POLSKA AKADEMIA NAUK
INSTYTUT GEOGRAFII I PRZESTRZENNEGO ZAGOSPODAROWANIA

POLISH ACADEMY OF SCIENCES
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BIOCLIMATIC RESEARCH OF THE HUMAN HEAT BALANCE

Krzysztof Błażejczyk, Barbara Krawczyk

Nr 28 **1994**

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BILANSU CIEPLNEGO CZŁOWIEKA

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PREFACE

The heat exchange between the human body and its surroundings is a main task in contemporary bioclimatic research. Heat equilibrium of an organism is an essential requirement for keeping constant core temperature and follows for preserve good physical as well as mental health. The precursors of this study branch were H. Pfleiderer and K. Büttner (Büttner 1938).

Studying of a balance of heat gains and losses is a complex way for evaluation of thermal state of man. It is forming under the influence of meteorological and physiological factors as well as of man's physical activity and physical properties of clothing. All components of the human heat balance are calculated on a basis of general physical laws of energy transfer. It is assumed that the human body surface is subjected to the same processes of heat exchange like all physical surfaces (Bligh & Johnson 1973; Parsons 1993; Terjung 1970, 1974).

The purpose of this issue is to present some results of bioclimatic studies carried out in Department of Climatology of the Institute of Geography and Spatial Organization of the Polish Academy of Sciences based on an analysis of the human heat balance. The studies deal with various models of heat exchange between the human body and its surroundings and they concern different spatial scales.

The first paper presents review of different models of the human heat balance used in bioclimatological and thermophysiological research (B. Krawczyk). The principles of models used in microclimatic, topoclimatic and regional scales were discussed.

The second article shows an example of bioclimatic research carried out in regional scale (B. Krawczyk). The author distinguished bioclimatic types of Poland on the basis of thermoinsulative properties of clothing and intensity of evaporative heat losses. Bioclimatic characteristics concern midday hours. The modified Budyko's model was used for estimation of the human heat balance.

The third paper presents principles and applications of a new climatological-and-physiological model of the man-environment heat exchange (**MENEX**). The **MENEX** model is adapted for fluctuating outdoor climate and it unites the results of previous studies carried out by the author (K. Błażejczyk) as well as by other bioclimatologists and physiologists. The model includes also non published results of investigations dealing with absorption of solar radiation by a new analog model of the human body - an ellipsoid. The studies were conducted in the frame of

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science co-operation between Institute of Geography and Spatial Organization (Warszawa, Poland) and National Institute of Occupational Health (Solna, Sweden). The paper is supplemented by a computer program of the **MENEX** model written in TURBO PASCAL 6.0. The program may be compiled on IBM or compatible computers.

Krzysztof Błażejczyk

Barbara Krawczyk

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HUMAN HEAT BALANCE AND ITS APPLICATIONS IN BIOCLIMATOLOGY

Barbara Krawczyk

Abstract: The paper presents principles of essential models of the human heat balance elaborated in different countries. The models were applied for bioclimatic studies indoor and/or outdoor. They considered the human heat balance in different spatial scales: microclimatic, topoclimatic (urban areas, recreation areas, health resorts) and regional (regions, countries, continents).

Key words: Human heat exchange - Heat balance models - Bioclimate

1. Introduction

During the last 20 years human heat balance became widespread in bioclimatic research due to its complex character. It is helpful, therefore, to quantify interaction between the human body and the environment in terms of heat gains and losses. A lot of mathematical-and-physical models describing process of heat exchange were elaborated. They analyse changes of biometeorological and bioclimatological conditions in different spatial scales:

- microclimatic (mainly indoor),
- topoclimatic (urban and recreation areas, health resorts),
- regional, i.e. macroclimatic (regions, countries, continents).

Methodological studies of the human heat balance were performed in different research centres of Australia, Austria, Bulgaria, Canada, former Czechoslovakia, Denmark, Germany, Israel, Japan, New Zealand, Poland, former Soviet Union, Sweden, Switzerland and United States (Tab. 1).

From the bioclimatological point of view the most interesting are models of the human heat balance considering an influence of atmospheric factors over the human being in topoclimatic and regional scales.

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Table 1

Applications of the human heat balance method for the bioclimatological purposes in different spatial scales.

