July covers 11 days only. The scale of wind force is as follows: 6= gale, or 45 miles per hour; 7=strong gale or 60 miles per hour, and 8=violent gale, or 75 miles per hour. Fog has been regarded as 10 on the scale of clouds. Observe that there was a vast deal of cloudy or foggy weather in March, April, May, June, and July. In June there was not a clear day. The cold in winter is keenly felt because of the high winds and by reason of the moisture in the air—there are open places in the ice.

## THE SLUGGISHNESS OF THERMOMETERS.

By C. F. MARVIN, Professor of Meteorology.

When a thermometer is placed in a medium, the temperature of which is not the same as that of the thermometer, an interchange of heat immediately sets in and presently the thermometer and the medium take on the same temperature. A sluggish thermometer will be slow to arrive at the temperature of the medium, whereas a sensitive thermometer will take this temperature much more quickly. The foregoing brings out the significance of the words sluggish and sensitive in the present connection, and, in what follows, methods will be described by which these qualities or properties of thermometers may be measured, and the results applied in estimating the accuracy of the observations obtained by the use of a given instrument to measure the temperature of a medium, especially when this temperature changes more or less rapidly.

It is obvious that if the temperature of the medium changes quickly, and more or less continuously, there will be a "lag" in the indications of the thermometer, depending upon its sluggishness and the rapidity with which the temperature continues to change; that is, the temperature indicated by the thermometer at a given moment of time will be a temperature experienced by the medium several moments before. In other words, the temperature of the thermometer will be a certain amount higher or lower than that of the medium, and the discrepancy will persist as long as the temperature of the medium continues to change in the same sense. This lag is especially marked when more or less sluggish thermometers and thermographs are used in the measurement and registration of the temperature of the air, since the latter has but a small capacity of carrying heat to or away from a thermometer bulb. Whenever it is practicable to do so, therefore, the air whose temperature is desired, is passed in a strong current over the bulb of the thermometer, or the thermometer itself is whirled through the air at a comparatively rapid rate; both accomplish the object of bringing the thermometer quickly to the temperature of the air, or, if the air temperature is changing, of reducing the error due to sluggishness to the minimum.

The effects of sluggishness are illustrated perhaps more strikingly in the accompanying diagram, Fig. 1. First let us suppose a thermometer to be quickly plunged into cold air of a constant temperature, represented on the diagram by the line *T T*. Owing to its sluggishness the thermometer does not instantly take on the temperature of the air, but reaches it gradually after a series of changes, such as represented by the curve $t_1$ $t_2$, for example. If, however, the temperature of the air changes steadily, the thermometer either does not acquire the temperature at all, or assumes it momentarily only to lag behind afterward, as shown in the diagram, where $d$ and $d'$ indicate the errors in the indications of the thermometer due to sluggishness, when the temperature changes uniformly. The error is larger the more sluggish the thermometer and the more rapid the rate of change in air temperature.

*Effects of ventilation.*—When the circulation of the air about the bulb of a thermometer is so rapid that the surface of the bulb is maintained at sensibly the same temperature as that of the air, the thermometer will then exhibit its maximum sensitiveness, and no increase in the rapidity of circulation will further affect the sensitiveness. The sluggishness in such cases has to do wholly with the flow of heat in the interior of the bulb and the movement of the mercury in the narrow bore of the tube. When, however, the temperature of the exterior surface of the bulb is not maintained at the same point as that of the medium as a whole, then we may consider that portions of the medium stagnate, as it were, about the thermometer and prevent the free escape of heat from the bulb, or its access thereto, as the case may be. The apparent sluggishness under these circumstances may be very considerable, and differs according to the degree of circulation. The degree of ventilation required to secure the maximum sensitiveness is hardly known, but for air it is doubtless very considerable, whereas for thermometers plunged in water, for example, it is probable that, under moderate agitation, the extreme surface of the bulb is sensibly at the same temperature as that of the liquid.

