TECHNICAL NOTE No. 123

THE ASSESSMENT OF HUMAN BIOCLIMATE
A LIMITED REVIEW OF PHYSICAL PARAMETERS

by
Professor H.E. LANDSBERG
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WORLD METEOROLOGICAL ORGANIZATION

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NOTE

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At its fourth session (Stockholm, 1965), the WMO Commission for Climatology (now Commission for Special Applications of Meteorology and Climatology) appointed Professor H. E. Landsberg as Rapporteur for Human Biometeorology.

In this capacity Professor Landsberg prepared a comprehensive survey paper on physical bioclimatology dealing with the expression in physical laws of the thermal influences of climate. At its fifth session (Geneva, 1969), the Commission expressed its satisfaction with this report and recommended that it be published as a WMO Technical Note.

In a somewhat revised form, the report is now reproduced in the present Technical Note.

I am glad to have this opportunity of expressing to Professor Landsberg the sincere appreciation of the World Meteorological Organization for the work and time he has spent in preparing this valuable paper.

(D. A. Davies)
Secretary-General
SUMMARY

Maintenance of stability in the human body in relation to the atmospheric environment by physiological or technological adjustments is essential for human survival in many parts of the Earth. The capability to adapt by acclimatization is limited. Various indices have been developed to assess the effects of heat and cold on human beings. Some are quite complex and include all elements of the energy balance. They require measurements not generally made by meteorological services. But at the cold end the simple factors of wind chill (a combination of temperature and wind speed) or cooling power (which also includes radiative factors) and at the warm end effective temperature (a combination of temperature, humidity and sometimes wind) have proved adequate for many biometeorological purposes. These indices can be readily obtained from regular meteorological measurements or easily available equipment.

Bioclimatic classifications to characterize comfort conditions at various localities or for mapping of these conditions for an area have been attempted. These are variously based on classes of atmospheric enthalpy, cooling power, or wind chill. Much work remains yet to be done to quantify health hazards caused by the atmospheric environment either as etiological parameters or as aggravators of existing pathological states.
Dans maintes régions du globe, pour pouvoir survivre, l'homme doit absolument assurer la stabilité thermique de son corps en dépit des fluctuations de l'environnement atmosphérique en s'adaptant physiologiquement ou techniquement aux circonstances. La capacité d'adaptation par acclimatation est limitée. Divers indices ont été mis au point pour évaluer les effets exercés sur les êtres humains par la chaleur et par le froid. Certains de ces indices sont très complexes et tiennent compte de tous les éléments du bilan énergétique. Leur établissement nécessite des mesures qui ne sont généralement pas faites par les services météorologiques. Par ailleurs, les facteurs simples sont, en ce qui concerne le froid, le refroidissement dû au vent (effet combiné de la température et de la vitesse du vent) ou le pouvoir réfrigérant (dans lequel entre également en jeu le rayonnement) et, en ce qui concerne la chaleur, la température effective (effet combiné de la température, de l'humidité et, parfois, du vent) se sont révélés suffisants pour satisfaire à de nombreux besoins de la biométéorologie. Ces indices peuvent être déterminés aisément à partir de mesures météorologiques régulières, ou grâce à un équipement qu'il est facile de se procurer.

Pour caractériser les conditions de confort en divers lieux ou pour les représenter cartographiquement pour l'ensemble d'une zone, on a essayé d'établir des classifications bioclimatiques en fonction de classifications de l'enthalpie et du pouvoir réfrigérant de l'atmosphère ou du refroidissement dû au vent. Il reste encore beaucoup à faire pour exprimer quantitativement les risques que l'environnement atmosphérique fait courir à la santé soit en étant à l'origine d'états pathologiques, soit en aggravant les états pathologiques qui existent déjà.
РЕЗЮМЕ

Поддержание устойчивости человеческого организма по отношению к атмосферной окружающей среде путем физиологического или технического приспособления к ней необходимо для сохранения человеческой жизни во многих частях мира. Возможность приспособиться путем акклиматизации ограничена. Разработаны разнообразные индексы для оценки влияния температуры и холода на человека. Некоторые из них довольно сложны и включают все элементы энергетического баланса. Они требуют измерений, которые в общем случае не проводятся метеорологическими службами. Но для условий холода простых факторов охлаждения ветром (совокупность температуры и скорости ветра) или охлаждающей способности (которая включает также радиационные факторы), а для условий температуры — эффективной температуры (совокупность температуры, влажности и в некоторых случаях — ветра) оказалось достаточно для многих биометеорологических целей. Эти индексы можно довольно просто получить по данным регулярных метеорологических измерений с использованием легко доступного оборудования.

Делались попытки провести биоклиматическую классификацию, с тем чтобы дать характеристику условий комфорта в различной местности или для нанесения этих условий на карту данного района. Эти классификации в различной степени основаны на классах атмосферной энергии, охлаждающей способности или охлаждения ветром. Предстоит проработать много работы, с тем чтобы количественно определить угрозу здоровью, вызываемую атмосферной окружающей средой, либо в виде этиологических параметров, либо в качестве обстоятельства, усугубляющих существующее патологическое состояние.
La conservación de la estabilidad del organismo humano en relación con el medio ambiente atmosférico mediante ajustes fisiológicos o tecnológicos es una cuestión fundamental para la supervivencia del hombre en muchas partes de la tierra. La capacidad de adaptación por el proceso de aclimatación es, sin embargo, limitada. A este respecto, se han establecido varios índices para evaluar los efectos del calor y del frío en los seres humanos. Algunos de ellos son muy complejos y comprenden todos los elementos del balance energético, por lo que exigen la realización de medidas que generalmente no efectúan los Servicios Meteorológicos. Sin embargo, cuando las temperaturas son muy bajas, los sencillos factores tales como el frío producido por el viento (una combinación de la temperatura y de la velocidad del viento) o el poder de enfriamiento (en el que también intervienen los factores radiactivos) y, cuando hace mucho calor, la temperatura efectiva (una combinación de temperatura, humedad, y, algunas veces, viento) han demostrado ser idóneos para muchos fines biometeorológicos. Estos índices pueden obtenerse fácilmente a partir de medidas ordinarias meteorológicas o con equipo fácilmente disponible.

Se ha tratado de establecer clasificaciones bioclimáticas para caracterizar las condiciones de bienestar en varias localidades o para transcribir en mapas estas condiciones para una zona determinada. Estas condiciones se fundan, según los casos, en diferentes clases de entalpía atmosférica, poder de congelación o frío producido por el viento. A este respecto, todavía queda una enorme labor por realizar para cuantificar las amenazas a la salud causadas por el medio ambiente atmosférico, bien como parámetros etiológicos o como factores de agravación de los estados patológicos existentes.
INTRODUCTION

The atmospheric environment plays a dominant role in the life of all plants and land animals, and is of great importance for aquatic forms of life. Man has become emancipated from, but not independent of, the atmospheric conditions. Aside from the fact that atmospheric oxygen is indispensable to his survival, he has adapted through clothing and technology to those circumstances which he cannot cope with by nature. His technical skills have surmounted natural barriers in millennia and led to the conquest of the globe, a feat that might have taken millions of years by natural evolution. Yet climate is still a major factor with which man has to cope. This makes the study of the interactions between the atmospheric environment and man's physiological make-up essential. This is not an easy task. The enormous complexity of the bodily functions and the equally complex atmospheric variations defy simple solutions. In an evaluation of the ecology of man, Charter (1962) even goes so far as to assert: "Attempts to impose mathematical values upon man as a total human being, when a measure for him remains elusive, are clearly unscientific. Such attempts generate chaos instead of assisting in the quest for clarity".

Perhaps a holistic point of view imposes restrictions on exact solutions, but such attempts in limited areas can be useful, if the analyst is clearly aware of their limitations. The most important of these limitations is the fact that for practical purposes we deal in the case of human beings, as well as in the atmospheric conditions, with statistical collectives rather than precisely defined physical quantities. There is a tremendously broad spectrum of people, by age, by nutrition, by health, by race and sex, which forms the human collective. Equally, there is really an almost infinite variety of combinations of the relevant atmospheric parameters of temperature, of humidity, of wind, of radiation, and all of these may still be affected by microclimatic modifications. Thus one can cope only with limited objectives. This will become amply clear in the following.
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Historical notes

The ancient physicians were well aware of the effects of atmospheric conditions on health. Their observations are summarized in the works of Hippocrates. These constitute the codification of centuries of medical wisdom. One of these texts specifically bears the title Of Airs, Waters, and Places. There we read about effects of exposure of cities to wind and are informed that in the ancient Greek circle of culture those exposed to south wind have an "unhealthy" climate. In the same treatise Hippocrates praises evenness of temperature for "healthy" climates. Yet he notes that a climate which is always the same induces indolence, while a changeable climate calls for "laborious exertions of both body and mind".

Most famous among Hippocrates' writings are the Aphorisms, which in their third chapter contain 24 dicta summarizing the effects of seasons and prevailing winds on health. Thus we read that:

"South wind induces dullness of hearing, dimness of vision, heaviness of head, torpor and languor... But if the north wind prevails, cough, afflictions of the throat, hardness of the bowels, dysuria attended by rigors of the sides and chest occur."

Or we learn that:

"Autumn is bad for people in consumption"

and that:

"Of the constitutions of the year, the dry, upon the whole, are more healthy than the rainy, and attended by less mortality."

Over two thousand years elapsed before the sceptical scientists of the 17th century began to ask for proof. Their attitude is best represented by Bohun (1671), who wrote:

"Those celebrated Aphorisms of Hippocrates concerning their* medicinal qualities ought to be considered; how far they are found Experimentally true and consonant to the observations of the moderns: For if we rightly understood the different temperatures of the Air and Winds, and how to apply this to many distempers, it might possibly prove the most successful part of Physick."

Bohun then proceeds with an analysis of his own, and attributes to the south wind "a thousand malignant influences" and quotes the English proverb: "The wind at east is good for neither man nor beast". Then he speculates:

"What directions this Doctrine might afford to architects, in choosing the Situations of Dwellings: whether the air of many houses might not be meliorated by giving freer admission to the Winds; since it has been observed, that several Dwellings here in England, which were environ'd with huge woods, or sometimes had only a clump of trees standing towards such a Quarter, have been always obnoxious to sickness, till they happen'd to be cut down, and the places render'd pervious to the Winds: Sometimes only changing of a window, or door, from the South and exposing it to the North has done a great cure. It is well observ'd in the Relation of my Lord Howard's voyage to Constantinople, that, at Vienna they have frequent Winds, which if they cease long in Summer, the plague often ensues; so that it is now grown into a Proverb: That, if Austria be not windy, it's subject to contagion."