Country	Author	Microclimatic		Topoclimatic		Regional
		A	B	C	D	E
1	2	3	4	5	6	7
Australia	Auliciems A. (1981)	x				
Austria	Hammer N. (1985)				x	
	Koch E. & Rudel E. (1989)					x
Bulgaria	Marinov V.K. (1971)					x
Canada	Tuller S.E. (1975)			x		
Czech Rep.	Jokl M.V.& Moos P. (1990)	x				
Denmark	Fanger P. (1970)	x				
	Nielsen B. et al. (1988)		x		x	
Germany	Höppe P. (1986 a,b, 1987)			x	x	
	Höschele K. (1970)	x				
	Jendritzky G. (1990)			x		x
	Jendritzky G.& Menz G (1987)			x		
	Mayer H. (1977 a,b, 1982)	x			x	
	Menz G. (1990)			x	x	
	Wenzel H.G. (1985)	x				
Israel	Givoni B. (1976)			x		
Japan	Nishi Y. (1980)	x				
New Zealand	de Freitas C.R. (1985, 1990)				x	
	de Freitas C.R. & Ryken M.G. (1989)		x		x	
Poland	Błażejczyk K. (1984, 1988, 1990 a, b,)			x	x	
	Błażejczyk K. (1991,1993a)		x	x	x	x
	Błażejczyk K. & Krawczyk B. (1991)		x			

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1	2	3	4	5	6	7
	Krawczyk B. (1979, 1980, 1983, 1984, 1993)				x	x
	Krawczyk B.& Błażejczyk K. (1991)		x			
	Skrzypski J. (1989)				x	x
Switzerland	Weihe W.H. (1987)				x	
Sweden	Holmér I. (1988)	x		x		
United States	Burt J.E. et al. (1982 a,b)			x		
	Morgan D.L.& Baskett R.L. (1974)			x		
	Terjung W.H. (1970, 1974)			x		
	Young K.C. (1979)				x	
former Soviet Union	Aizenshtat B.A. (1973, 1978, 1987)			x		x
	Aizenshtat B.A.& Lukina L.P. (1982)			x		x
	Budyko M.I. (1971)					x
	Gvasalija N. (1986)					x
	Liopo T.N. & Tsytsenko G.V (1971)				x	
	Oksenich I.G. (1981)			x		
	Povolotskaya N.P. (1975)				x	
	Rusanov V.J. (1973, 1977)				x	x
	Sakali L.I. et al. (1981)		x			
	Savikovskij I.A. (1986)		x			

A - indoor, B - outdoor, C - towns, D - health resorts, recreative areas,
E - regions, countries, continents.

2. Microclimatic studies

Microclimatic studies of the human heat balance deal mainly with indoor climate. They evaluate thermal conditions for different kinds of work and define requirements for keeping heat equilibrium of an organism, e.g. clothing properties, work load and its duration (Fanger 1970; Nishi 1980; Holmér 1988).

Some models of the human heat balance were used outdoor as well. Nielsen et al. (1988) studied heat strain of subjects cycling on an ergometer. They examined the human heat balance in sun and in a shadow.

de Freitas and Ryken (1989) considered heat balance of man running on a stadium. They estimated heat load and thermal sensations of subjects with the use of

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BIODEX model (Index of heat strain based on duration of exercise). Interesting studies in microclimatic scale indoor were conducted by Mayer (1982). He compared the heat exchange in church, brew house, industrial hall, and hot-house with the use of the Fanger's model.

Krawczyk and Błażejczyk (1991) studied the structure of heat balance of man on sand dune on the Kara kum desert (subtropical climate). In another paper (Błażejczyk & Krawczyk 1991) they compared man-environment heat exchange formed under the influence of the microclimatic conditions outdoor in different climatic zones: maritime warm, continental cool, dry subtropical and tropical monsoon. Moreover Błażejczyk (1991) considered the problem of thermal stress of man in yet different weather conditions over the Lake District (Northeast Poland).

3. Topoclimatic studies

Most of the human heat balance models were used for evaluation of urban bioclimate. As the first attempt in this field the maps of solar radiation absorbed by man in Los Angeles agglomeration were made by Terjung and collaborators (1970).

Morgan and Baskett (1974) evaluated thermal sensations of man in different types of urban landscape in Sacramento, e.g. villa district, downtown, industrial area, park, using the MANMO human heat balance model. They considered various human activities.

Tuller (1975, 1981) estimated the structure of a heat balance of man in downtown and suburban areas of Victoria in Canada. He paid special attention to heat exchange by long-wave radiation.

