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PAPERS ON THE RELATION OF THE ATMOSPHERE TO HUMAN COMFORT

The following group of five papers represent an experiment in the treatment of climatic data. Even two decades ago climatologists had carried the separation of climatic data into the elements so far that a swing toward synthesizing them was made. Prof. R. De C. Ward has vivified American climates in his extensive discussion, The Weather Element in American Climates.[1] The next step was, obviously, to express our weather in terms of a scale of human comfort, or at least to describe climates with the aid of frequencies of well-recognized weather types. The first two papers are but suggestions of lines along which may be developed a satisfactory scale of human comfort in terms of weather. The other three papers illustrate three types of treatment of climate as the aggregate or succession of daily weather.—*C. F. B.*

[1] Annals of the Association of American Geographers, Vol. IV, pp. 3-54, 1915.

THE COOLING OF MAN UNDER VARIOUS WEATHER CONDITIONS

By C. F. BROOKS

[Clark University, Worcester, Mass., 1922]

Dr. Leonard Hill, in his recent work, The Science of Ventilation and Open Air Treatment,[1] has compiled a great deal of information concerning the rate at which a man cools under various weather conditions. Valuable though this material is, however, the various experiments and observations have not been coordinated into any systematic statement of the cooling power of the atmosphere on man.

In this paper an attempt has been made to reduce these observations to a mathematical form, in an effort to find a basis by which weather might be classified according to its relation to human comfort. No claim is made that the formulæ and tables deduced are of satisfactory accuracy, but merely that the method employed and the application made (see Donnelly's paper, following) justifies the collection of more experimental data so that accurate studies of the relations of weather to man may be made on these lines.

The human cooling data presented by Hill are of three sorts: (1) Calorimetric observations by Lefevre, (2) metabolism (Douglas bag) observations by Hill and his associates, and (3) human comfort observations in conjunction with those of the katathermometer and various weather factors.

(1) The calorimetric observations by Lefevre were for various temperatures between −1 and +20° C., on a subject naked and clothed, with wind velocities of 3.5 meters per second, and on a subject clothed, with a wind velocity of 1 meter per second. (Tables 15 and 16, Hill, Pt. I, pp. 45–46.) These data represent the actual output of heat from the man's body (C_m). They may be given fairly accurately by the following formula (for clothed man):

$$C_m=\left(\frac{19.5-\theta_1}{603}+\frac{3.0+\theta_1}{222}\sqrt{v}\right)(0.10+0.40/\sqrt{v})\theta_1+0.35$$

in which θ_1, is the depression of the air temperature below 36.5° C., v the wind velocity in meters per second, and the last term the assumed loss of heat from the lungs and skin owing to evaporation (in millicalories per square centimeter of body surface per second). A table showing smoothed values derived from this formula is presented in the second paper of this group.

(2) The metabolism observations by Hill and his associates are given principally in Tables 31 and 32, Part I, pages 90–93. Here are presented the heat production of various subjects sitting out of doors in all kinds of weather at all seasons (H_m). Unfortunately, the data are not sufficiently extensive to be expressible in well-founded mathematical formulæ. Those obtained from plotted data, to which lines were fitted by the eye rather than by the least square method (which was not used because of the insufficiency of the data) are as follows: $H_m=(0.025+0.004\sqrt{v})\ (0.10+0.40/\sqrt{v})\ \theta_1+0.35$ for velocities 0.25 to m/s. $H_m=(-0.016+0.08\sqrt{v})\ (0.10+0.40/\sqrt{v})\ \theta_1+0.35$ for velocities above 1 m/s. Except in warm weather, the rate of heat production by Hill and his subjects is less than the rate of heat emission by Lefevre's subjects.

(3) The comfort indications given in the latter portions of Hill's Part I have used as a rough check, when extrapolations were made, to derive tables for comparing the cooling power of various weather conditions.

With these data of heat emission, heat production, and comfort, it appeared possible to construct tables which would show for any weather conditions approximately the rate at which a man will cool. (See the second paper of this group.)

The indications of the katathermometer have not shown any simple relation to man's cooling. The reasons are several:

Man's heat regulatory apparatus varies with respect to:
First. The flow of blood through the surface capillaries;
Second. The rate of evaporation from the skin;
Third. The conductivity of the skin; and
Fourth. The temperature of the skin.

There are differences between subjects and between the basic conditions of the same subject at different times. Hill found, however, that if the kata had a temperature like that of the subject's cheek, the rate of cooling of the kata would be roughly 6.5 times the rate of heat production of a clothed man.

[1] Pt. I, Medical Research Committee, Spec. Report Ser., No. 32, 1919; Pt. II, Medical Research Council, Spec. Report Ser., No. 52, 1920, London, H. M. Stationery Office.

