heat from the earth into the clear sky. The effect was so marked that at the time of the observations the temperature increased with height up to about 4,000 feet, after which it decreased. This phenomenon of temperature *increasing* with height is usually referred to as an inversion. Inversions are particularly liable to occur on winter mornings (and to a less extent in spring and autumn) after a clear night with light winds. For low trajectories it is legitimate to use the uncorrected surface temperature in the middle of the day with moderate or strong winds, but usually accurate shooting is only possible when a ballistic temperature is available.

If no observations are available, a meteorologist can usually give a fairly reliable estimate of the ballistic temperature, but estimates should only be regarded as of value if made by a meteorologist of experience.

Humidity.

There is always a certain amount of water vapour present in the atmosphere, and although it never amounts to more than a small fraction of the total mass of air, it is necessary to take account of its effect on density, particularly at high temperatures. The most convenient measure of the state of the air as regards water vapour content is relative humidity, which expresses the amount of water vapour present as a percentage of the amount of water vapour necessary to saturate the air at that temperature. Relative humidity is subject to considerable variations with time, place, and altitude, and on any particular occasion direct measurements are necessary. These measurements are made by observing the difference in temperature between an ordinary thermometer (dry bulb) and another thermometer whose bulb is covered with a piece of muslin which is kept moist, or it may be observed by means of a hair hygrometer.

In the construction of range tables the standard humidity is taken as 50 per cent., corresponding to half saturated air. Allowance for variations from the standard is readily made by increasing or diminishing the observed temperature in such a way that half saturated air at the corrected temperature is at the same density as the air under consideration. In practice the temperatures observed at different heights are corrected for humidity in this way, and the corrected temperatures are entered in the second column of the table on page 12, so that the "ballistic temperature" takes account of variations of humidity.

The "Meteor" Telegram.

The telegrams sent out by Meteor give all the necessary meteorological information. They give the equivalent constant wind, and the ballistic temperature for projectiles whose time of flight are 50, 40, 30, 20, 10 and 7 seconds. (For higher times of flight the necessary data can usually be supplied on demand). The telegram also gives the height of the barometer at mean sea level. A specimen telegram is shown below:—

5056 41267 4058 34262 3055 27256 2052 23242
1050 19231 0746 16223 Bar. 3060 Meteor 10.45 a.m.

The first two figures in each 4-figure group give the time of flight to which the next two figures and the following 5-figure group refer. The third and fourth figures in each 4-figure group give the ballistic temperature. The first two figures of the 5-figure group give the velocity in ft./s., and the last three figures the direction in degrees from North of the equivalent constant wind. The barometer is given at M.S.L. to the nearest hundredth of an inch.

The telegram thus means.

For 50 secs. time of flight ballistic temperature is 56°F . and wind 41 ft./s. at 267° (3° S. of W.). For 40 secs. time of flight the ballistic temperature is 58°F . and wind 34 ft./s. at 262° (8° S. of W.), and so on. These are the values which should be used in correcting the assumed range in accordance with tables appended to the range tables.

Directions are measured in degrees, not from Magnetic North, but from True North, *i.e.*, for all practical purposes from Grid North; velocities are always given in ft./s. If the velocity is less than 10 ft./s. a "0" is inserted before the unit figure, and, similarly, if the direction angle is less than 100° . For example, the five figure groups (a) 09043, (b) 09009 mean:

(a) The wind is 9 ft./s. at 43° (*i.e.*, 43° E. of N.).

(b) The wind is 9 ft./s. at 9° (*i.e.*, 9° E. of N.).

If the velocity is 100 ft./s. or more the five figure group becomes a six figure group, and the first three figures give the velocity, *e.g.*, 112270 means that the wind is 112 ft./s. at 270° (West). Barometer 3060 means the barometer at M.S.L. is 30.60 inches. This ought to be corrected for the height of the battery; the height in feet divided by 1,000 gives the amount in inches which must be subtracted from the M.S.L. reading with sufficient accuracy. *e.g.* Height of battery 200 feet. Correction .20 inches.

Reading supplied 30.60 inches.

Actual reading at battery level 30.40 inches.

The following are examples of the application of corrections from meteorological results given in the above telegram:—

Battery height 200 feet, barometer correction for height .20 inches.

1. 8-inch B.L. Howitzer. Firing due east at 6,000 yards with 4th charge.

Time of flight 18.3 secs. Take values for 20 secs., *i.e.*, 23 ft./s. at 242° and 52°F .

Map range 6,000 yards.

Barometer, 30.40 +18 "

Air temperature, 52° +21 "

Following wind, 20 ft./s. -96 "

Right deflection to correct for cross wind 11 ft./s. = $8'$.

2. 8-inch B.L. Howitzer. Firing NE. at 10,000 yards with 4th charge.

Time of flight = 39.5 secs. Take values for 40 secs., *viz.*, 34 ft./s. at 262° and 58°F .

Map range 10,000 yards.

Barometer, 30.40 +37 "

Air temperature, 58°F +11 "

Following wind, 27 ft./s. -273 "

Cross wind blows from left to right, therefore left deflection for cross wind 20 ft./s. = $25'$.