But even though Bohun raised questions it took another century and a half before environmental observations became quantitative. Here we must refer to the perspicacious physician W. Heberden (1826), who invented the

* the winds.
principle of the katathermometer. He used a Fahrenheit thermometer with small bulb and quick response. He heated it to 120°F, watched when the thermometer passed 100°F, and then observed every ten seconds for half a minute. With this method he demonstrated the effect of the wind on the rate of cooling. He also showed that high moisture content (fog) had little influence on heat flow in absence of wind. A quotation will show that Heberden had a good appreciation of the atmospheric cooling effect:

"... it cannot have escaped the attention of any person moderately conversant with natural philosophy, that the index of a thermometer is a very imperfect measure of what I may call the sensible cold, that is, of the degree of cold perceptible to the human body in its ordinary exposure to the atmosphere. For while the thermometer truly marks the temperature of the medium in which it is placed, the sensations of the body depend altogether upon the rapidity with which its own heat is carried off. And this is by no means confined to the actual temperature of the air; but whatever alteration of quality increases its power to conduct heat; and, above all, whatever currents increase the succession of its particles in contact with the body, the same will increase the sensation of cold. Hence it is, that in very hot weather, the same stream of air which would heat a chamber, will nevertheless be cool to the feeling; on the other hand, when the thermometer was more than 80° below the freezing point, Captain Parry observed, that while the air was still, the cold was borne without inconvenience."

Basic considerations

The problem is fundamentally one in which we try to assess the sensations caused in the human body by the atmospheric environment. This latter can be characterized by a number of discrete physical parameters or their combinations. These parameters are usually represented by the common meteorological elements: temperature, intensity of radiation, wind speed, and a moisture measure such as vapour pressure, dew point, wet-bulb temperature or relative humidity. Among various combinations of these elements are complex variables such as cooling power, wind chill, effective temperature, which by their very labels indicate their intent to depict a reaction of the body to the environment. But these names are suggesting more than the physical measures can actually express. Some of these quantities are amenable to direct measurement by mechanical or electro-mechanical devices. Among them are katathermometers and frigorimeters. The techniques for making physical measurements of the environment for simple bioclimatic purposes are well summarized in a short book by Bradtke and Liese (1952).

Even if we restrict ourselves to the healthy human being, the problem of assessing its physiological reaction to an environmental change is much more difficult than to measure the physical magnitude of this change. It cannot be our task here to review the field of environmental physiology. But it should be emphasized that the human reactions to the environment are perhaps best divided into those taking place when the equilibrium is unbalanced on the hot side and on the cold side. A good guide to the former is a book by Leithead and Lind (1964) and to the latter one by Burton and Edholm (1955). Later thoughts on the problems of human adaptations to the environment are discussed in a symposium volume edited by Baker and Weiner (1966).

One of the difficulties in judging the physiological factors involved in the problem has been the fact that most data and experimentation have been concentrated on healthy, young men under laboratory conditions. Even in field work this particular segment of the population has figured prominently. Thus many questions concerning realistic representation of the natural environment, of influence of motivation, and a lack of the broad age spectrum of the real population affect the data. Moreover, there is only a smattering of knowledge on the subjective evaluation of the environmental conditions compared with objective measurements on the human body. Yet subjective reactions are usually the dominant element in reaching decisions, such as increasing the heating or cooling in dwellings, or what to wear when being outdoors, or what precautions to take when normal physiological functions are impaired.

The most fundamental fact about reaction to the environment is the necessity for the body to maintain its core temperature at or near 37°C. It is also essential that the body can dispose of the heat developed by the
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metabolism. The metabolic rate cannot usually be reduced much below 40 kcal m\(^{-2}\) of body surface. But it can be increased by almost an order of magnitude in the heaviest exercise. This permits a very wide range of subjective reactions to the environment. Edholm (1966) gives a very vivid account of the problems of acclimatization. He makes the very fundamental point that man in his natural state can survive only in very restricted climatic zones on Earth:

"Naked man, without clothing, shelter or fire, is very vulnerable. At rest his heat production is such that he will maintain a constant body temperature at an environmental temperature of 28 to 29\(^{\circ}\)C."

He might have added here that this presupposes absence of radiative factors and only very slight air motion. Edholm then mentions that the nearly naked aborigines of Tierra del Fuego maintain a higher heat production and that the Australian aborigines can tolerate a lower nocturnal environmental temperature only because of wind protection by bushes and fires. He also notes that under very adverse conditions, such as experienced by personnel stationed at Halley Bay (75\(^{\circ}\)S), the time spent outdoors, even with proper clothing, is less than ten per cent. He says:

"Polar man adapts by not becoming exposed to cold."

As many others, Edholm comments that the atmospheric reference measurements for human physiology needed are different from the meteorological data collected for synoptic purposes. This may require instrumentation of the subjects under study. Of great importance here is the wide variation in hours spent outdoors by persons in different occupations and in various environments. In England a laboratory worker may spend only an hour per day outdoors, compared with six and a half hours for a farmer.

It is notable that by far the greatest effort in the physiological studies has been spent on the thermal environment. Here the most rational approach is through the tracing of the heat balance. At the cold end this is governed by the radiative, conductive, and convective heat loss from the body and smaller losses by evaporation of insensible perspiration, and the heat and evaporation loss through the lungs by breathing. At the warm end the same radiative and convective heat exchanges exist, which may, in fact, add heat to the body, and the evaporative cooling by perspiration. As a physical system this can be assessed by a heat-balance equation (see, e.g., Gates, 1963). Assuming equilibrium, we have:

\[
O = M \pm C_1 \pm C_2 - LE - R_B \pm R_S + S(1-a)
\]

In this equation all elements have to be expressed in heat units (such as kcal hr\(^{-1}\)). The symbols represent:

- \(M\): the metabolic rate of the body;
- \(C_1\): heat gained or lost by convection; this generally involves a temperature and a wind factor;
- \(C_2\): heat gained or lost by conduction; this is usually a negligible amount;
- \(LE\): an evaporation factor, governing both evaporation of sweat from skin and moisture from the lungs, with \(L\) the heat of vaporization and \(E\) the specific moisture loss;
- \(R_B\): the infra-red radiation from the body;
- \(R_S\): the infra-red radiation from the surroundings (soil, walls, vegetation);
- \(S\): short-wave radiation from sun and sky;
- \(a\): albedo of body.

It is readily seen that none of the environmental elements included in this equation is immediately available from ordinary meteorological measurements. For example, the short-wave radiation from sun and sky is not the usually measured global radiation, but a complex geometric derivative which depends on the body posture. Obviously, the metabolic rate and sweat loss can be measured only for laboratory subjects; for ordinary people they have to be inferred. The convective and conductive heat exchanges are most influenced by clothing and hence subject to a wide variety of values under realistic environmental conditions. The infra-red radiative exchanges with surroundings are not readily ascertained with precision.
The present state of affairs is, therefore, that we have only empirical approximations. The gap between the ordinary climatic measurements in the atmosphere and the physiological factors, largely obtained under laboratory conditions, is wide. Only better understanding of the realities at both ends can lead to applications that are useful to ordinary populations engaged in their normal pursuits.

Some physiological aspects

As already mentioned, the principle of homeothermy requires man to keep his internal body temperature at 37°C. The body has several mechanisms to achieve this. One is regulation of peripheral blood flow. By an increase (vasodilation), the skin temperature can be raised. This will also increase the infra-red radiation from the skin and may increase the temperature gradient to the environment, thus permitting higher heat flux. The opposite, in a cool environment, is a decrease of peripheral blood flow (vasoconstriction), decreasing the skin temperature and thus radiative and sensible heat flux. Over longer periods of time, changes in metabolism such as by shivering, i.e. muscular activity in cold weather, or resting in hot weather, will influence the heat balance toward the desired equilibrium stage. Sweating is, of course, a very good defence against overheating because of the high heat of vaporization. Nutritional changes over a longer period of time can have the desired results.

Edholm and Goldsmith (1966) studied this under climatic extremes. In sledging expeditions in the Antarctic, at temperatures at around -30°C air temperature there were metabolic expenditures of 500 kcal hr⁻¹ per man. The mean daily energy expenditure of 5260 kcal was compensated by food intake but even so weight losses did occur. At the fixed bases with expenditures of 3600 kcal day⁻¹, intakes of 3900 kcal day⁻¹ per man were noted. This resulted in weight gains. One may rightly ask: Is this an attempt by the body to gain an insulating layer of fat?

Hot climatic conditions were studied at Aden, where the temperature rarely goes below 30°C. Wet-bulb temperatures ranged from 24 to 29°C (i.e. relative humidities from 40 to 90 per cent). The region also has high solar radiation. Energy expenditures at hard work were 4000 kcal day⁻¹, on holidays 2600 kcal day⁻¹. Water intake was eight litres per day. Food intake was low and weight losses were noted. These did not result from dehydration.

Appetites are reduced in hot climates and increased in cold environments. The UN Food and Agriculture Organization recommends to increase food three per cent for every 10°C below a reference base of 10°C, and to decrease it by five per cent for every 10°C above this base.

It may be inserted here that the 37°C body temperature equilibrates well with the original equatorial home of the human race. Marinov (1966) presents an approximate heat-balance calculation. Assuming an air temperature of 30°C, a vapour pressure of 33 mb, a noon-time radiation of 1.4 ly, he estimates a rough heat balance for a standing person for three different body temperatures. The first is assumed to be 30°C. There will be no sensible heat exchange; loss by long-wave radiation and evaporation will be 0.175 cal cm⁻² min⁻¹ and the gain is about 0.3 cal cm⁻² min⁻¹ from radiation. Thus there would be a gradual net gain of heat and imbalance for a homeotherm. For a body temperature of 44°C the losses would be between 0.38 cal cm⁻² min⁻¹ and 0.74 cal cm⁻² min⁻¹ which includes a marked amount of sensible heat; this exceeds the radiative gain and would lead to a drop in body temperatures. For a body temperature of 37°C balance is achieved and can be maintained for a variety of metabolic rates by the sweat-evaporation mechanism. Thus man is genetically bound to these conditions. They correspond to mean skin temperatures around 33°C. This value produces the subjective feeling of comfort.

To maintain this level at lower air temperatures, clothing is the primary protection. Although there are ways of measuring skin temperatures by fastening sensors to the body, this can be readily accomplished only in experimental set-ups. But the biometeorological practitioner can approximate this value by a formula of Green (1967) based on Brunt's (1947) original work.

\[ t_s = t_a + \frac{1}{4} \theta h M + \frac{M - 15 + 120s (1-a)}{2 + 9 (0.1 + v)^{1/2}} \] (2)
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where:

\( t_s \) = skin temperature, °C
\( t_a \) = air temperature, °C
\( v \) = wind speed, m/sec
\( s \) = sunshine (for England = 1.0 at noon in summer, 0.2 in winter)
\( h \) = thickness of clothing in cm (\( h = 0.5 \) thin clothing, \( h = 1 \) thick sweater)
\( a \) = albedo of clothing (\( a = 0.7 \) for white clothing, \( a = 0.45 \) bare skin, \( a = 0 \) for black cloth)
\( M \) = metabolic rate in cal sec\(^{-1}\) (\( M = 25 \) at rest; \( M = 40 \) light exercise; \( M = 100 \) walking at moderate pace; \( M = 200 \) very strenuous exercise)

Recent laboratory work by Gagge et al. (1967) has shown that the equilibrium skin temperature value of 33°C and Marinov's assumed environmental temperature in balance with metabolism and other thermofunctions are very close to an air temperature adjudged "comfortable" and "pleasant" by laboratory subjects. Although in this work again healthy young men, at rest and wearing shorts, were the only "voters" on experimental exposures, covering a range from 12 to 48°C (air motion 5 cm sec\(^{-1}\); relative humidity = 40 per cent), the result is that physiological thermal neutrality is between 28 and 30°C air temperature. Figure 1 is reproduced from this work. It shows sensation, subjective evaluation, and thermal estimates of these subjects in relation to ambient temperature.