Burt et al. (1982a, 1982b) worked out some mathematical models (HUMAN, URBAN 3, CANOPY) which were used for studying the influence of different kinds of active surface in a city on the human heat balance.

Some mathematical models simulated the human heat balance in an urban areas were elaborated in Germany: MEMI - Münchener Energiebilanzmodell für Individuen (Höppe 1986a, 1986b, 1987), MUKLIMO - Microscaliges Urbanes Klima Modell (Sievers & Zdunkowski 1986) and "Klima Michel Modell" (Jendritzky 1990, Jendritzky & Menz 1987). The above models estimate the human heat balance into near ground air layer and they define the influence of different anthropogenic factors (type of settlement, street canyons etc.) on thermal sensations of man.

In the former Soviet Union the human heat balance was used for evaluation of urban bioclimate of Tallin (Palm 1974), Kiev (Sakali 1980), Ashkhabad (Oksenich 1981), Ushgorod (Sakali et al. 1981), Tashkent (Aizenshtat & Lukina 1982), Minsk

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(Savikovskij 1986).

Process of heat exchange between man and his surroundings has special importance for recreation areas and in health resorts where local outdoor climate is an important treatment factor.

Povolotskaya (1975) evaluated bioclimatic conditions in North Caucasian health resorts basing on man-environment heat exchange. She recommended specific weather situations and specific sites for different forms of climathoterapy.

Mayer (1977a, 1977b) studied bioclimatic conditions of forested areas using the MEMI heat balance model. de Freitas (1985, 1990) assessed bioclimatic conditions of Australian beach with the use of two models of the human heat balance: HEBIDEX (Heat Budget Index) and STEBIDEX (Skin Temperature Index).

In Poland the method of the human heat balance was used in topoclimatic investigations performed in small health resorts in the Beskidy Mts. (Iwonicz) and at the sea-shore (Dźwirzyno). The structure of the heat balance of the human body was examined according to Budyko's model. Physiological and climatological evaluation of studied areas was made by the author (Krawczyk 1979, 1980, 1983, 1984).

Budyko's model was also a basis for a original concept of "biotopoclimatic" mapping elaborated by Błażejczyk (1984, 1990a). According to K Błażejczyk biotopoclimates are small areas with similar structure of the human heat balance. They are formed under the influence of specific, local features of environment (land use, plant cover, inclination and orientation of slopes, kind of ground surface etc.). Biotopoclimatic maps of different types of Poland's landscape were made (Błażejczyk 1988, 1990b, 1991).

Skrzypski (1989) has adapted Fanger's model for bioclimatic studies outdoor. It was applied for bioclimatic evaluation of thermal conditions for climatotherapy in health resorts of Poland.

4. Regional studies

Models of the human heat balance were also used for the evaluation of a bioclimate in regional scales. Bioclimatic maps of Austria (Koch & Rudel 1989), Germany (Jendritzky 1990) and the former Soviet Union (Gvasalija 1986; Liopo & Tsytsenko 1971; Rusanov et al. 1977) were made. The special attention should be paid for bioclimatic atlases of Bulgaria (Marinov 1971) and Central Asia (Aizenshtat 1973). The authors mentioned above used their own, original models of the human heat balance and assumed that evaporative heat losses determine heat equilibrium and thermal sensations of man.

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Bioclimatic maps of Germany (Jendritzky 1990; Menz 1990) were made with the use of the "Klima-Michel Modell". Characteristics of the human heat balance were supplemented by data of air pollution. Hipsometric differentiation and land use were obtained by remote sensing, space data. The maps used for whole country and for separate parts of Germany may be applied in regional and urban planning.

Krawczyk (1993) studied structure of a heat balance of man over the territory of Poland from the point of view of the optimal clothing insulation required for heat equilibrium of an organism . It was a basis for bioclimatic typology of Poland.

* * *

Human heat balance models can be also examined from another point of view. According to the conditions of man-environment heat exchange and the purpose of investigations all models can be gathered in two groups:

- models of unstationary conditions of heat exchange,
- models of stationary conditions of heat exchange.

Unstationary conditions occur with temporary fluctuations of meteorological and physiological parameters. In particular moments heat exchange between the human body and its surroundings is unbalanced. However stationary conditions assumed that man-environment heat exchange is balanced as well as core temperature is constant. Such conditions occur in relatively long periods (minimum 24 hours). Heat balance is calculated taking into account average values of meteorological and physiological parameters.