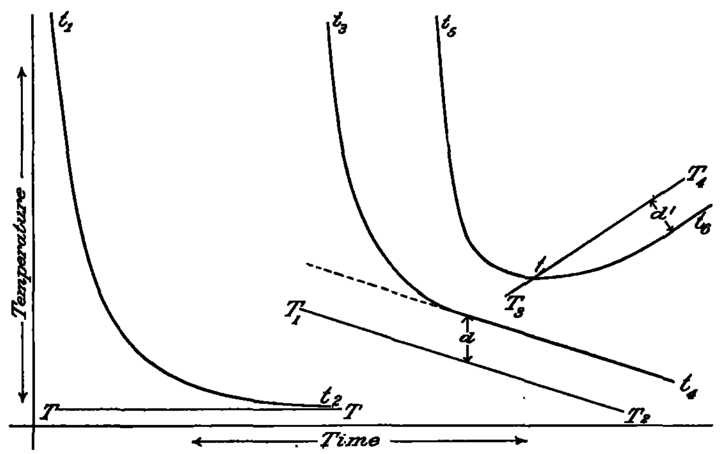


FIG. 1.—Curves illustrating sluggishness of thermometers.

$t_1$ $t_2$ temperature curve of a warm thermometer placed in a colder medium whose temperature remains constant.

$t_3$ $t_4$ temperature curve for a warm thermometer in a colder medium whose temperature steadily falls. The temperature of the thermometer continues $d$ units higher than that of the medium.

$t_5$ $t_6$ temperature curve for a warm thermometer in a colder medium whose temperature steadtly rises. At $t$ the temperature of the thermometer and the medium are momentarily the same and the curve is horizontal, but owing to its sluggishness the thermometer presently thereafter indicates a temperature $d'$ units too low.

According to the accepted theory of the flow of heat under these circumstances, it is assumed that the rate at which the thermometer will change its temperature at any given instant is proportional to the difference between its temperature at the moment and that of the ambient medium. In order to express this in the form of an equation—

Let $U$ = the temperature of the air at any moment.

Let $u$ = the corresponding temperature indicated by the thermometer.

Then, the momentary rate at which the thermometer changes its indications will be

$$\text{Rate} = r = k\,(U - u) = \frac{du}{dt}$$

In which $k$ is a coefficient of sensitiveness to be determined by experiment. The greater the value of $k$ the more sensitive the thermometer.

This equation is one of the most convenient for computing the value of $k$ from experiments, especially when the thermometer traces its own record, as in the case of thermographs recording on sheets moving at a comparatively rapid rate.

When thermographs are sent up into the free air on balloons, kites, etc., which generally pass more or less quickly through strata of air having successively different temperatures, it is highly desirable that the instruments should be as sensitive as possible, but it is quite as important that the errors due to sluggishness, whatever they are, be more or less carefully determined. For this purpose the writer made, during February, 1899, a large number of experiments with the thermographs that had been employed by the Weather Bureau during the summer of 1898, in procuring temperature data in the free air by means of kites.

The meteorograph, which in addition to temperature, records also the velocity of the wind, the humidity and pressure of the air, is shown in Fig. 2, Plate I. The thermometer is the part with which we are now especially concerned. What corresponds to the bulb of this is made compound, in order to secure greater sensitiveness, and is shown separately in Fig. 3, Plate I. It consists of two small Bourdon pressure tubes coupled together, side by side. This compound bulb is mounted in a concentric position, nearly in the middle of the cylindrical tube seen at the top portion of the picture of the meteorograph, Fig. 2. When so mounted, one end of the bulb, *a*, Fig. 3, is adjustably fastened to the cylindrical tube; the other end, *b*, Fig. 3, is connected by suitable linkages to the second recording pen from the left, as seen in Fig. 2. Thus arranged, the pen moves laterally over a portion of the record sheet according to changes taking place in the temperature of the bulb. The pressure tubes composing the bulb are made of very thin, hardened, and highly elastic steel. In the process of filling, the ends of the bulbs are first spread apart a certain distance, and, while in this strained condition, pure alcohol or ether is introduced until the bulbs are completely filled, every bubble of air being carefully excluded. The tubulure is then closed and hermetically sealed. When the spreader is taken out from between the ends of the tubes, the latter tend to resume their normal distance, but, are prevented from doing so by the liquid, within. Every change in the volume of the liquid, with change of temperature, is thereafter accompanied by a corresponding movement of the free end of the tube. This motion, suitably magnified and recorded, suffices to indicate and record the temperature of the bulb. The meteorograph is so attached to the kite that throughout an ascension the wind blows with full force through the tube containing the thermometer bulb, thereby securing the greatest possible circulation of the air around the bulb, which, at the same time, is fully screened from direct radiation.