![Figure 1](image-url)

Figure 1 — Estimates of pleasantness (open squares), comfort (open circles), and temperature (solid circles) by young, resting subjects in relation to measured air temperature (after Gagge et al., 1967)

Rather notable in this work is also the difference in reactions noted in transient changes from one temperature régime to another. Such conditions happen in nature with day-to-night changes or, on occasion, with sharp frontal passages. Yet these are not so abrupt as the artificial changes from hot dwellings in winter into a cold atmosphere outdoors; or conversely, in summer from air-conditioned enclosures into the heat of open air. In these transient changes the physiological adaptations take place relatively slowly, a "hysteresis effect", as Gagge et al. call it. But the sensory response is rapid. In other words "comfort" and "discomfort" are felt before temperature changes in skin and body have taken place.

Many have been the efforts to obtain objective measures of relative strain imposed by the atmospheric environment on man. A notable step in this direction has been the strain index developed by Lee (1958). This included at the time air temperature and a humidity value as well as air motion. Radiation was not explicitly included. The formula derived for the strain \( G \) was:

\[
G = a \left[ \frac{M - W - 5.55(34 - t_a) - 0.00033V(46 - p)}{t_a + T_c} \right] d
\]

where:

\( M \) = metabolic rate in cal sec\(^{-1}\)
\( W \) = metabolic rate from work
\( V \) = wind speed
\( p \) = relative humidity
\( T_c \) = air temperature

The formula is valid for

\( t_a + T_c \) < 60

\( 0 \leq V \leq 9 \text{ m/sec} \)

\( 0 \leq p \leq 1 \)

\( 0 \leq M \leq 200 \text{ cal sec}^{-1} \)

\( 0 \leq W \leq 200 \text{ cal sec}^{-1} \)

\( 0 \leq V \leq 9 \text{ m/sec} \)

\( 0 \leq p \leq 1 \)

\( 0 \leq T_c \leq 48 \text{ °C} \)

\( 0 \leq t_a \leq 30 \text{ °C} \)

\( 0 \leq T_c \leq 48 \text{ °C} \)

\( 0 \leq M \leq 200 \text{ cal sec}^{-1} \)

\( 0 \leq W \leq 200 \text{ cal sec}^{-1} \)

\( 0 \leq V \leq 9 \text{ m/sec} \)

\( 0 \leq p \leq 1 \)
where:

- \( M \) = metabolic rate, kcal hr\(^{-1}\)
- \( t_a \) = air temperature, °C
- \( p \) = vapour pressure, mm Hg
- \( W \) = energy expended in external work
- \( V \) = volume of expired air, litres
- \( I_a \) = resistivity of ambient air to outward passage of heat
- \( I_c \) = resistivity of clothing to outward passage of heat, "clo" units
- \( r_a \) = resistivity of ambient air to outward passage of water vapour mm, still-air equivalent
- \( r_c \) = resistivity of clothing to outward passage of water vapour.

This rather complex index varies from 0 to 200. Lee coupled it with a sensation table for \( G \) values, as follows:

- None comfortable below 1\( \frac{1}{2} \)-3;
- Most comfortable at 4-4\( \frac{1}{2} \);
- None comfortable above 6-8\( \frac{1}{2} \);
- Recommended upper limit for day's work (winter): 10;
- Recommended upper limit for day's work (summer): 20;
- Mental performance of average man commences to deteriorate: 22;
  - 30: distress in two hours, collapse in five hours;
  - 45: distress in one hour, collapse in three hours;
  - 75: collapse in one hour;
  - 100: collapse in 40 minutes;
  - 200: collapse in 30 minutes.

At this point it is necessary to introduce the "clo" unit of insulation by clothing. This quantity, established by Gagge, Burton and Bazett (1941), is the insulation value of a garment needed to keep the skin temperature at 33°C, for an ambient air temperature of 21°C, in a room with relative humidity of 50 per cent and air speed < 10 cm sec\(^{-1}\). One clo is then defined as 0.18 X °C kcal\(^{-1}\) m\(^{-2}\) hr\(^{-1}\).

It is quite clear that the emphasis of Lee's and, as we shall see later, many other attempts to characterize the strain resulting from the environmental conditions has more relevance at the hot end of the spectrum than at the cold end. One reason for this is the relative ease with which man can protect himself even outdoors, against excessive heat loss at the cold end of the spectrum, by clothing, except perhaps under the most severe conditions of arctic or mountain climate.

In further extension of this work, Lee and Henschel (1966) discuss the relative strain imposed by the air environment for hot conditions on the basis of an equation by Burton. In order to simplify the assessment of relative strain they reduce the problem first to a set of standard conditions. These assume the metabolism of a person walking at moderate pace (3.2 km hr\(^{-1}\)) with the insulation of a light business suit in air motion of 1/2 m sec\(^{-1}\). Under those conditions the relative strain is given by

\[
RS_s = \frac{[10.7 + 0.74 (t_a - 35)]}{[44 - p_a]} \tag{4}
\]

where \( RS_s \) stands for relative strain under standard conditions, \( t_a \) the air temperature in °C, and \( p_a \) the vapour pressure in mm Hg. Lines of equal relative strain can then be shown in one of the usual psychrometric diagrams. These lines, shown in Figure 2, have values from 0.1 to 1.5. In case of non-standard conditions, suitable additions or subtractions can be made for different metabolic rates and wind speeds from the air temperature value entering formula (4). These are shown in Table I.
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Figure 2 — Psychrometric diagram (vapour pressure vs. dry-bulb temperature), also showing scales of wet-bulb temperature and curved lines of relative humidity; with slanting lines showing relative strain for person in light activity and normal business suit, indoors with slight air movement and with air temperature and wall temperature being equal (after Lee and Henschel, 1966)

TABLE I
Corrections to air temperature for non-standard conditions
(after Lee and Henschel, 1966)

<table>
<thead>
<tr>
<th>Metabolic rate, kcal m(^{-2}) hr(^{-1})</th>
<th>Air motion, m min(^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>15</td>
</tr>
<tr>
<td>40</td>
<td>-3 1/2</td>
</tr>
<tr>
<td>50</td>
<td>-2 1/2</td>
</tr>
<tr>
<td>60</td>
<td>-4</td>
</tr>
<tr>
<td>100</td>
<td>0</td>
</tr>
<tr>
<td>190</td>
<td>+3 1/2</td>
</tr>
</tbody>
</table>

Lee and Henschel interpret these relative strain values then for two persons, one healthy and one with moderately severe cardio-pulmonary disturbances. These are shown in Figure 3 (a) and (b). One can immediately see the much greater response elasticity of the healthy young man compared with that of the impaired individual. Only very few studies give us even an estimate of the distinction of environmental stress on “non-standard” individuals.

For the cold end of sensations Prokop'ev (1966) has called attention to the importance of introducing a weighted heat flux for the body. He points out that skin temperatures reach different equilibria according to thermal insulation value of the various garments worn on head, body, legs, hands and feet. Thus in sub-freezing temperatures
the skin temperature of the trunk may stay at 34°C, but hand and head temperatures may be 12°C lower. The heat fluxes in kcal m⁻² hr⁻¹ from the hands or feet under those conditions can be twice as large as those from the trunk and even four times as large from an exposed face.

Kerslake (1964) gives a "preferred" skin temperature distribution for persons not fully acclimatized to the tropics. This is probably close to man's innate equilibrium. The range between various parts of the body is about 6°C. It should be noted that the head and trunk represent about 50 per cent of the body area and hence figure most prominently in the heat balance. For a case of light activities and with the beginning of sweating Kerslake gives the temperature distribution shown in Table II.
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TABLE II

Probable preferred distribution of skin temperature and heat loss for acclimatized subjects; 90 per cent loss as sensible heat, 10 per cent evaporative (after Kerslake, 1964)

<table>
<thead>
<tr>
<th>Region</th>
<th>Area, m²</th>
<th>Temp., °C</th>
<th>Body heat loss, kcal hr⁻¹</th>
<th>kcal m⁻² hr⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>Head</td>
<td>0.20</td>
<td>34.6</td>
<td>8</td>
<td>41</td>
</tr>
<tr>
<td>Trunk</td>
<td>0.70</td>
<td>34.6</td>
<td>29</td>
<td>41</td>
</tr>
<tr>
<td>Thighs</td>
<td>0.33</td>
<td>33.0</td>
<td>12</td>
<td>36</td>
</tr>
<tr>
<td>Calves</td>
<td>0.22</td>
<td>30.8</td>
<td>15</td>
<td>75</td>
</tr>
<tr>
<td>Feet</td>
<td>0.12</td>
<td>28.6</td>
<td>10</td>
<td>83</td>
</tr>
<tr>
<td>Arms</td>
<td>0.10</td>
<td>33.0</td>
<td>8</td>
<td>80</td>
</tr>
<tr>
<td>Forearms</td>
<td>0.08</td>
<td>30.8</td>
<td>9</td>
<td>113</td>
</tr>
<tr>
<td>Hands</td>
<td>0.07</td>
<td>28.6</td>
<td>8</td>
<td>114</td>
</tr>
<tr>
<td></td>
<td>1.82</td>
<td></td>
<td>99</td>
<td>(≈ 55 kcal m⁻² hr⁻¹)</td>
</tr>
</tbody>
</table>

It is quite obvious that the meteorologist in the normal service to the public has to deal with a population rather than individuals. He, at present, is also generally not in a position to evaluate all the variables that should enter equations describing the strain caused by the environment. This problem has long been recognized by the professions of heating and air-conditioning engineers. Although primarily concerned with indoor conditions, they devised over 30 years ago a measure which is essentially based on the reactions of normal persons to the environment, characterized by temperature, humidity, and wind conditions. This index was labelled “effective temperature” and has been widely used as a corollary measure in physiological investigations. For this reason it is introduced at this juncture. Effective temperature is defined as a sensation in which, for a given air temperature and humidity, the state of comfort is equal to that experienced for an environment at a lower temperature with saturated water vapour, i.e. when dry-bulb and wet-bulb temperatures are equal. In other words, an effective temperature of 20°C is attributed to the room air if the ambient air feels the same as air at 20°C and 100 per cent relative humidity. This would for most people represent a case of 22.5°C and 50 per cent r.h., or 25°C and 10 per cent r.h. A psychrometric diagram with lines of equal effective temperature is shown in Figure 4. This also indicates a preferred comfort zone.