Most of bioclimatic models of the human heat balance describe stationary conditions of heat exchange. New climatological-and-physiological model of **Man-ENvironment** heat **EXchage**, worked out by Błażejczyk (1992,1993a, 1993b), may be used both for unstationary and for stationary conditions. It may be applied in different branches of bioclimatic research. The model bases on the results of detail physioclimatological investigations of the human heat balance outdoor performed in various weather conditions, in different climatic zones and in diverse types of terrain. The principles of the **MENEX** model will be presented in this issue.

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EVALUATION OF BIOCLIMATE OF POLAND ON THE BASIS OF MODIFIED BUDYKO'S MODEL OF THE HUMAN BODY HEAT BALANCE

Barbara Krawczyk

Abstract: In the study the modified Budyko's model is discussed. Thermal insulation of clothing (**Icl**) is treated as a bioclimatological index. The maps of **Icl** distribution are presented as well as the structure of heat balance and thermal state of man are considered.

Key words: Human heat balance - Clothing insulation - Bioclimate.

1. Method

In stationary conditions, the man-environment heat exchange may be expressed by the following energy balance equation:

$$\mathbf{R} + \mathbf{M} = \mathbf{C} + \mathbf{E} + \mathbf{L} + \mathbf{Res} \qquad (1)$$

where:

R - solar radiation absorbed by the human body surface,
M - metabolic heat production,
C - sensible heat loss (by convection),
E - evaporative heat loss,
L - heat exchange by long-wave radiation,
Res - heat exchange due to respiration.

The heat exchange by conduction (through a contact with the ground) was not taken into consideration because of its insignificant values. All components of the equation are expressed in $W \cdot m^{-2}$. A vertical cylinder is assumed as an analog model of the human body. Taking into account the low of an isotropic distribution of diffuse and reflected solar radiation the quote of absorbed solar radiation of nude man is calculated as follows:

$$\mathbf{R} = (\mathbf{K}_{dir} \cot \mathbf{h}/\pi + 0.5 \cdot \mathbf{K}_{dif} + 0.5 \cdot \mathbf{K}_{ref}) \cdot (1 - \mathbf{a}) \qquad (2)$$

where:

$\mathbf{K}_{dir}$ - intensity of direct solar radiation on horizontal plane (in $W \cdot m^{-2}$),

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h - Sun altitude (in °),
K_{dif} - intensity of diffuse solar radiation (in $W \cdot m^{-2}$),
K_{ref} - intensity of reflected solar radiation (in $W \cdot m^{-2}$),
a - albedo of skin and clothing (assumed as 0.30).

Intensity of reflected solar radiation is calculated as follows:

$$K_{ref} = (K_{dir} + K_{dif}) \cdot a_g \qquad (3)$$

where:
a_g - albedo of ground surface (fraction).

Measurements of solar radiation are carried out at only on a few meteorological stations in Poland. Thus it had to be estimated with the use of the Black's formula. It bases on relationship between global solar radiation and relative sunshine duration and has the following form:

$$K\downarrow = K_o\downarrow \cdot (0.17 + 0.58 \cdot sh/sh_o) \qquad (4)$$

where:
$K\downarrow$ - global solar radiation on horizontal plane (in $W \cdot m^{-2}$),
$K_o\downarrow$ - extra-terrestrial solar radiation (in $W \cdot m^{-2}$)
sh - observed sunshine duration for midday hours (12^{oo}- 13^{oo}),
sh_o - astronomically possible sunshine duration for midday hours (12^{oo}-13^{oo}).

The regression coefficients (0.17 and 0.58) illustrate the relationship between monthly values of global solar radiation and sunshine duration. Mean error of $K\downarrow$ estimation is 15%. Transforming Black's formula, direct and diffuse solar radiation (for midday hours) was calculated as follows:

$$K_{dif} = 0.17 \cdot K_o\downarrow , \qquad (5)$$
$$K_{dir} = 0.58 \cdot K_o\downarrow \cdot sh/sh_o . \qquad (6)$$

An albedo of ground surface (a_g) was assessed with the use of the method worked out in Department of Climatology of the Institute of Geography and Spatial Organization by Paszyński and Miara (1990).