If, then, it is possible to express cheek temperatures in terms of air temperature and wind velocity, it should be possible to express man's cooling by means of a meteorological formula. For all of Hill's data I plotted θ_2/θ_1 against $\sqrt{v}$, θ_2 being the depression of the cheek temperature below 36.5° C. (roughly blood temperature) and θ_1 the depression of the air temperature below 36.5° C., and v the wind velocity in meters per second. Locating a curve by eye, the following formula was obtained:

$$\theta_2 = (0.10 + 0.40\sqrt{v})\,\theta_1$$

Tables (see Table 1 and Figure 2 in the paper by Donnelly, following) were constructed from the formula derived from Lefevre's experiments, except for temperatures above 70° F., for which the dry katathermometer formula multiplied by a factor for clothing and divided by 10, was used. This factor for clothing was derived from various tables and statements in Hill's Part I, and is represented by the formula:

$$F = (8.5 - \sqrt{v}) \div 11.8$$

The factor 10, by which the kata indications were divided, was arbitrarily chosen, as it gave cooling powers which accorded well with those obtained from the Lefevre experiments. The reason for using a different formula above 70° F. was that it was not thought safe to extrapolate Lefevre's results to higher temperatures; while the justification for using the kata formula is that at such temperatures the skin temperature of the body (including the cheek) is likely to be but little below blood temperature.

For the effects of very high air temperatures and wind velocities at these temperatures, consult C. W. B. Normand in Quarterly Journal of Royal Meteorological Society, January, 1920, volume 46, pages 1–14, diagram. This article will provide a zero of cooling power for various wind velocities at temperatures above 100° F.

The effects of changing moisture and changing intensity of radiation were to be taken care of by additive terms: the moisture effects could be reasonably handled by using the wet-kata formula, $H^1 = (0.13 + 0.47\sqrt{v})\,\theta_1 + (0.35 + .098\sqrt[3]{v})\,(F - f)^{4/3}$ (see proceedings of the Royal Society B, 1922, vol. 93, pp. 198–206), minus the dry-kata formula $H = (0.13 + 0.47\sqrt{v})\,\theta_1$, multiplied by the factor for clothing $F = (8.5 - \sqrt{v}) \div 11.8$, divided by 10. It was recognized, however, that the temperature of the skin is more likely to depart from the blood temperature when the skin is wet than when it is try. As insufficient data were at hand, it was thought best not to attempt to evaluate this. The effect of changing vapor pressure on the evaporation from the lungs was recognized, but as the greatest changes to be found in most climates would vary with the cooling power above or below the average by the equivalent of but 0.05 millicalories per square centimeter of body surface, this factor was neglected.

The effect of sunshine and, on clear nights, of outgoing radiation was evaluated by comparing the maximum intensity of sunlight and radiation in the clearest weather, with the amount that could be received by a man standing vertically, and by dividing this by an arbitrary figure thought to be appropriate for the direct loss of heat from the surface of the clothing without appreciably affecting the body.

Thus, taking 1.4 gram-calories as the maximum intensity at normal incidence per square centimeter per minute (=1,400/60 =23 millicalories per square centimeter per second), the total heat (in millicalories per second per centimeter²) received by a man would be twenty-three times the area of a man's shadow on a plane normal to the sun's rays. With the sun at an altitude of 60° the receipt per square centimeter of body surface of a man of average size would average about 3.5 millicalories per second. Dividing by 2 or less, for the loss directly from the surface of the clothing, we have left only about 2 millicalories per square centimeter of body surface. Thus the factor taken was 2.0 x S, where S = bright sunshine in per cent of the possible sunshine for the day. For the conditions at a particular time a factor less than 2 should be taken if the sunshine is not at its brightest, while under conditions of bright sun shine and a snow cover or water surface a factor of 3.5 and 3, respectively, would be reasonable. On a clear night a negative factor of small degree, about −0.2, would generally show the cooling effect of net radiation.

Summary and outlook.—Our study of the physiological significance of weather types may be outlined and our hopes stated, briefly as follows:

Object.—To present climatic data in a form which has direct significance in any study of the comfort of man in any region at any time, and under any conditions of work and shelter.

Method.—It is necessary in considering the most obvious physiological effect of the weather to use (*a*) the rate of cooling as the unit so far as the weather is concerned and (*b*) the rate of heating so far as the man is concerned.

a. Rate of cooling.—The rate of cooling is a complex of the following factors:

(1) Air temperature (effects well worked out with katathermometer).

(2) Wind velocity (effects well worked out with katathermometer).

(3) Rate of evaporation from a man's body. (Average of 570 kg. cal. heat loss per 24 hours. Extremes vary with humidity, water imbibed, work performed, and air temperature.)

(4) Intensity of radiation (combined with air temperature).

(5) Clothing (variable).

b. The rate of heating involves the following:

(1) Metabolism from food recently eaten. (Variable, but an average may be used.)

(2) Work being performed. (Variable, but the heating effects of well-known sorts can be specified.)

(3) Sunlight and incoming sky radiation. (Variable with cloudiness, humidity, and solar altitude, and with color and texture of surface.)

(4) Air temperature when above 98.6° F. (Effect depends on wet-bulb temperature and wind velocity.)

(5) Wind velocity when air temperature is above 98.6° F. (Heating only when wet-bulb temperature rises above 98.6° F.)

Discussion of a practicable combination.—What we need are tables showing for any kind of weather the feeling of cooling which a man will experience under any degree of activity and in any kind of clothing. How near can we get to fulfilling this need? The factors, air temperature, wind velocity, metabolism, and work, can be taken care of to some extent, as indicated above. Doctor Hill has some data for these in his books. But other data are required. More calorimetric observations of the actual cooling and heating of man are required. It is hoped that this discussion will be helpful as a pioneering effort.