The instrument is designed primarily to measure and record the temperature of a *current* of air in which it is placed. Special precautions are taken to cut off radiation and to prevent loss or gain of heat by conduction to or from the remaining metalic parts of the instrument. Under these circumstances, if the air is prevented from circulating freely through the tube enclosing the thermometer bulb, there is so little opportunity for the bulb to change its temperature that seemingly the instrument is very sluggish. This characteristic was brought out in the first experiment made. Meteorograph No. 1, after having acquired the temperature of the room (70° F.), was quickly placed outdoors in front of a small electric fan which forced the air in a moderately strong current over the thermometer bulb. The circulation was judged to be equivalent to that during an average kite ascension. After about three minutes exposure the thermometer had reached the temperature of the air (30° F.). The instrument was then returned quickly to the room, but not subjected to any artificial ventilation whatever. At the end of thirty-seven minutes the instrument recorded 68° with a slight rising tendency. The apparent extreme sluggishness in this case is due to the stagnation of the air near the bulb of the thermometer.

In order to measure accurately the sluggishness of these instruments a number of experiments similar to the above were made, that is, the instrument was moved quickly from a warm room to the cold outside air and vice versa, the recording pen tracing its record of the change of temperature automatically on the record sheet; the air in every case was artificially circulated by means of an electric fan. Experiments of this character were had in mind when the meteorograph was designed by the writer, and a simple arrangement of the clockwork driving the recording cylinder was employed whereby a sufficiently rapid motion of the record sheet (0.2 of an inch per minute) was secured at will by simply tightening a screw. The normal speed of the record cylinder is one revolution in twelve hours or one inch per hour on the record sheet.

It was soon found in the first experiments that the results were rendered indefinite by the circumstance that during the few minutes occupied by the thermograph in assuming the same temperature as that of the air, the latter itself had changed appreciably and in an irregular manner. This was largely remedied by conducting the tests within a closed box approximately circular in form, measuring about 12 inches in depth and nearly 36 inches in diameter. The fan and meteorograph being completely enclosed in this box the same air was driven around and around, so that its change of temperature was a very gradual and progressive one.

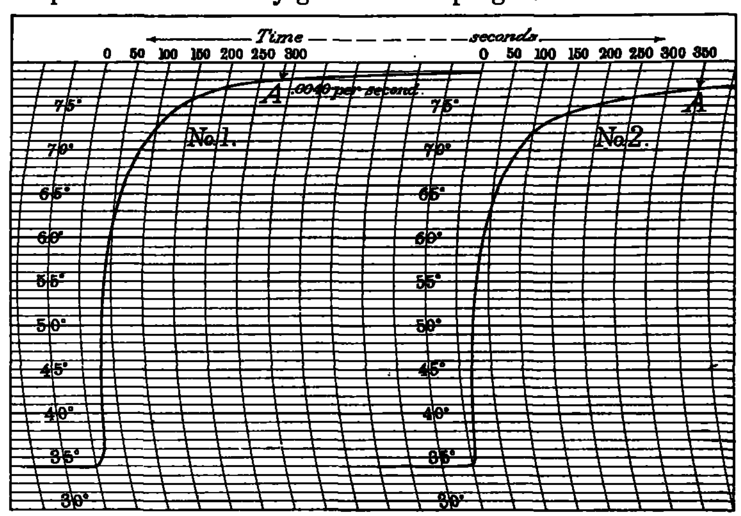


FIG. 4.—Record from kite thermograph.