According to the low of isotropic distribution of radiant fluxes, net long-wave radiation on an unit of the body surface is equal to the half quote of long-wave radiation of the ground surface (estimated by Yefimova's empirical formula). Including corrections due to temperature differences between the human body and the atmosphere as well as the ground heat exchange by long-wave radiation of nude man is calculated as follows:

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$$\mathbf{L} = 0.5\cdot[\mathbf{s}\cdot\sigma\cdot\mathbf{T}^4\cdot(0.254-0.005\cdot\mathbf{e})\cdot(1-\mathbf{c}\cdot\mathbf{n})] - 2\cdot\mathbf{s}\cdot\sigma\cdot\mathbf{T}^3\cdot(\mathbf{Tg}-\mathbf{Ta}) + 4\cdot\mathbf{s}\cdot\sigma\cdot\mathbf{T}^3\cdot(\mathbf{Ts}-\mathbf{Ta}) \quad (7)$$

where:

s - emissivity of the radiating surface (= 0.95),

σ - Stefan-Boltzman constant (= $5.67\cdot10^{-8}$ $W\cdot m^{-2}\cdot K^{-4}$),

T - air temperature (in K),

Ta - air temperature (in °C),

Tg - ground temperature (in °C),

Ts - mean skin temperature (in °C),

e - air vapour pressure (in hPa),

n - cloudiness (in 0-1 scale),

c - coefficient characterising the type of clouds.

Mean values of **c** coefficient were taken after K.J. Kondratev for the latitude of 50-60°N (Krawczyk 1993).

The heat exchange by convection and evaporation is the most important way of heat losses. They depend on temperature and humidity differences between the human body surface and the atmosphere. The turbulent flux of sensible heat of nude man was calculated with the use of the following formula:

$$\mathbf{C} = \rho\cdot\mathbf{Cp}\cdot\mathbf{D}\cdot(\mathbf{Ts}-\mathbf{Ta}) \quad (8)$$

where:

ρ - air density (in $g\cdot m^{-3}$),

Cp - heat capacity of the air (in $J\cdot g^{-1}\cdot K^{-1}$),

D - coefficient of turbulent diffusion ($cm\cdot s^{-1}$).

D coefficient is equal to the square root of wind speed (Budyko 1971), as follows:

$$\mathbf{D} = \mathbf{m}\cdot\sqrt{\mathbf{v}} \quad (9)$$

where:

v - wind speed at 2 m above ground (in $m\cdot s^{-1}$),

m - numerical constant (equal to 1.0).

Turbulent flux of latent heat (due to evaporation) was calculated as follows:

$$\mathbf{E} = \mathbf{Le}\cdot\rho\cdot\mathbf{D}\cdot(\mathbf{q_s} - \mathbf{q})\cdot\mathbf{w} \quad (10)$$

where:

Le - latent heat of vaporisation (in $J\cdot g^{-1}$),

q_s - specific humidity of saturated air at skin temperature (in $g\cdot g^{-1}$),

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q - specific humidity of air (in $g \cdot g^{-1}$),
w - skin wettedness coefficient, equal to 1.031/(37.5 - **Ts**) - 0.065.

Considering heat balance of moving man it was necessary to take into account relative velocity of human body into the air - **v'** (Fanger 1970). Thus **D** coefficient was equal to:

$$\mathbf{D} = \mathbf{m} \cdot \sqrt{\mathbf{v} + v'} \quad . \tag{11}$$

The heat loss due to respiration (**Res**) is the less significant component of the heat balance equation. According to Liopo and Tsytsenko (1971) it may be estimated as follows:

$$\mathbf{Res} = \mathbf{Ta} \cdot (0.0005 \cdot \mathbf{f} + 0.112) + (0.0133 \cdot \mathbf{f} - 9.6533) + 0.147 \tag{12}$$

where:
f - relative humidity of the air (in %).

The Budyko's model of the heat balance of the human body takes into account a clothing factor by means of heat conductivity coefficient **D'** which is estimated as follows:

$$\mathbf{D'} = 0.53/\mathbf{Icl} \tag{13}$$

where:
Icl - thermal insulation of clothing (in clo).