3. 28-pdr. quick-firing gun. Firing due east at 7,000 yards with cordite charge.

Time of flight 23.0 secs. Take values for 20 secs., *viz.*, 28 ft./s. at 242° and 52°F .

Map range 7,000 yards

Barometer, 30.40 +36 "

Air temperature, 52° +42 "

Following wind, 20 ft./s. -132 "

Right deflection to correct for cross wind of 11 ft./s. = $15'$.

Other Variations.

The information contained in the Meteor telegram includes all meteorological data that we have learned to apply to artillery corrections.

It cannot be claimed, however, that all variables have been thereby accounted for, *e.g.*, the temperature of the charge. Deviations of the temperature of the charge from the standard values modify the M.V. of the projectile, and hence affect the range. Corrections which allow for this effect are included in range tables.

In addition, deviations of the temperature of the air from standard values not only produce an effect through the consequent changes of density which we have already considered, but also through their effect on the elasticity or compressibility of the atmosphere. This effect is negligible at velocities below about 900 ft./s, but may be considerable at velocities near that of sound.

The corrections which have to be made to allow for this effect, have been evaluated for a number of guns and for different trajectories. It has been found that the effect is usually small. The correction for elasticity is included with the temperature correction for density in recently published range tables.

The physical explanation of the elasticity variations is closely bound up with the variation of the velocity of sound with temperature. As a shell moves through the air, it compresses the air immediately in front of it, and this compression tends to travel away with the velocity of sound. If the shell is travelling with a velocity lower than that of sound, the wave of compression gains on the shell, while if the velocity of the shell is greater than that of sound the shell gains on the wave of compression. In either of these cases the compression in front of the shell is being continually dissipated, and continually recreated. If, however, the velocity of the shell is approximately that of sound in the air, the compression will be continually reinforced, so that the resistance to the motion of the shell becomes relatively very great. The velocity at which the maximum effect of compressibility will enter is thus dependent on the temperature of the air.

Densities at Great Altitudes.

Below 35,000 feet the mean density is represented with great accuracy by the formula given on p. 9. Above this height the temperature does not vary appreciably with height, and so the density decreases less rapidly than can be allowed for by the use of the formula.

Various formulæ have been suggested, the simplest and most accurate being

$$\log \frac{\rho_0}{\rho} = .4935 + .21 \left(\frac{h - 35,000}{10,000} \right)$$

where ρ is the density at height h feet, and ρ_0 is the density at the ground.

On account of the small density of the atmosphere at these heights, the head resistance to the motion of a projectile is very small, so that any projectile with high value of C_0 fired at a high Q.E. with sufficiently high muzzle velocity to attain these heights will have long range.

Some Practical Questions.

1. Battery and Target at Different Levels.

It has been found in the computation of the effects of wind and density changes in a trajectory that the variations occurring after the shell has reached the vertex are of much less relative importance than variations occurring early in the trajectory. For example, if the variation commences when the shell has completed half its flight from the vertex to the ground, the weighting factors seldom exceeds 4 per cent., and averages about 2 per cent. It follows, therefore, that if the target lies at even a considerable height above or below the level of the gun, the meteorological corrections may be taken as being the same as for fire on the flat with the same Q.E.

The exceptional case in which the target is so far below the gun as to require a negative Q.E. has never been considered from the meteorological standpoint, but weighting factors could readily be evaluated for these cases from existing computations should they ever be needed.

2. The Effect of Cloud and Rain.

It must be noted that if water particles are present in the atmosphere they will not behave simply like a gas. On encountering the cap of compressed air which immediately precedes a shell, the water drops will acquire some of its velocity, and to this extent they act merely in the sense of increasing the effective density of the air. But in addition to this, a certain fraction of the water drops will be actually picked up by the shell, and by their impact will retard its motion. The "density effect" may be regarded as the minimum and the "impact effect" as the maximum which can be produced. To what

extent the "impact effect" actually occurs there is at present no means of knowing exactly, and we are therefore compelled to adopt what seems a reasonable figure.

Numerical calculation shows that at ground level the "density effect" of cloud or mist is equivalent to an increase of 0.4 per cent. in the density of the air, whilst the maximum "impact effect" of the same is about ten times as large, or 4 per cent. The effects of even very heavy rain are only about one-fifth of these.

The practice adopted at Shoeburyness in connection with artillery experiments is to increase the tenuity factor by 2 per cent. if the trajectory lies wholly in cloud, and proportionally if it is only partly in cloud. The correction of 2 per cent. to the tenuity factor may be very simply made by subtracting 10° from the ballistic temperature.

The effect of rain is ordinarily so small that it is neglected.

3. The Effect of Increase or Decrease of Density on the Correction for Wind.

The displacements due to wind are calculated for air of standard density, and moreover the displacements are directly proportional to the density. If, therefore, the density of the air is above the standard value by, say, 2 per cent., then the corrections for wind will be 2 per cent. higher than those given in the range tables. This correction is, however, a small one, being in fact "a correction to a correction," and in practice is usually so small that it need not be considered.