Fig. 4 is a full scale reproduction of a portion of one of the record sheets, showing two curves for rising temperature. The numbers at the top indicate the elapsed time, in seconds, from an arbitrary starting point; the numbers at the left represent the temperature in degrees, Fahrenheit. At the point *A*, on curve No. 1, careful inspection shows that the thermograph had attained a temperature after which the rate of change was very uniform, as shown by the portion of the record at the right. We assume that this portion of the trace shows the uniform rate at which the air in the box changed its temperature. This conclusion is abundantly sustained by numerous eye readings of a fixed mercurial thermometer, showing practically the same steady change. In the case of the No. 1 record the steady change was at the rate of 0.0040° per second. A large portion of the No. 2 record was omitted in the reproduction of Fig. 4, but the measured rate, after the point *A* was passed, was 0.0039° per second.

It may be remarked here that the record sheets employed by the Weather Bureau on automatic instruments, such as the thermograph in the present case, for example, are printed from photo-engravings on copper or zinc, made by a special process devised by the writer. All the lines are traced automatically by a special dividing engine, and the finished engraving is practically perfect as regards dimensions and spacings in every detail. It was impossible to bring out all the excellent qualities of the original record in the reproduction shown in Fig. 4, but the originals admit of accurate analysis and measurement.

It was pointed out on page 458, in connection with Fig. 1, that when the medium is steadily changing its temperature there is a certain amount of temperature "lag" in the indications of the thermometer placed therein, depending upon its sluggishness and the change going on in the temperature.

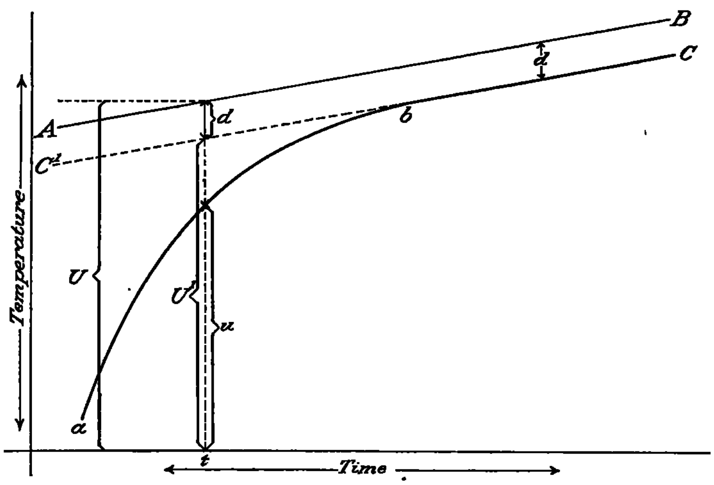


FIG. 5.—Diagram illustrating sluggishness.

These considerations lead to the following method of deducing the coefficient of sensitiveness from such automatic records as shown in Fig. 4. Referring to Fig. 5, let the curved line *a b c* represent the changes of temperature of a thermometer when placed in a medium whose steadily changing temperature is represented by the line *A B*. A portion, *b c*, of the curve *a b c* will, under these circumstances, be parallel to *A B*, and will represent the fact that the thermometer has attained as nearly as it can the changing temperature of the medium, but differs from it by some constant quantity, *d*, as represented. Let the line *b c* be prolonged backward, as shown. Now, at any given instant of time, *t*, let *u* represent the temperature of the thermometer, and *U* that of the air. Also let *U'* be the temperature up to the prolonged portion of *b c*. Then the equation given on page 458 becomes:

$$\text{Rate} = r = k\,(U' + d - u),$$

from which we may write

$$(U' - u)\,k = r - kd.$$

The rate at which the thermometer is changing its temperature at any given instant is easily found from the automatic traces by measuring the inclination of the tangent to the curve at the point in question. This is best done by the aid of a small piece of glass having smooth and straight edges and a fine diagonal line etched on one face. Placing this over the record sheet the line can be adjusted to coincidence with any desired portion of the curve with the utmost exactness. If now a straight edge be adjusted against one edge of the glass, the plate may be shifted along the straight edge and the engraved line made to intersect the rulings of the record sheet in such a manner that the rate may be conveniently and accurately read off. In the present case the number of degrees traversed by the line for one hundred seconds of time was generally made the basis of a measurement, and the rate expressed in degrees per second. Owing to the curved nature of the time rulings on the sheet the rates thus determined are subject to some error, which is quite small at low rates of change, but for large rates the result is entirely vitiated. When the thermometer differs 8° to 10° and less from the air temperature, the corresponding rates can be measured with sufficient exactness. The results thus obtained quite satisfy the object of the present discussion.

The point *A*, Fig. 4, at which the curves merge into the straight line portion, is first carefully located by aid of the line on the glass plate, the rate of change of temperature represented by this line being also determined at the same time. The actual temperature, corresponding to the point *A*, is also noted. This gives us the quantity *U'*, corresponding to the point *A*. The value of *U'* for any preceding instant of time is easily computed from the measured rate for that portion of the record to the right of the point *A*. By way of illustrating further the method of analyzing these records, the following results for curve No. 1, shown in Fig. 4, are given:

TABLE 1.—*Curve No.* 1, *Fig.* 4.

| Time. | $U'$. | $u$. | $U'-u$. | Rate. | Equations. | $k$. |
|---|---|---|---|---|---|---|
| *Seconds.* | ° | ° | ° | | | |
| 50 | 77.01 | 59.00 | 18.01 | .......... | * | .......... |
| 75 | 77.11 | 68.04 | 9.07 | 0.2560 | $9.07\,k=0.2560-kd$ | 0.0278 |
| 100 | 77.21 | 72.30 | 4.91 | 0.1900 | $4.91\,k=0.1900-kd$ | 0.0379 |
| 125 | 77.31 | 74.75 | 2.56 | 0.0720 | $2.56\,k=0.0720-kd$ | 0.0266 |
| 150 | 77.41 | 76.00 | 1.41 | 0.0365 | $1.41\,k=0.0365-kd$ | 0.0231 |
| 175 | 77.51 | 76.60 | 0.91 | 0.0260 | $0.91\,k=0.0260-kd$ | 0.0242 |
| 200 | 77.61 | 77.01 | 0.60 | 0.0147 | $0.60\,k=0.0147-kd$ | 0.0217 |
| 285 | 77.95 | 77.95 | 0.00 | 0.0040 | $0.00\,k=0.0040-kd$ | .......... |

* Equation indeterminate because of curved rulings, see Table 3.

It will be noticed that each measurement of a rate gives an equation containing *k* and *kd*, also that when the point *A* is reached the term containing *k* vanishes and the equation gives directly a value of the product *kd*. Inasmuch as it seemed probable the value of *k* was not strictly constant for all parts of the curve, it was concluded best to compute individual values of *k* from each equation, using throughout the approximate value of *kd* given at the point *A*. These individual values of *k* are given in the last column of the foregoing table.

Tests of this character were made on four different meteorographs, namely: No. 1, used at the Washington kite station; No. 2, used at Sault Ste. Marie, Mich., and Pierre, S. Dak.; and No. 13, used at Dodge, Kans. The last instrument tested was No. 6, but the arrangement of magnifying levers was changed, so that the rulings on the sheet normally representing degrees corresponded to only 0.31°. This, of course, gave an entirely different character of curvature to the automatic records and rendered the determination of the rates more satisfactory for the smaller differences between the temperatures of the air and the thermometer.