In recent years the American Society of Heating, Refrigerating and Air Conditioning Engineers has designated as indoor comfort zone the ranges from air temperature 22.8 to 25°C (73-77°F), and 20 to 60 per cent relative humidity. Differences of opinion on “comfort” are, of course, quite inevitable, depending on clothing and state of activity. It should be made clear also that the effective temperature is not without drawbacks, but a number of studies have shown that effective temperatures depict physiological reactions to atmospheric environment reasonably well. Wachter (1949) discussed this and recently also showed (1966) that in the absence of wind the lines of effective temperature are also lines of equal heat transfer, based on the heat flow caused by air-skin temperature difference and radiation from skin. When air flow becomes an important factor, lines of equal heat transfer depart from effective temperature lines. At higher wind speeds the radiative and humidity effects on effective temperature decrease. Yet, by and large, we can set effective temperature (ET) 24°C as the boundary of sultriness. Skin temperature rises linearly with effective temperature in the range from ET 25 to 40°C. The minute volume of heart effort rises with ET, first gradually and linearly to about ET 33°C, and then abruptly. Between ET 30 and 31°C the body temperature begins to rise. This was impressively shown by Macpherson (1962), whose diagram is reproduced in Figure 5. The ET of 35 is a good upper limit of tolerance; it corresponds about to a value of 40 of Lee’s strain index, which causes distress in a little over an hour’s exposure. It is also close to the top value of the Lee-Henschel strain diagram (see Figure 2).
Figure 4 - Psychrometric diagram (mixing ratio vs. dry-bulb temperature). Also indicated are relative humidity (curved lines), wet-bulb temperature (gently sloping lines), effective temperatures (steeply sloping lines). Stippled area indicates an accepted area of indoor comfort for a majority of healthy persons in appropriate clothing.

Figure 5 - Relation of rectal temperature to effective temperature, in two subjects (after Macpherson, 1962).
High metabolic rates, because of heavy work, and clothing shift the effective temperature boundaries to lower values (Blockley, 1966). The physical impairment at high effective temperatures has a parallel in mental performance. This was first demonstrated by Blockley and Lyman (1950) in standard tests. Mackworth (1961) showed a progressively higher error rate of simple mental tasks. At ET 27.2°C the error rate was 21 per cent. This stayed nearly constant to ET 28.3°C, increased to 27 per cent at ET 30.8°C, rose to 33 per cent at ET 33.4°C and finally at 36.1°C had doubled to 42 per cent. Wing and Touchstone (1965) showed in memory tests on word lists that between performance at ET 22.2°C and ET 35°C a highly significant memory loss of 13 per cent took place. Wing (1965) also showed that for very short exposure times arithmetic, memory, and coding tasks will be handled without loss of efficiency, but that for performance of any longer duration ET 30°C is about the limit of unimpaired mental performance, as shown in Figure 6.

Wyndham (1969) stresses that physiological tests have shown how important a role acclimatization plays in withstanding heat stress. Long residence in an area seems to be more important in the adaptation process than ethnic origin. Physiological heat-stress conditions not only cause discomfort but also induce psychological reactions. One of these is irritability which can turn into aggressiveness. Mild cases of psycho-neurosis are induced. Significant deterioration, according to this author, begins at ET 28 to 30°C, with a large motivational component involved. Actually, all present indices are only moderately able to predict productivity loss in manual labour. Heat-stroke incidence and deaths increase sharply with ET >33°C. Wyndham's experiments were performed on mine workers.
Recently Höschle (1970) attempted development of a physical model of heat transfer from the interior of the body through the outer body layers, the skin, and the clothing to the environment. The latter is represented by air temperature, radiative temperature, vapour pressure, and wind speed. The heat flow is modelled as simple linear function of temperature difference of body to air, and heat-transfer resistance coefficients in the three-layer system. Values for these resistances, which are, of course, highly variable, were taken from earlier literature. Heat loss through respiration was considered separately as a correction factor. The skin temperature is the ultimate dependent variable and is treated as the measure of comfort. The complex calculations are best carried out by computer. They make it possible, for example, to choose for any set of environmental conditions proper thickness of clothing in order to achieve a comfortable skin temperature of 33°C.

For further details on the physiology of performance and tolerance the reader is referred to the following papers: Lee (1964), who sets forth a series of 12 principles which should govern tests for establishing relations between meteorological variables and performance; Aderswald and Bornschein (1949), who give a useful review of skin-temperature reactions in cooler temperatures of various parts of the body; Schuman (1962), who stresses the importance of sweat in heat regulations; additional information is to be found in Baetjer (1965). Most valuable for information on the physiological results obtained at the end of the spectrum is a very comprehensive review, covering 696 citations, by Ladell (1957).

It remains here to refer to some experiments of Tromp (1966), which relate physiological information to cooling. He calls attention to the fact that from a biological point of view physiological factors other than the customary skin and body temperatures may give a superior assessment of cold exposure in the case of persons with efficient thermo-regulation. He showed that if a person is exposed to only one hour of environmental cold in a 12-hour period, the urine volume increases sharply, and so does the 17-ketosteroid excretion, while the alkalinity of the urine rises. He advocates the use of these variables as measure of cold stress.

**Meteorological measures to represent environmental stress**

Meteorologists and physicists have tried for well over four decades to simulate the physiological reactions of the body by analogy in physical bodies. In this most designs follow the early experiment of Heberden. First was Hill’s katathermometer, used originally in mines. The thermometer body is warmed to body temperature and the time for a specific temperature drop measured. This gives a quantity termed the “cooling power”, which represented the combined effects of ambient temperature, radiation exchange and wind on the thermometer bulb. It can be made somewhat to simulate the effect of the humidity factor on a sweating body by placing a wet wick around the thermometer bulb.

This system was refined by Dorno and Thilenius in order to obtain continuous records. Their system keeps a metal bulb at a constant temperature by electric heating. The current needed to maintain this temperature is a measure of the combined cooling effects of the environment. More complex systems based on the same principle simulating the human body by a dummy, have been designated and primarily used for testing the insulating quality of clothing in the laboratory.

It was obvious to try approximating the cooling power (dry or wet), usually given in mcal cm⁻² sec⁻¹, by the various basic meteorological elements. A rash of various formulae was the result. Most of them represent the dry cooling power based on air temperature and wind speed. Nearly all of them give cooling power as a linear function of the difference of skin or body temperature and the air temperature, and a power of the wind speed. In a majority of cases this power is the square root. Cena et al. (1966) have performed a most useful service by comparing a large number of these empirical formulae with frigorimeter and katathermometer observations. The results are given in Table III.
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TABLE III
Comparison of frigorimeter (1-11) and katathermometer (12-16) observations at Wroclaw with various empirical formulae expressing cooling power (after Cena et al., 1966)

<table>
<thead>
<tr>
<th>Author</th>
<th>( H = (a+bv^2) / (t_b - t) )</th>
<th>( v )</th>
<th>( H_{\text{calc}} )</th>
<th>( r )</th>
<th>( \pm e )</th>
<th>( \pm \sigma )</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) Dorno, 1925</td>
<td>((0.22 + 0.25 \sqrt{v}) (33.0 - t))</td>
<td>(1 &lt; v &lt; 10)</td>
<td>0.853 ( H_F ) + 1.641</td>
<td>0.9528</td>
<td>0.0051</td>
<td>3.422</td>
</tr>
<tr>
<td>(2) Lahmayer, Dorno, 1932</td>
<td>((0.22 + 0.20 \sqrt{v}) (36.5 - t))</td>
<td>(-)</td>
<td>0.855 ( H_F ) + 2.821</td>
<td>0.9441</td>
<td>3.464</td>
<td></td>
</tr>
<tr>
<td>(3) Dorno, 1934</td>
<td>((0.22 + 0.25 \sqrt{v}) (36.5 - t))</td>
<td>(1 &lt; v &lt; 10)</td>
<td>0.887 ( H_F ) + 3.564</td>
<td>0.9491</td>
<td>0.0055</td>
<td>3.582</td>
</tr>
<tr>
<td>(4) Büttnert, 1934</td>
<td>((0.23 + 0.47 \cdot v^{0.35}) (36.5 - t))</td>
<td>(1 &lt; v &lt; 16)</td>
<td>1.217 ( H_F ) + 5.926</td>
<td>0.9516</td>
<td>0.0053</td>
<td>11.074</td>
</tr>
<tr>
<td>(5) Matzke, 1954</td>
<td>((0.249 + 0.258 \cdot v^{0.44}) (36.5 - t))</td>
<td>(0.6 &lt; v &lt; 7.2)</td>
<td>0.874 ( H_F ) + 4.192</td>
<td>0.9529</td>
<td>0.0051</td>
<td>3.664</td>
</tr>
<tr>
<td>(6) Matzke, 1954</td>
<td>((0.241 + 0.096 \cdot v) (36.5 - t))</td>
<td>(0.6 &lt; v &lt; 7.2)</td>
<td>0.854 ( H_F ) + 4.248</td>
<td>0.9580</td>
<td>0.0046</td>
<td>3.410</td>
</tr>
<tr>
<td>(7) Meissner, 1952</td>
<td>((0.275 + 0.25 \cdot v^{0.20}) (36.5 - t))</td>
<td>(2 &lt; v &lt; 15)</td>
<td>0.979 ( H_F ) + 3.984</td>
<td>0.9500</td>
<td>0.0054</td>
<td>4.914</td>
</tr>
<tr>
<td>(8) Heineberger, 1948</td>
<td>((0.276 + 0.117 \cdot v) (36.5 - t))</td>
<td>(v &lt; 5)</td>
<td>0.816 ( H_F ) + 2.265</td>
<td>0.9406</td>
<td>0.0064</td>
<td>3.825</td>
</tr>
<tr>
<td>(9) Goldschmidt, 1952</td>
<td>((0.25 + 0.20 \sqrt{v}) (36.5 - t))</td>
<td>(-)</td>
<td>1.062 ( H_F ) + 2.205</td>
<td>0.9301</td>
<td>0.0075</td>
<td>5.561</td>
</tr>
<tr>
<td>(10) Goldschmidt, 1952</td>
<td>((0.30 + 0.16 \cdot v) (36.5 - t))</td>
<td>(1 &lt; v &lt; 6)</td>
<td>1.049 ( H_F ) + 2.234</td>
<td>0.9317</td>
<td>0.0074</td>
<td>5.345</td>
</tr>
<tr>
<td>(11) Bidor, 1931</td>
<td>((0.31 + 0.112 \cdot v) (36.5 - t))</td>
<td>(0.5 &lt; v &lt; 4)</td>
<td>0.821 ( H_F ) + 2.678</td>
<td>0.9463</td>
<td>0.0058</td>
<td>3.549</td>
</tr>
<tr>
<td>(12) Bedford, Warner, 1933</td>
<td>((0.123 + 0.465 \sqrt{v}) (36.5 - t))</td>
<td>(-)</td>
<td>1.079 ( H_F ) + 4.836</td>
<td>0.9492</td>
<td>0.0055</td>
<td>7.406</td>
</tr>
<tr>
<td>(13) Weiss, 1926</td>
<td>((0.14 + 0.49 \sqrt{v}) (36.5 - t))</td>
<td>(-)</td>
<td>1.146 ( H_F ) + 5.212</td>
<td>0.9496</td>
<td>0.0055</td>
<td>9.041</td>
</tr>
<tr>
<td>(14) Bradtke, 1926</td>
<td>((0.10 + 0.403 \sqrt{v}) (36.5 - t)^{1.06})</td>
<td>(-)</td>
<td>1.202 ( H_F ) + 3.666</td>
<td>0.9535</td>
<td>0.0071</td>
<td>8.452</td>
</tr>
<tr>
<td>(15) Hill, 1937</td>
<td>((0.105 + 0.485 \sqrt{v}) (36.5 - t))</td>
<td>(v &lt; 1)</td>
<td>1.106 ( H_F ) + 4.785</td>
<td>0.9482</td>
<td>0.0056</td>
<td>7.892</td>
</tr>
<tr>
<td>(16) Hill, 1937</td>
<td>((0.205 + 0.385 \sqrt{v}) (36.5 - t))</td>
<td>(1 &lt; v)</td>
<td>0.982 ( H_F ) + 5.153</td>
<td>0.9525</td>
<td>0.0052</td>
<td>5.832</td>
</tr>
<tr>
<td>(17) Cena, Gregorczuk, Wójcik, 1966</td>
<td>((0.412 + 0.087 \cdot v) (36.5 - t))</td>
<td>(0 &lt; v &lt; 6)</td>
<td>0.787 ( H_F ) + 3.990</td>
<td>0.9583</td>
<td>0.0046</td>
<td>3.306</td>
</tr>
</tbody>
</table>