The final equation of the human heat balance has the following form:

$$\mathbf{R} \cdot \mathbf{Irc} + \mathbf{M} = \mathbf{C} \cdot \mathbf{Irc} + \mathbf{E} \cdot \mathbf{Ie} + \mathbf{L} \cdot \mathbf{Irc} + \mathbf{Res} \tag{14}$$

where:
Irc - coefficient of heat transfer through clothing (for convection and radiation),
Ie - coefficient of heat transfer through clothing (for evaporation):

$$\mathbf{Irc} = \rho \cdot \mathbf{Cp} \cdot \mathbf{D'}/(\rho \cdot \mathbf{Cp} \cdot \mathbf{D'} + \rho \cdot \mathbf{Cp} \cdot \mathbf{D} + 4 \cdot \mathbf{s} \cdot \sigma \cdot \mathbf{T}^{3}) \tag{15}$$

$$\mathbf{Ie} = \rho \cdot \mathbf{Cp} \cdot \mathbf{D'}/(\rho \cdot \mathbf{Cp} \cdot \mathbf{D'} + \rho \cdot \mathbf{Cp} \cdot \mathbf{D}) \tag{16}$$

The presented model of the heat balance may be applied for many practical purposes (Fig. 1). Heat exchange may be equilibrated by the change of skin temperature (**Ts**) or clothing insulation (**Icl**). The successive approximation method was put into calculations. In polish bioclimatology both factors (**Ts and Icl**) were used for evaluation of climatic conditions in local as well as in regional scales (Błażejczyk 1984, 1988, 1990a; Krawczyk 1979, 1980, 1983, 1984, 1992, 1993).

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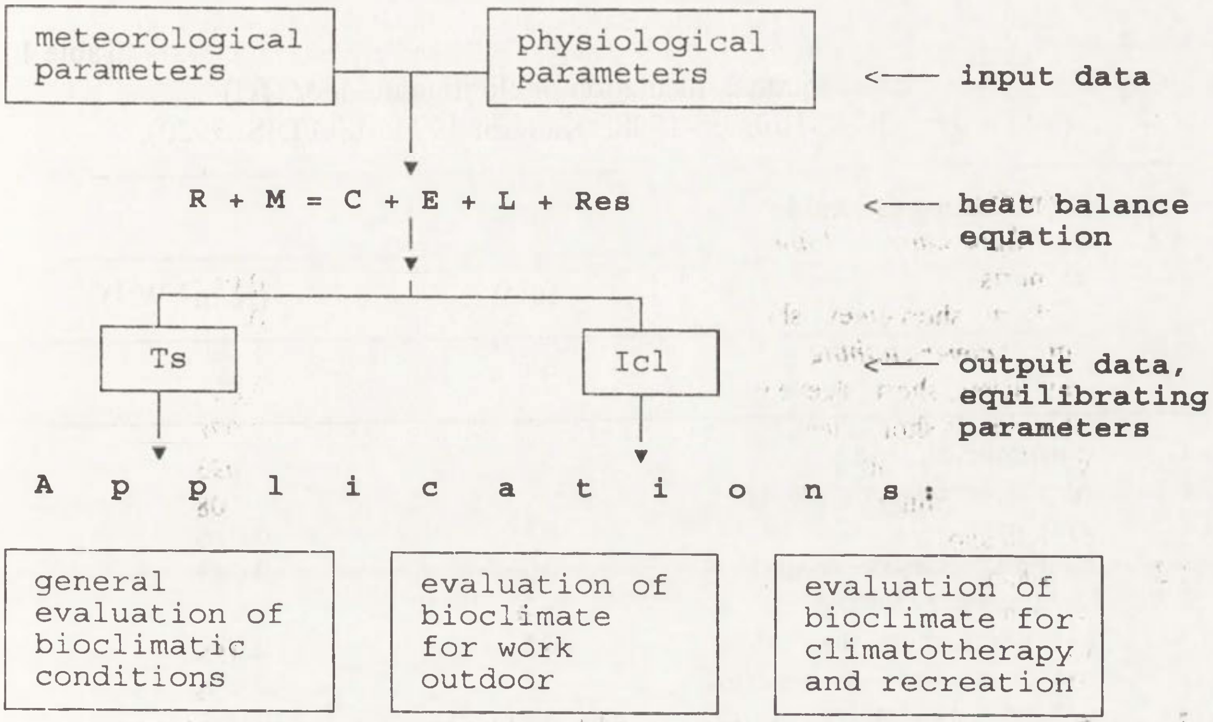

Fig. 1. The human body heat balance model and its bioclimatological applications

2. Thermal insulation of clothing as a bioclimatological index

Equilibrium of heat exchange between the human body and its surroundings is possible to keep, not only by the thermoregulative reactions, but also by wearing suitable clothing. Bioclimatic conditions of Poland was evaluated by the **Icl** index which illustrates clothing insulation required for heat equilibrium and the thermal comfort of man (i.e. at mean skin temperature of 32 -33°C).