The following tables give the results for the four different meteorographs, the entry *U—u* being the actual difference between the temperature of the air in each case and that indicated by the thermometer. This is computed from the expression: $U' - u + d$; in which *d* is computed (after *k* has been found) from the equation of the type, *kd*=rate at point *A* on curves. For example $kd = 0.0040$ for curve No. 1 in table 1 above. A careful inspection of the successive values of *k* led to the conclusion that the experiments failed to show definitely any marked variation of *k* with different magnitudes of the difference *U—u* between the limits of zero and 10°. The mean values of *k* show a comparatively close agreement.

In order to check the results against possible errors introduced by the curved rulings on the sheets, two curves were carefully redrawn by hand on a larger scale, with strictly rectilinear coordinates. The values of *k* deduced from these curves, together with the corresponding values derived from the original record, are given in the table below.

Except that results could be computed from the curves as redrawn for much greater differences, *U—u*, than on the originals, the foregoing tables show that the results computed directly from the original curves are quite satisfactory, within the limits desired.

TABLE 2.—*Summary of results.*

**Meteorograph No. 1.**

| Rising temperature. | | | Falling temperature. | | |
|---|---|---|---|---|---|
| Number of observations. | $U-u$. | $k$. | Number of observations. | $U-u$. | $k$. |
| | ° | | | ° | |
| 4 | 7.90 | .0280 | 1 | 6.48 | .0217 |
| 4 | 4.37 | .0257 | 6 | 4.08 | .0291 |
| 4 | 2.52 | .0284 | 7 | 2.19 | .0244 |
| 6 | 1.36 | .0230 | 9 | 1.27 | .0244 |
| 8 | 0.77 | .0199 | 10 | 0.69 | .0185 |
| 8 | 0.26 | .0257 | 9 | 0.34 | .0264 |
| Means. | ....... | 0.243 | ........ | ....... | .0241 |

Mean $k$ from rising and falling temp., .0242

**Meteorograph No. 2.**

| Rising temperature. | | | Falling temperature. | | |
|---|---|---|---|---|---|
| Number of observations. | $U-u$. | $k$. | Number of observations. | $U-u$. | $k$. |
| | ° | | | ° | |
| 1 | 8.25 | .0352 | 2 | 4.74 | .0474 |
| 2 | 4.90 | .0254 | 2 | 3.42 | .0398 |
| 2 | 2.62 | .0252 | 5 | 1.58 | .0272 |
| 4 | 1.29 | .0211 | 5 | 0.78 | .0188 |
| 3 | 0.67 | .0198 | 4 | 0.44 | .0241 |
| 3 | 0.32 | .0186 | 5 | 0.23 | .0296 |
| Means. | ....... | .0242 | ........ | ....... | .0301 |

Mean $k$ from rising and falling temp., .0272

**Meteorograph No. 13.**

| Rising temperature. | | | Falling temperature. | | |
|---|---|---|---|---|---|
| Number of observations. | $U-u$. | $k$. | Number of observations. | $U-u$. | $k$. |
| | ° | | | ° | |
| 1 | 9.00 | .0358 | 6 | 4.43 | .0338 |
| 3 | 6.85 | .0282 | 3 | 3.24 | .0354 |
| 4 | 3.56 | .0262 | 7 | 1.82 | .0318 |
| 4 | 1.78 | .0262 | 9 | 0.94 | .0282 |
| 5 | 0.87 | .0229 | 11 | 0.47 | .0245 |
| 5 | 0.26 | .0268 | 14 | 0.21 | .0254 |
| Means. | ....... | .0277 | ........ | ....... | .0298 |

Mean $k$ from rising and falling temp., .0288

**Meteorograph No. 6.**

| Rising temperature. | | | Falling temperature. | | |
|---|---|---|---|---|---|
| Number of observations. | $U-u$. | $k$. | Number of observations. | $U-u$. | $k$. |
| | ° | | | ° | |
| 6 | 3.44 | .0307 | 7 | 3.44 | .0221 |
| 10 | 2.18 | .0310 | 10 | 1.87 | .0298 |
| 12 | 1.19 | .0272 | 10 | 1.10 | .0240 |
| 15 | 0.72 | .0217 | 14 | 0.63 | .0302 |
| 19 | 0.41 | .0231 | 18 | 0.30 | .0298 |
| 16 | 0.21 | .0295 | 15 | 0.10 | .0278 |
| Means. | ....... | .0272 | ........ | ...... | .0272 |

Mean $k$ from rising and falling temp., .0272

General mean, 0.0268° F. per second.