The symbols in Table III signify the following quantities: \( H \) is the cooling power calculated by the various formulae, in which \( a, b \), and \( c \) are constants; \( v \) is wind speed in m/sec; \( t_b \) is the body temperature or skin temperature; \( t \) is the air temperature; the Beale column gives the regression equation between \( H \) and the frigorimeter recording \( H_r \); \( r \) is the correlation coefficient between the calculated and observed value with a standard error \( e \) and a standard deviation \( \sigma \).

All correlation coefficients are between 0.93 and 0.96 and have high statistical significance. Formula 17 evolved by the authors has the highest correlation and the lowest standard deviation. But it is quite evident that actually none of the formulae is vastly better than the others and each may well represent, in its original setting, the best fit to the observational data. Conversely, one may conclude that any of the formulae will serve adequately for conversion of temperature and wind observations to cooling power.

There are several heat-loss formulae not included in the above given tabulation. One is by Vinje (in contrast to the others, expressed in the units used more by physiologists, hence the factor 36):

\[
H = 0.57v^{0.42} (36.5 - t) \times 36 \text{ kcal m}^{-2} \text{ hr}^{-1}
\]

where \( v \) denotes the wind speed in m sec\(^{-1} \) and \( t \) the air temperature in °C.

It is an alternative to an earlier formula by Siple and Passel (1945), which was primarily evolved to establish the wind chill at very low temperatures, essentially with temperatures below freezing. That formula, with skin temperature as a basis, originally gave

\[
H = (\sqrt{100}v + 10.45 - v) (33 - t).
\]
The constants were later revised to read:

\[ H = (10.9 \sqrt{v} + 9 - v) (33 - t). \]  

(7)

Recent observations in the Antarctic have shown that with a wind chill index of 1400, according to Vinje's formula, frostbite ensues, and fingers will freeze when the index exceeds 1500 kcal m\(^{-2}\) hr\(^{-1}\).

Because of the fact that thermal quantities mean little to the layman attempts have been made to express the wind chill at low temperatures as an equivalent temperature by simply transposing the calculated value to an equivalent chilling with zero wind speed. This results in values as given in Table IV, adapted from Eagan and Kolb (1965).

For the sake of completeness we should mention that Court (1948) pointed out certain shortcomings of this index, resulting from the neglect of radiative and other factors and the temptation to use non-simultaneous observations of temperature and wind or even mean values. But the wind chill factor has the advantage of simplicity and is readily understood by laymen (Falconer, 1968).

So far all formulae given for cooling power refer to dry conditions, i.e. without sweat on the skin. Wet cooling powers have been represented by

\[ H' = (0.37 + 0.51 v^{0.63}) (36.5 - t') \text{ mcal cm}^{-2} \text{ sec}^{-1} \]  

(8)

where \( t' \) is the wet-bulb temperature.

The cooling powers have been related to sensation scales. These can be classified according to one system, as follows, for dry cooling values:

<table>
<thead>
<tr>
<th>( H, \text{ mcal cm}^{-2} \text{ sec}^{-1} )</th>
<th>Sensation</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;5</td>
<td>Hot</td>
</tr>
<tr>
<td>5-10</td>
<td>Pleasant or mild</td>
</tr>
<tr>
<td>11-15</td>
<td>Cool</td>
</tr>
<tr>
<td>16-22</td>
<td>Cold</td>
</tr>
<tr>
<td>23-30</td>
<td>Very cold</td>
</tr>
<tr>
<td>&gt;30</td>
<td>Extreme cold</td>
</tr>
</tbody>
</table>

Recently, Flach and Mörikofer (1962, 1965, 1966) have provided a detailed climatological analysis of frigorimeter measurements at six middle-latitude localities with rather different climatic conditions. In their assessment they indicate that, for the sensation of "cold", wind is the strongest contributing factor, temperature the least effective, with the long- and short-wave radiation fluxes taking an intermediate position.

An attempt to represent atmospheric environments for climato-therapeutic purposes, e.g. free air rest, was made by Hentschel (1969). This considers only wind-protected exposures (\( v \leq 1 \text{ m sec}^{-1} \)). Observed terciles of air temperature (cold, normal, warm) and of global radiation (dull, normal, bright) result in a series of classes by combination of these various conditions. The diurnal and annual course of these classes, based on the frequency distribution of the two basic elements, can furnish guidance on the environmental physio-climatic challenge. Hentschel gives graphical methods of simulating the equivalent frigorimeter observations, which are not available for many places, by evaluating the formula

\[ t_f = t_a + \frac{0.16 + 0.6 \cdot \frac{G - H}{4} \cdot \sin h + 0.6 \cdot \frac{H}{2}}{0.008 + 0.020 \cdot \sqrt{v}} \]  

(9)
where:

\( t_a \) = air temperature, °C

\( t_f \) = frigorimeter temperature

\( G \) = global radiation, cal cm\(^{-2}\) min\(^{-1}\)

\( H \) = diffuse sky radiation, cal cm\(^{-2}\) min\(^{-1}\)

\( h \) = solar elevation

\( v \) = wind speed, m sec\(^{-1}\).

Experience has shown that cooling power is reasonably representative in the middle ranges of the sensation scale. At the extremely cold end of the scale the wind chill factor offers better resolution for the physiological events. For the hot end of the scale a large number of other factors bring out the details of human reaction in better fashion than cooling power.

The two factors already discussed, namely effective temperature and strain index, are distinctly more discriminating at the warm end of the scale than at the cold end. A large number of variants of the effective temperature have been proposed. One of these, which has the virtue of simplicity, is the discomfort index \((DI)\) of E. C. Thorn (1957, 1958). It is given by

\[
DI_f = 0.4(t_d + t_w) + 15 \quad (10a)
\]

\[
DI_e = 0.4(t_d + t_w) + 4.8^* \quad (10b)
\]

where \( t_d \) and \( t_w \) are the dry- and wet-bulb temperatures respectively given in \((10a)\) for Fahrenheit and \((10b)\) for Celsius degrees. Over a considerable range the values of the discomfort index are essentially identical to the effective temperature, between 65 and 88 ETF (18.3-31.1 ETC). Thorn was primarily concerned with devising a scheme which would permit ready calculation of air-conditioning needs on the basis of available climatic data. Degree-day sums for \(DI_f\) values above 60 \((DI_e = 15.6)\) were used to estimate relative monthly cooling requirements.

Other indices based on Thorn's pattern but lacking the relation to effective temperature include the following:

1. An index by Kawamura (1965), given by

\[
DI_{(K)} = 0.99 t + 0.36 t_{dp} + 41.5 \quad (11)
\]

where \( t \) and \( t_{dp} \) are air and dew-point temperatures, respectively. Kawamura found this index useful in distinguishing regional differences of summer climate in Japan;

2. An index by Tennenbaum et al. (1961) which is defined as

\[
DI_T = \frac{(t_d + t_w)}{2} \quad (12)
\]

where \( t_d \) and \( t_w \) are dry- and wet-bulb temperatures.

According to these authors discomfort starts for \( t_d = t_w = 24^\circ C \), i.e. 24°C temperature with 100 per cent relative humidity. This index is determined hourly and a cumulative index determined by subtracting 24 and adding the values for the duration of exposure. Tennenbaum and his colleagues applied this to young soldiers marching 27 km per day at a rate of 4.5 km hr\(^{-1}\) with a 20 kg pack. A correlation coefficient of +0.98 was found to individual sweat loss and a regression equation for the daily loss of fluid was obtained:

\[
FL = 0.022\Sigma(DI_T - 24)c + 0.027\Sigma(DI_T - 24)r + 0.549T + 3.58 \quad (13)
\]

where \( \Sigma (DI_T - 24)c \) is the hourly cumulative discomfort index during "effort"

\( \Sigma (DI_T - 24)r \) is the hourly cumulative discomfort index during "rest"

\( T \) is the duration of march in hours.

* For \( t_d < 24^\circ C \), Schulze (1966) recommends an improved formula:

\[
ET = 0.4(t_d + t_w) + 4.8 \frac{k}{t_d} \quad \text{where} \ k = 20, \quad (10c)
\]
<table>
<thead>
<tr>
<th>Wind velocity (mph)</th>
<th>Dry-bulb ambient temperature (°F and °C)</th>
<th>Equivalent temperature (°F and °C) (equivalent in cooling power on exposed flesh under calm conditions)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 (10.0)</td>
<td>41 (5.0) 32 (0.0) 23 (−5.0) 14 (−10.0) 5 (−15.0) −4 (−20.0) −13 (−25.0) −22 (−30.0) −31 (−35.0) −40 (−40.0) −49 (−45.0) −58 (−50.0)</td>
<td></td>
</tr>
<tr>
<td>48 (8.9)</td>
<td>38 (5.3) 27 (−1.7) 20 (−6.7) 10 (−12.2) 1 (−17.2) 0 (−22.8) −9 (−27.8) −18 (−33.3) −28 (−43.9) −37 (−48.9) −47 (−53.9)</td>
<td></td>
</tr>
<tr>
<td>40 (4.4)</td>
<td>29 (−1.7) 18 (−7.8) 7 (−13.9) −4 (−15.6) −15 (−26.1) −25 (−32.2) −37 (−38.3) −49 (−44.4) −61 (−50.6) −73 (−56.7) −85 (−62.8) −97 (−68.9)</td>
<td></td>
</tr>
<tr>
<td>36 (2.2)</td>
<td>24 (−4.4) 13 (−10.6) −1 (−18.3) −13 (−25.0) −25 (−31.7) −37 (−38.3) −49 (−45.0) −61 (−51.7) −73 (−58.3) −85 (−65.0) −97 (−71.7) −109 (−78.3)</td>
<td></td>
</tr>
<tr>
<td>32 (−0.8)</td>
<td>20 (−6.7) 7 (−13.9) −6 (−12.1) −19 (−28.3) −32 (−35.6) −44 (−42.2) −57 (−49.4) −70 (−56.7) −83 (−69.9) −96 (−71.8) −109 (−78.3) −121 (−85.0)</td>
<td></td>
</tr>
<tr>
<td>30 (−1.1)</td>
<td>17 (−8.4) 3 (−16.1) −10 (−23.3) −24 (−31.1) −37 (−38.3) −50 (−45.6) −64 (−60.6) −77 (−67.8) −90 (−75.6) −104 (−82.8) −117 (−90.0)</td>
<td></td>
</tr>
<tr>
<td>28 (−2.2)</td>
<td>14 (−10.0) 1 (−17.2) −13 (−25.0) −27 (−32.8) −41 (−40.6) −54 (−47.8) −68 (−63.3) −82 (−71.7) −97 (−78.3) −109 (−86.1) −123 (−93.9)</td>
<td></td>
</tr>
<tr>
<td>27 (−2.8)</td>
<td>13 (−10.6) −1 (−18.3) −15 (−26.1) −29 (−33.9) −43 (−41.7) −57 (−49.4) −71 (−65.0) −85 (−73.3) −100 (−80.6) −113 (−88.3) −127 (−96.6)</td>
<td></td>
</tr>
<tr>
<td>26 (−3.3)</td>
<td>12 (−11.1) −3 (−19.4) −17 (−27.2) −31 (−35.0) −45 (−42.8) −59 (−50.6) −74 (−58.9) −87 (−66.1) −102 (−74.4) −116 (−82.2) −131 (−90.6) −145 (−98.3)</td>
<td></td>
</tr>
<tr>
<td>25 (−3.9)</td>
<td>11 (−11.7) −3 (−19.4) −18 (−27.8) −32 (−35.6) −46 (−43.3) −61 (−51.7) −75 (−59.4) −89 (−67.2) −104 (−75.3) −118 (−83.3) −133 (−91.7) −147 (−99.4)</td>
<td></td>
</tr>
<tr>
<td>24 (−4.5)</td>
<td>10 (−12.2) −4 (−20.0) −18 (−27.8) −33 (−36.1) −47 (−43.9) −62 (−52.2) −76 (−60.6) −91 (−68.3) −105 (−76.1) −120 (−84.4) −134 (−92.2) −148 (−100.0)</td>
<td></td>
</tr>
<tr>
<td>22.4</td>
<td>Little danger Increasing danger Great danger</td>
<td></td>
</tr>
</tbody>
</table>

**Danger from freezing of exposed flesh (for properly clothed persons)**

**Note 1.** To temperature reproduced originally in °F, corresponding values in °C in brackets are added.

**Note 2.** For wind values of < 1 m sec⁻¹, conditions are assumed to be calm.

The table indicates the limits of danger of frostbite even for appropriately dressed persons.
The fluid loss, according to these authors, is a better index of heat load than pulse rate or rectal temperature.

(3) Webb (1960) proposed an index which is primarily designed for indoor conditions in equatorial zones. It has considerable resemblance to cooling-power formulae:

\[ I = t_w + 0.447(t - t_w) - 0.231 \nu^{1/2} \]  

(14)

where \( t \) and \( t_w \) are dry- and wet-bulb temperatures in °F, \( \nu \) wind speed in ft min\(^{-1}\).

Webb designed a nomogram to represent the variables, which is reproduced here as Figure 7. This index, according to Webb, corresponds better to the thermal assessments of the environment by fully acclimatized individuals than wet-bulb temperature alone or effective temperature. Healthy adults, sitting indoors and working at light occupation, dressed to suit themselves and with air, wall, floor, and ceiling temperatures the same as air temperature, were asked to rank their sensations according to a nine-step scale. The ranks \( C \) were as follows:

<table>
<thead>
<tr>
<th>( C ) sensation</th>
<th>0 - very cold</th>
<th>1 - cold</th>
<th>2 - cool</th>
<th>3 - comfortably cool</th>
<th>4 - neither cool nor warm</th>
<th>5 - comfortably warm</th>
<th>6 - warm</th>
<th>7 - hot</th>
<th>8 - very hot</th>
</tr>
</thead>
</table>

Figure 7 – Nomogram of a comfort index for hot, humid climates, after Webb (1960), as function of dry-, wet-bulb temperatures, and wind speeds (upward sloping lines). "Equatorial Comfort Index" is given by vertical lines.
A regression equation gives this rating as a function of the environmental conditions, expressed as follows:

\[ C = 0.258t + 0.218p + 0.103v^{1/2} - 21.19 \]  

where \( t \) = dry-bulb temperature  
\( p \) = vapour pressure in mm Hg  
\( v \) = wind speed in ft min\(^{-1}\).

According to Webb’s observations, onset of sweating can be placed at 78°F (25.6°C) wet-bulb temperature. At 80°F (26°C) wet-bulb temperature, profuse sweating occurs. This jibes with observations of Stephenson (1963) at Singapore, who uses an effective temperature with a ventilation factor as comfort index. He finds that acclimatized persons show an optimum of efficiency at ET 20.6°C, with 24.4 to 25.6°C the highest acceptable for sedentary workers and 29.4 to 32.2°C approaching the danger limit.

(4) Lambor (1966) defines a biological temperature \( t_b \) in which he tries to apply temperature equivalents of wind and humidity. His index is expressed by the following set of equations:

\[ t_b = t - \Delta t_v - \Delta t_e \]  

where

\[ \Delta t_v = \frac{1}{2}v - \frac{t}{10} \left( \frac{v}{10} + 1 \right) + 3 \left( \frac{e}{10} - 1 \right) \]  

and

\[ \Delta t_e = \frac{1}{T_k} (30 - 1.5E) (U - 30) \]

where \( t \) = air temperature, in °C  
\( v \) = wind speed, in m sec\(^{-1}\)  
\( T_k \) = temperature, in °Kelvin  
\( e \) = prevailing vapour pressure, in mb  
\( E \) = maximum vapour pressure at \( t \), in mb  
\( U \) = relative humidity, in per cent.

This complex variable is represented as corresponding to sensations of the human skin as the receptor organ.

(5) Several authors have attempted to represent particularly the sensation of sultriness by vapour pressure alone. Scharlau originally fixed a value of 18.8 mb (14.1 mm Hg) as the limit of sultriness. This obviously establishes a gradient to the maximum vapour pressure at skin temperature which is about 60 mb (46 mm Hg). Marinov (1964) discussed this gradient but fixes the comfortable vapour pressure at considerably higher values (23-33 mm). These should perhaps be interpreted better as tolerable rather than comfortable values. He defines a transfer coefficient

\[ W = \frac{2.1}{D} \frac{\lambda}{C(Re)^m} \left( E_B - e \right) \]

where \( \lambda \) = coefficient of thermal conductivity  
\( D \) = body diameter  
\( Re \) = Reynolds number  
\( E_B \) = saturated vapour pressure at skin temperature  
\( e \) = prevailing vapour pressure  
\( C \) and \( m \) and constants (values not given in reference).

Although no test results are shown, there appears some merit in introducing a measure of turbulent flow into vapour transfer problem. In that connexion, Bartkowski (1966) has pointed out that sultriness should not be determined by reference to aspirated psychrometers, because the psychrometric constant is lower at wind speeds less than 2 m sec\(^{-1}\).

In an interesting study Troll (1969) has extended Scharlau’s work to depict annual-diurnal variations of sultriness in diagrams showing “kaumato isopleths”, with application to a series of central African stations.
(6) One of the psychological drawbacks of the effective temperature concept is the fact that the values are lower than the dry-bulb temperature. Several authors have tried to overcome this by establishing a different base. H. C. S. Thom (1957) proposed to accomplish this by transforming the ET lines based on 100 per cent relative humidity to a new base of 30 per cent relative humidity. This results in making the humidity factor additive to the temperature. Thom gave this index the label “sentient temperature”. A set of representative values are given in Table V.

<table>
<thead>
<tr>
<th>Sentient temperature °C (after H. C. S. Thom, 1957)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Dry-bulb temperature, °C</strong></td>
</tr>
<tr>
<td>20</td>
</tr>
<tr>
<td>25</td>
</tr>
<tr>
<td>30</td>
</tr>
<tr>
<td>35</td>
</tr>
<tr>
<td>40</td>
</tr>
</tbody>
</table>

This index has been fairly useful in relating air-conditioning loads to the atmospheric environment.

(7) Another quite empirical index, first proposed by Lally and Watson, labelled “humiture” and renamed “humidex” by the Canadian Meteorological Service (Thomas, 1965), has the simple form

$$H_t = t + h$$

(18)

where \( h = e - 10 \)

with \( t \) as air temperature in °F

and \( e \) vapour pressure in mb.

It has been used in climatological analysis at Toronto, where a five-year interval showed that \( H_t \) equalled or exceeded the 100 value for 130 hours. As several of the other indices, it does not represent any physical quantity and is dimensionally deficient. No published information on relations to either air conditioning or physiological reactions is available. Yet a number of this type has a public relations value in a weather service and conveys, in a simple way, to the layman a general idea on atmospheric comfort.

At the conclusion of this brief look at all the hygrothermal indices for biometeorological purposes it may be noted here that the effective temperature concept is simple and that others are not clearly superior in use. Many have, of course, a better physical or physiological basis. One might perhaps add here also that, for outdoor conditions, temperature equivalents of factors not included in ET may provide a significant improvement.

A very important experiment in this connexion was performed by Lee and Vaughan (1964). They tried to obtain a measure of the additional heat load caused in deserts by radiation from sun, sky and desert floor. The experiments were conducted in a transparent chamber where temperature and ventilation conditions were controlled. The radiation could be excluded and a temperature rise brought about to equal the effects of the radiation load. Subjects were healthy young men in shorts or desert uniforms (0.7 absorption), walking for two hours on treadmills with energy expenditures of 92 to 185 kcal m⁻² hr⁻¹. Vapour pressure was kept between 6 and 10 mm Hg and wind speeds from 0.75 to 2.5 m sec⁻¹. The equivalent air temperature to radiation at high elevations of the sun and an air temperature of about 37°C was 9°C for men in shorts, with ventilation, and a degree higher without ventilation. For those in uniform, the corresponding values were 11 and 12°C equivalent air temperature.
Gregorczuk (1966) also discusses the increment to effective temperature. He presents two useful diagrams which show the value to be added. One is based on a formula by Klein (1948), giving the temperature increment equivalent to various radiation values at different wind speeds. The other represents the radiation effect only. The two diagrams are shown in Figure 8 (a) and (b).

Figure 8 - Radiative and wind influence on effective temperature. Diagram (a) shows corrected effective temperature (slanting lines) as function of effective temperature, as determined by air temperature and humidity (ordinate) and global radiation (abscissa). Diagram (b): correction to effective temperature, ΔIT (curved lines) as function of wind speed (ordinate) and global radiation (after Gregorczuk, 1966)
Gregorczuk (1968) also noted that net effective temperatures even for negative °C air temperatures are a meaningful quantity, corresponding to sensations of "cold". He evaluated this in terms of the Missenard formula

\[ NET = 37 - \frac{37 - t_a}{0.68 - 0.0014v + \frac{1}{1.76 + 1.4v^{0.5}}} - 0.29 t_a \left(1 - \frac{\gamma}{100}\right) \]  

(19)

where 
- \( t_a \) air temperature, °C
- \( v \) wind speed, m/sec
- \( \gamma \) relative humidity.