Icl - expressed in clo unit (1.0 clo=0.155 $K \cdot m^2 \cdot W^{-1}$) - was estimated basing on mean monthly values of meteorological parameters from the midday hours (13°°official time) from 57 meteorological stations for the period (1961-1970) The calculations were performed for two levels of human activity:

a) standing (M=70 $W \cdot m^{-2}$).

b) walking with a speed of 5 km per hour (M=174 $W \cdot m^{-2}$).

For the practical purposes the thermal insulation of garments wearing in

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different seasons in temperate latitudes was established (Table 1). **Icl** < 0.5 clo characterises very light summer clothing, **Icl** of 0.5-1.0 clo - light summer clothing, **Icl** of 1.0-1.5 clo -ordinary summer clothing with additional insulation, **Icl** of 1.5-2.5 clo - spring and autumn clothing, **Icl** of 3.0-3.5 clo - light winter clothing, **Icl** of 3.5-4.0 clo - ordinary winter clothing and **Icl** >4.0 clo - heavy winter clothing (arctic clothing system).

Table 1

Basic thermal insulation of clothing outdoor (**Icl**)
(by Fanger 1974; Holmér 1988; Kandror 1974; ISO/DIS 9920),

Type	Clothing ensemble	**Icl** (clo)	**Icl** ($K \cdot m^2 \cdot W^{-1}$)
1	2	3	4
1.	**Summer clothing**		
1.1.	*Very light summer clothing*		
	a) shorts	0.1	0.016
	b) shorts, short-sleeve shirt	0.3	0.045
1.2	*Light summer clothing*		
	a) trousers, short- sleeve shirt	0.5	0.078
	b) woman's short- sleeve dress	0.5	0.078
	c) light work clothing	0.6	0.093
	d) military fatigue dress	0.7	0.108
	e) light sport clothing	0.9	0.140
1.3	*Ordinary summer clothing*		
	a) man's suit	1.0	0.155
	b) jacket, woollen skirt	1.0	0.155
	c) typical work dress	1.0	0.155
2.	**Spring and autumn clothing** (traditional european business clothing)		
	a) man's suit, coat or jacket	1.5	0.232
	b) jacket, woollen skirt, thin coat	1.5	0.232
	c) typical work dress, insulated overall	1.5	0.232
	d) typical military uniform	1.5	0.232
	e) garment as in 2 a and 2b type with add of head-dress, woollen scarf, gloves	2.5	0.388
3	**Winter clothing**		
3.1	*Light winter clothing*		
	garment as in 1.3 a and 1.3 b type with add of high insulating coat or jacket, head dress, woollen scarf, gloves	3.0	0.465

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1	2	3	4
3.2	*Ordinary winter clothing* garment as in 3.1 type with add of insulated underwear	3.5	0.542
3.3	*Heavy winter clothing* (arctic clothing system), fury coat, fluffy jacket, fury gloves, head-dress	>4.0	0.620

The kind of footwear and underwear are neglected because of they are suitable for garments.

As an example of spatial distribution of mean **Icl** values over the territory of Poland three maps are presented: for the coldest (January) and for the warmest (July) month of the year as well as for mean annual values.

In January insulation of clothing of man in standing posture varied in the midday hours from 3.9 clo in the mountain basins to 4.8 clo on the Northeast. The highest **Icl** values were observed on the Tatra and Sudety peaks (5.3 clo). It suggests that thermal comfort of man living in western Poland may be protected by ordinary winter clothing, whereas living in Northeast region need heavy winter (arctic) clothing for the same purpose (Fig. 2).