TABLE 3.—*Comparison of results based on curved and rectilinear coordinates.*

CURVE NO. 1.

| $U-u$. | Original trace curved ordinates. | Trace redrawn rectilinear coordinates. |
|---|---|---|
| 23.44 | .......... | .0320 |
| 12.57 | .......... | .0328 |
| 6.92 } | .0260 | .0258 |
| 6.94 } | | |
| 3.66 } | .0260 | .0275 |
| 3.62 } | | |
| 1.92 } | .0206 | .0260 |
| 1.91 } | | |
| .82 } | .0163 | .0280 |
| 1.07 } | | |
| .81 | .......... | .0209 |
| .34 } | .0260 | .0268 |
| .25 } | | |

CURVE NO. 2.

| $U-u$. | Original trace curved ordinates. | Trace redrawn rectilinear coordinates. |
|---|---|---|
| 28.43 | .......... | .0310 |
| 21.04 | .......... | .0333 |
| 14.91 | .......... | .0283 |
| 6.96 } | .0286 | .0272 |
| 6.95 } | | |
| 3.57 } | .0238 | .0283 |
| 3.56 } | | |
| 1.77 } | .0232 | .0248 |
| 1.76 } | | |
| 1.22 } | .0186 | .0157 |
| 1.18 } | | |
| .72 } | .0131 | .0119 |
| .71 } | | |
| .29 } | .0160 | .0183 |
| .28 } | | |
| .08 | .......... | .......... |

We may therefore fairly conclude that these tests show that $k$ is practically a constant for different values of the difference $U-u$ from 1° to 10° F. Also, that different meteorographs of this same construction are about equally sluggish, even when the scale of temperature is considerably amplified. The sluggishness for rising and for falling temperatures appears to be about the same. Finally, no sensible error is introduced in the method of analysis on account of the curved ordinates of the original records.

The individual determinations show rather large variations from each other and the final mean, it was, however, difficult to maintain a sufficient control over either the temperature conditions or the rate of circulation of the air in the box, and a great part of the variations observed can be attributed to irregular variations of temperature in the box and differences in the circulation of the air through the tube of the meteorograph.

The mean result of all the experiments gives us a coefficient of sensitiveness for the kite thermographs of 0.027° per second. That is to say, under ordinary conditions of ventilation, such as obtain during kite ascensions, the thermographs will change temperature at the rate of 0.027° per second (that is, 1.62° per minute) for each degree of difference between the air temperature and that of the thermograph. This result may be expressed in a different manner by saying that if, for example, the kite in ascending experiences a diminution of air temperature at the rate of 1.62°, F., per minute, then the indicated temperature by the kite thermograph will be just one degree too high. Under ordinary atmospheric conditions this would correspond to an ascension at the rate of over 300 feet per minute, a speed which is not maintained in practical kite flying.

An effort was made to determine the sensitiveness of one of the heavy thermographs, such as used in regular Weather Bureau work. It was impracticable to procure an automatic record from which to deduce the sensitiveness, owing to the very slow speed of the record cylinder. Eye readings were therefore made, but the instrument could not be placed in the closed box used for the meteorographs, and the results obtained show an abnormally high coefficient of sensitiveness for small differences of temperature between the air and the bulb.

Somewhat similar results were obtained from eye readings of mercurial thermometers. In fact the results seem to show the thermograph more sensitive than the mercurial thermometers with small delicate bulbs. It was obviously impossible that this could be the case, and further experiments were deferred until suitable devices could be arranged whereby a more constant air temperature could be maintained and automatic traces secured of the temperature of the bulb under test.