The work of Underwood and Ward (1966) discussing anew the radiation area of man is also relevant here.

It is useful in this context to refer also to a number of climatic comfort diagrams, advocated by various authors. The simplest are the psychrometric diagrams, as shown earlier in Figures 2 and 4.

A variant of these charts is advocated by Gregorczuk (1966a). He uses air temperature and enthalpy as arguments with lines of equal relative humidity, equal effective temperature and equal physiological vapour deficit added. The latter value refers to the water vapour difference between saturation at skin temperature and the prevalent value in the air. Gregorczuk uses this diagram to plot actual observations, marked by points in the field, and then derives frequencies in various categories by marginal sums along the peripheral axes.

Roth (1966) uses a rectilinear diagram with dry-bulb temperature as ordinate and relative humidity as abscissa. Lines of equal saturation vapour pressure and relative thermal strain, according to Lee and Henschel, are added. He calls this a humidi-thermal chart and also uses it for plotting climatic values at different localities for comparative purposes.

A human comfort diagram based on a construction of Olgyay has a similar co-ordinate net. It is shown in Figure 9, reproduced here from Newman (1966). In this temperature/relative humidity diagram are entered zones of comfort which take some wind and radiation effects qualitatively into account. At the lower temperatures wind would, even in the outlined "comfort area", undoubtedly cause discomfort, but otherwise this seems to be a simple approach that may be useful for quick assessment of meteorological conditions for outdoor activities.

![Figure 9](image-url)
Bioclimatic classification attempts

As is obvious from the foregoing, the relation of meteorological parameters to human comfort and physiology is rather complex. If this is true for instantaneous values representing the environment, clearly the task becomes even more difficult for overall climatic conditions. Let us define here as climate the collective of all meteorological conditions at a locality over a suitable interval of time. Usually this collective is described by statistical measures of which the mean value is the most commonly used statistic. In bioclimatology, as we have seen, the simultaneous action of four parameters (temperature, humidity, wind speed, and radiation) is the essential ingredient. The separate mean values of these elements do not necessarily represent the common or most frequent occurrence of a time segment (such as a day or month). This is a reservation that applies to many of the bioclimatic classifications that have been attempted.

Another problem applies to climatic classifications in general. There are, with a few exceptions, no sharp boundaries between various climates. Moreover, there are usually many mesoclimatic and microclimatic sub-zones, governed by orographic conditions, in each climate. For bioclimatic purposes certain critical values of the combined climatic elements that are relatively rare may be of greater importance than more frequently encountered conditions. Obviously, too, bioclimatic classifications can have different purposes and for each purpose a classification can be designed. Thus we can have classifications for physiological survival, for design and issue of clothing, for design and construction of housing, for design and operation of heating and air-conditioning plants, and others.

An important polemic to the rationale of climatic classifications has been contributed by Carter and Mather (1966). Although their reference to environmental biology is primarily directed toward natural and, to some extent, crop vegetation, the principles of energy conversion laid down are, of course, applicable to all biological reactions to the environment.

In presenting actual classifications we may perhaps begin with a relative simple concept. This is based on an essentially arbitrary decision by some authority, such as a government agency establishing a criterion for air conditioning in government buildings. In the United States, for example, the Bureau of Management and Budget has laid down as a requirement for approving air conditioning in (non-hospital) government buildings that the mean annual number of hours of wet-bulb temperature $19.4^\circ C$ in the six warmest months has to exceed 1000 hours, or that the dry-bulb temperature has to exceed, in the same span, $26^\circ F$ for an average of 900 hours. Using a five-year record of hourly observations as a basis one can then derive at a boundary line between areas where air conditioning is justified or not justified according to these criteria (see Figure 10).

Similarly, arbitrary conditions are fixed for issue of clothing to military personnel. One of the earliest discussions, still worth reading, is a brief manual by Mast and Ennes (1943), which contains the U.S. Quartermaster General's world map of temperature zones according to wind chill factors (Siple), with the express stress on the importance of this type of concept for a biological assessment of climate, rather than by temperatures alone. The most recent version of clothing zones of the U.S. Army is shown in Figure 11 (a). In the latest clothing almanacs (Anstey, 1966) this simple scheme is modified by special considerations according to elevation above sea-level and by latitude, as given in Figure 11 (b); not counting special requirements for mountains and ice caps, a total of seven zones has been considered adequate for military clothing issuance.

In passing, we should mention three indices advocated by Rivoller (1966). One of them is designed to classify climates for tourists, based on monthly data:

$$I_R = \frac{S + T - 5D}{S}$$

where $S$ = the mean monthly hours of sunshine
$T$ = mean monthly temperature, $^\circ C$
$D$ = mean number of hours of precipitation per day.
Figure 10 — Example of arbitrary climatic line dividing areas in the United States, south of which air conditioning is authorized in government buildings. Criteria are 1000 hours annually of wet-bulb temperature > 19.4°C or 900 hours in the six warmest months > 26.7°C, or both.
Figure 11 - Example of a world clothing chart, based on climatic criteria (developed by U.S. Quartermaster General). Map (a) indicates seven major clothing zones; in lower left is a diagram giving the approximate temperature range between warmest and coldest month. Mountain areas require special consideration, as given in diagram (b), showing altitude-latitude differentiation for one world region (South-east Asia).
A second index is based on weekly mean data:

$$C_R = \frac{30s + t - 150d}{35}$$

(21)

where the small letters represent the same quantities as in formula (20) on a weekly basis.

The third index, given the name "aggressive biometeorological index for asthmatic patients" by Rivolier, has the form

$$IBA = K_1 + \Delta t + v + K_2 + K_3 - 2 I$$

(22)

where $K_1$ is a combined humidity and rainfall coefficient, representing the hours of relative humidity $> 50$ per cent and height of precipitation in mm

$\Delta t$ is the number of degree hours $< 12$ or $> 25^\circ C$

$I$ hours of insolation

$K_2$ and $K_3$ local coefficients

$v$ wind speed in m sec$^{-1}$.

Obviously, all these formulations are highly arbitrary and, until tested against large bodies of information on the reaction of tourists or asthmatics (a very loose term in itself, needing specific definition in terms of the disease provoking asthma), one can dismiss them as contributing little to the problem.

In a general way mapping of bioclimatically important factors in the classical climatological sense may give at least a first glimpse into the geographic distribution of bioclimates. Jauregui and Soto (1966) for example compared the index of Tennenbaum et al. (1961) for the area of Mexico. When the sum of dry- and wet-bulb temperature in °C exceeds 48, the limit of comfort for most persons is exceeded. For 2:00 p.m. values the isoline of this value coincides well with that enclosing areas of wet-bulb temperature $> 20^\circ C$ and delineates regions where uncomfortable day-time conditions prevail.

In a similarly general sense world charts of effective temperature, for January and July, by Gregorczuk and Cena (1967) give a quick impression of broad-scale distribution of comfort conditions. These are based on substitution of mean monthly values of temperature $t$ and relative humidity $\gamma$ into a formula of effective temperature given by Missenard:

$$ET = t - 0.4(t - 10) \left(1 - \frac{\gamma}{100}\right)$$

(23)

These maps are reproduced here as Figures 12 (a) and (b). Areas within the isolines $20^\circ C$ ET are likely to be, at least part of the time, on the uncomfortable side at the warm end of the spectrum. Those beyond $15^\circ C$ ET lines, toward the cold end, will be partly or wholly too cool without adequate protection.

Brazol (1954) developed a bioclimatic classification, using air enthalpy as a comfort criterion. He gives 12 categories which are shown in Table VI. These he applied to Argentinian climatic conditions.
Figure 12 – Generalized isolines of average effective temperature over the world. Map (a) for January; map (b) for July (after Gregorczuk and Cena, 1967)
A LIMITED REVIEW OF PHYSICAL PARAMETERS

TABLE VI
Scale of climatic sensation (after Brazol, 1954)

<table>
<thead>
<tr>
<th>Class</th>
<th>Climatic sensation</th>
<th>Air temperature, °C</th>
<th>Air enthalpy kcal kg⁻¹</th>
<th>Anthro-po-climatic classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>Lethal heat</td>
<td>–</td>
<td>&gt; 35</td>
<td>&gt; 31</td>
</tr>
<tr>
<td>11</td>
<td>Intolerable heat</td>
<td>–</td>
<td>32-35</td>
<td>26-31</td>
</tr>
<tr>
<td>10</td>
<td>Suffocating heat</td>
<td>–</td>
<td>26-32</td>
<td>19-26</td>
</tr>
<tr>
<td>9</td>
<td>Uncomfortable heat</td>
<td>–</td>
<td>18.3-26</td>
<td>12-19</td>
</tr>
<tr>
<td>8</td>
<td>Very warm</td>
<td>–</td>
<td>16.6-18.3</td>
<td>11-12</td>
</tr>
<tr>
<td>7</td>
<td>in summer, acceptably warm</td>
<td>–</td>
<td>14.8-16.6</td>
<td>10-11</td>
</tr>
<tr>
<td>6</td>
<td>in autumn, most comfortable</td>
<td>–</td>
<td>12.8-14.8</td>
<td>8.5-10</td>
</tr>
<tr>
<td>5</td>
<td>in winter, acceptably cool</td>
<td>–</td>
<td>10.8-12.8</td>
<td>7.5-8.5</td>
</tr>
<tr>
<td>4</td>
<td>Cool</td>
<td>10-15</td>
<td>8.5-10.8</td>
<td>6.0-7.5</td>
</tr>
<tr>
<td>3</td>
<td>Moderately cold</td>
<td>5-10</td>
<td>3.5-8.5</td>
<td>3.5-6.0</td>
</tr>
<tr>
<td>2</td>
<td>Cold</td>
<td>0-5</td>
<td>0.5-3.5</td>
<td>2.5-3.5</td>
</tr>
<tr>
<td>1</td>
<td>Icy</td>
<td>&lt;0</td>
<td>&lt;0.5</td>
<td>&lt;2.5</td>
</tr>
</tbody>
</table>

It is noteworthy that all homeo- and hyperthermal classes are essentially identified by wet-bulb temperatures. As was the case for some earlier discussed indices, because of the lack of a wind factor this scale is not sufficiently discriminating at the cold end.

Gregorczuk (1967) bases a world climatic analysis on a formulation of a six-step classification, based on the three major sub-categories of Brazol. He distinguishes these by classifying the warmest and coldest month into these three groups. If these are designated as a, b, and c the bioclimatic types shown in Table VII result.