It is seen from the foregoing that the coefficient of sensitiveness of a thermometer is a number which expresses the rate at which the instrument will change temperature in a unit (a second or a minute, for example) of time for a difference of one degree between the temperature of the medium and that of the thermometer. A difference of two degrees will give rise to twice as rapid a change, and so on.

Conversely, if the medium is changing its temperature at a more or less steady rate, the amount of steady "temperature lag" in the indications of a thermometer placed therein will be

$$\text{Lag} = \frac{\text{Steady rate of change of temperature.}}{\text{Coefficient of sensitiveness of thermometer.}}$$

These principles enable us to judge of the degree of accuracy attainable in the use of thermometers for measuring temperatures of the air in the various cases met with in ordinary practice.

## SERPENTINE LIGHTNING.

By Dr. J. W. KALES, M. D., Voluntary Observer (dated Franklinville, N. Y., November 13, 1899).

At 8:30 p. m., August 26, a thunderstorm moving from west by south to east by north, passed directly over this station. Heavy clouds obscured the southern sky, while the northern sky remained clear. It was quite dark when the storm reached the zenith. The lightning flashes from west to east were in the upper air, between two and three miles from the earth. Just as the anterior border of the storm cloud reached the zenith a lightning flash appeared about 20° south of zenith

Plate 1.

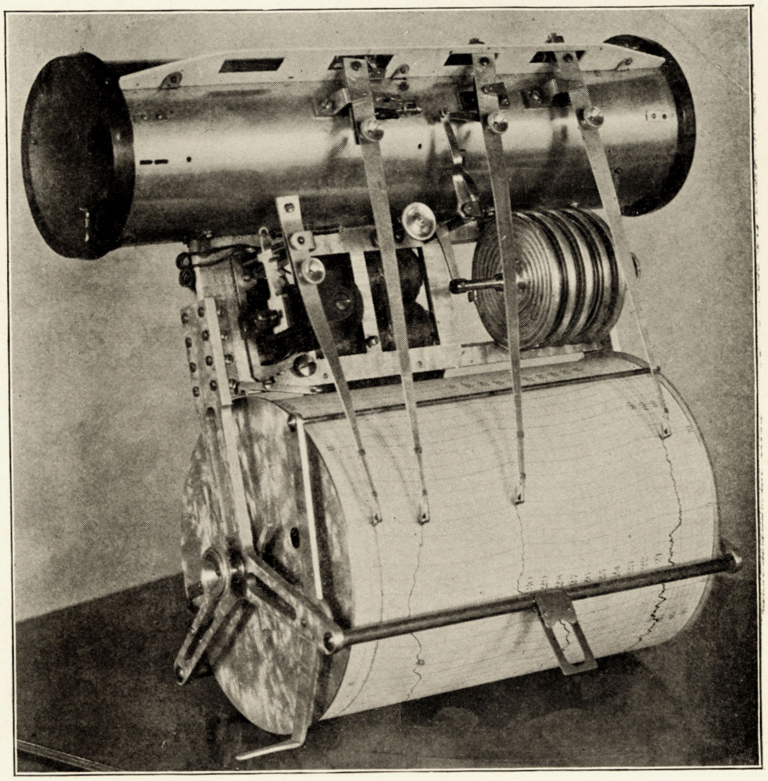

Fig. 2.—Marvin's kite meteorograph.

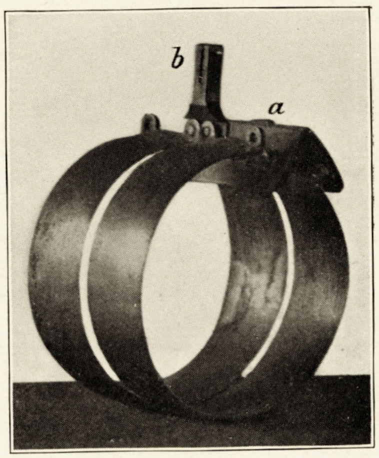


Fig. 3.—Thermograph bulb of Marvin's kite meteorograph.