TABLE VII
Gregorczuk’s bioclimatic types according to enthalpy

<table>
<thead>
<tr>
<th>Class</th>
<th>Type</th>
<th>Enthalpy, kcal kg⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Warmest month</td>
</tr>
<tr>
<td>aa</td>
<td>permanently hyperthermal</td>
<td>&gt;11.0</td>
</tr>
<tr>
<td>ab</td>
<td>hyperthermal/comfortable</td>
<td>&gt;11.0</td>
</tr>
<tr>
<td>ac</td>
<td>hyperthermal/hypothermal</td>
<td>&gt;11.0</td>
</tr>
<tr>
<td>bb</td>
<td>permanently comfortable</td>
<td>7.5-11.0</td>
</tr>
<tr>
<td>bc</td>
<td>comfortable/hypothermal</td>
<td>7.5-11.0</td>
</tr>
<tr>
<td>cc</td>
<td>permanently hypothermal</td>
<td>&lt;7.5</td>
</tr>
</tbody>
</table>

These classes are shown on a large-scale world map in Figure 13. Obviously one can only convey a gross picture on such a scale, but the broad patterns have didactic value.
Along similar lines is an effort of Cena and Slomka (1966). These authors designate five categories of cooling power:

1. $< 10$ mcal cm$^{-2}$ sec$^{-1}$ — hot
2. 10-20 mcal cm$^{-2}$ sec$^{-1}$ — warm
3. 20-30 mcal cm$^{-2}$ sec$^{-1}$ — moderate
4. 30-40 mcal cm$^{-2}$ sec$^{-1}$ — cold
5. $> 40$ mcal cm$^{-2}$ sec$^{-1}$ — freezing

These cooling powers are based on monthly mean temperatures and wind speed, and are obviously different from sensations based on instantaneous cooling power. If the warmest and coldest month of the year are categorized as in the preceding classification by two-letter combination, a total of 15 combinations results ($aa$, $ab$, $ac$, $ad$, $ae$, $bb$, $bc$, $bd$, $be$, $ce$, $cd$, $de$, $ee$). For general purposes this system is perhaps already too detailed, yet not specific enough for closer analytical work in bioclimatology.

Another attempt in this direction was made by Terjung (1966, 1967). He starts out promisingly enough by categorizing effective temperatures, modified by wind chill, and applying an arbitrary correction for solar radiation by decreasing wind chill by 200 kcal m$^{-2}$ hr$^{-1}$ for every hour of bright sunshine. The number of classes introduced becomes very large, because of the many possible "physioclimatic associations" which this author, perhaps rightly, deems necessary. However, the effort is largely vitiated by using combinations of the mean monthly daily maximum temperature in combination with the lowest monthly humidity, and the highest monthly humidity with the daily mean minimum temperature. Consequently the results neither have the merit of generality as the preceding ones nor do they represent the detailed data ensemble, which can only be reflected through the use of simultaneous values of meteorological elements, and summarized from discrete hourly observations. World patterns using this classification of 11 steps are shown in a series of one annual and 12 monthly world maps (Terjung, 1968).
In that respect, methodologically by far the most appealing is the work of Bultot (1962, 1966). Unfortunately it has not yet found much attention. He uses a temperature (abscissa) and vapour pressure (ordinate) diagram, using simultaneous hourly values. In it isolines of Lee's (1958) relative climatic strain are shown. Both temperature and vapour pressure are given on a probabilistic scale. This was possible by showing that temperature values at the station for which the analysis was carried out follow a logarithmically normal frequency distribution and that the vapour pressures can be represented by a cubic distribution. The probabilities of the joint frequency values can be calculated. This results in probability-density ellipses. Mean values for various hours of the day can be plotted as a climogram. An example of the Congolese station Bambesa is shown in Figure 14. This shows the 95 per cent probability ellipse, indicating that 95 per cent of the data ensemble can be expected to be within. Obviously, other probability levels could be indicated. The diagram also shows three-hourly mean values from 0600 to 1800 hours. On the ordinate an index by LeRoy, based on vapour pressure, is shown. This was called by the originator the pulmonary climatic index. It has the following categories, obviously designed only for tropical climates:

<table>
<thead>
<tr>
<th>Category</th>
<th>Sub-category</th>
<th>Vapour pressure (mb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Healthy</td>
<td></td>
<td>&lt; 12</td>
</tr>
<tr>
<td>Healthy</td>
<td>Mild</td>
<td>12-16</td>
</tr>
<tr>
<td></td>
<td>Soothing</td>
<td>16-21.2</td>
</tr>
<tr>
<td></td>
<td>Depressing</td>
<td>21.2-26.4</td>
</tr>
<tr>
<td></td>
<td>Debilitating</td>
<td>&gt; 26.4</td>
</tr>
</tbody>
</table>

Figure 14 -- Example of biometeorological diagram based on probability distribution of vapour pressure (ordinate; also showing Le Roy's response index) and temperature (abscissa) at Bambesa. Curved lines slanting from left to right show Lee's (1958) strain index. Ellipse indicates 95 per cent probability density curve, i.e., 95 per cent of all observed values fall inside. Polygon inside ellipse shows average values for selected hours of the day (after Bultot, 1966)
The procedure of Bultot is, of course, applicable to any diagram. It requires the establishment of the frequency distribution of the variables and the calculation of probability values in a joint frequency distribution. If the data are in machine-processable form, these are relatively simple tasks. In many meteorological elements the form of the frequency distribution is already known so that the appropriate probability scales can be chosen a priori. It would certainly be desirable if future bioclimatic classification attempts were based on probability levels of the observed elements.

The expanding scope of human bioclimatology

Under this heading let us add a few notes based on recent literature which indicates some interesting trends in research.

Hamilton and Heppner (1967) stirred up a lively discussion by suggesting that in homeotherm animals dark pigmentation is of considerable importance in the energy budget, by reducing the metabolic cost of maintaining a body temperature. The evidence, to these authors, even implies that dark human skin coloration may be advantageous for conserving energy, by absorbing solar radiation, "as at dawn and dusk" in otherwise hot climates. Others argued that, at least in animals, colour is essentially a camouflage mechanism. But who can look far back into the genetic heritage of man and assess the survival value of various attributes under primitive conditions?

The complex question of skin colouring under the influence of solar radiation and the related questions of skin-cancer development are hardly reduced, as yet, to clear-cut effects. The lack of routine meteorological measurements of solar ultra-violet at a widespread network of stations contributes to the level of ignorance. The biochemical complexity has been pointed out by Chian and Wilgram (1967). They showed that the enzyme tyrosinase is bound in the skin's melanoma cells. It oxidizes tyrosin to melanin by way of dihydroxy phenylalanine. Also present in the cells is a tyrosinase inhibitor, which can be inactivated by ultra-violet radiation. Tanning is produced by the temporary inactivation of this inhibitor, permitting the oxidation reaction to proceed.

Epidemiological studies by Urbach (1969) indicated that squamous-cell carcinoma is closely related to exposure to ultra-violet radiation. It occurs more in rural than in urban areas, quite at variance with other skin cancers, which are far more frequent in cities than the countryside. It shows also a notable latitudinal variation with considerably lower incidence in high, cloudy latitudes than in low sunny ones. This evidently has had a genetic selective effect with much higher morbidity rate for persons of Celtic origin, when exposed, than for those with highly pigmented skin, who apparently rarely or never contract this type of cancer.

Other cancer problems have also been related to environmental factors. Lea (1966) contends that in various parts of the world the death rate from neoplasms of the breast in women is related to mean annual temperature. Allegedly, this rate falls with increasing mean temperature and mean annual range of temperature. What mysterious concatenations are operative here?

In gerontology environmental factors are playing a big but yet not fully defined role. Institutional management has become an important factor here. A number of reports cover the living-quarter conditions. Rudeiko (1965) pointed out a few interesting facts. Observations of skin temperature in a home of reasonably healthy aged persons with respect to environmental temperatures showed interesting age gradients compared with a control group. Skin temperature rises in all age groups with increasing air temperature, but less rapidly for the oldest groups. Table VIII shows some characteristic relations.

Constriction of capillaries is probably the cause of the considerably poorer adjustment of skin temperature in the old.
TABLE VIII
Skin-air temperature relations in various age groups

<table>
<thead>
<tr>
<th>Age group</th>
<th>Skin temperature (°C)</th>
<th>Mean comfort temperature (°C)</th>
<th>Temperature of foot skin, at 20-21°C air temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25 - 47 years (control)</td>
<td>0</td>
<td>19 - 21</td>
<td>28.0</td>
</tr>
<tr>
<td>61 - 70 years</td>
<td>1/3 lower than control group</td>
<td>21 - 22</td>
<td>27.7</td>
</tr>
<tr>
<td>71 - 80 years</td>
<td>1 1/2</td>
<td>21 - 23</td>
<td>26.5</td>
</tr>
<tr>
<td>81 - 90 years</td>
<td>2 1/4</td>
<td>22 - 24</td>
<td>25.0</td>
</tr>
</tbody>
</table>

The case of poor adaptation of sufferers from heart disease in extreme heat and cold has often been made. A startling case of heat effects occurred in the summer of 1966 in New York City when a large number of excess deaths occurred. This is clearly shown in Figure 15. An interesting new hypothesis has also been advanced by the health commissioner of the city of Chicago on heart attacks during cold weather. S. L. Andelman, supported by L. A. Terman, claims that exertion is not the immediate cause of these attacks, even when the victims shovel snow. Rather the cause is attributed to the breathing of considerable volumes of cold air, which extract large quantities of heat from the cardio-pulmonary system.

Figure 15 - Excess deaths caused by heat wave in New York in summer 1966. Ordinate on left pertains to weekly death rate represented by solid curve, open circles; expected number within 95 per cent confidence band marked by hatched area. Ordinate on right represents weekly mean temperature; dashed line, crosses (after Landsberg, 1969)
Meteorological effects on the nervous system have also often been cited. Facts in this field are hard to come by because of the complexities pointed out in the introduction. Often these effects may well be mediated by the physical environment. Dogniaux (1968) pointed out the rather notable influences of radiative factors on temperature and thermal comfort and then indirectly on psychosomatic feeling. He also called attention to the attenuation of radiation by urban aerosols. And there are, of course, biochemical effects of the pollutants, the concentration of which is so intimately related to atmospheric stability and wind conditions.

These problems alone would justify that weather services pay closer attention to biometeorological problems than heretofore. They warrant that appropriate information and warnings be included in forecasts, just as information on hazardous driving conditions or smog has become a regular feature (Falconer, 1968).
REFERENCES


Bartkowski, Z., 1966: Czy Parnosc jest obliczana wlaściwie? (Is suitlness being measured properly?). Wiadomosci Uzdrowiskowe, Rok XII(1-2), 101-104.


Gregorczuk, M., 1967: Bioclimates of the world under air enthalpy point of view. Typescript, 4 pp + 1 world map.


Heberden, W., 1826: An account of the heat of July 1825; together with some remarks upon sensible cold. Philos. Transact. 1826, Pt. II.


REFERENCES


Lambor, J., 1966: Skala temperatur epidemicznie odzuwalnych w funkej elementow meteorologicznych (Temperature scale sensible to the skin as a function of meteorological elements). Wiedomosci Uzdrowiskowe, Rok XI (1-2), 69-76.


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REFERENCES