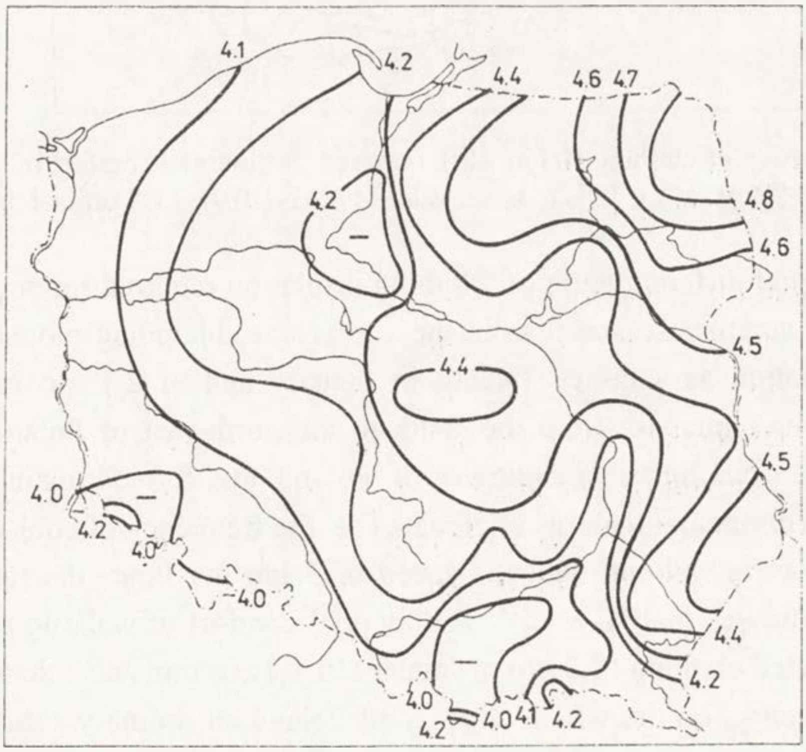

Fig. 2. Insulation of clothing (**Icl** in clo) required for thermal comfort of standing man ($M=70\ W\ m^{-2}$), JANUARY, mean values (1961-1970), 13°° official time

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In July on the almost whole territory of Poland **Icl** values are the lowest during the year and they varied from 0.9 to 1.6 clo (Fig. 3). Only at the seaside and in the mountain areas the annual minimum of **Icl** occurs in August. It means that ordinary summer clothing, with additional pieces increasing thermal insulation, is sufficient for heat equilibration. In the Tatra and Sudety Mts. even in July winter clothing is necessary for keeping thermal comfort of standing man (**Icl** - 3.0 clo).

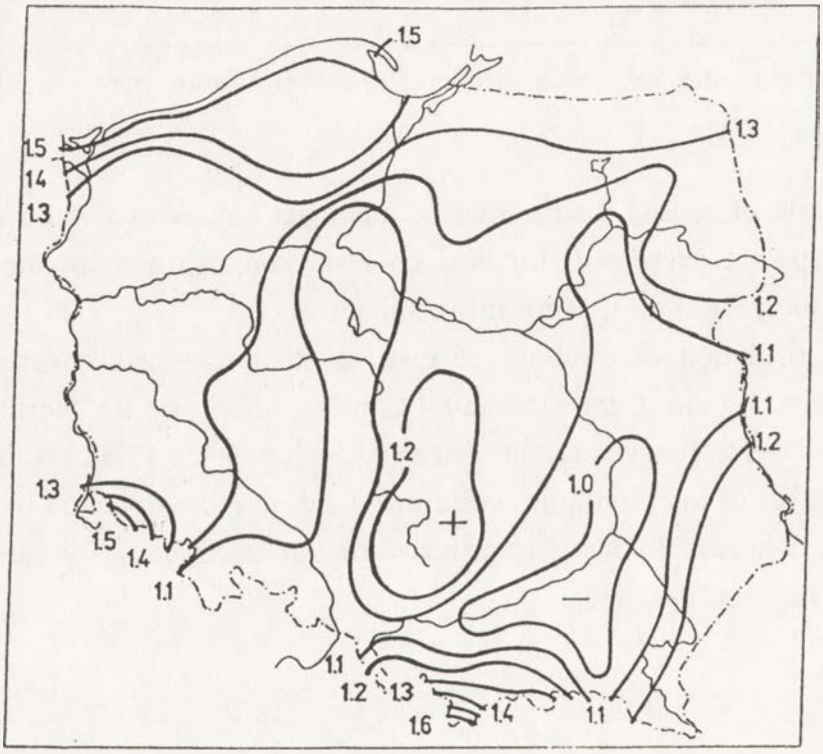

Fig. 3. Insulation of clothing (**Icl** in clo) required for thermal comfort of standing man ($M=70\ W \cdot m^{-2}$), JULY, mean values (1961-1970), 13°° official time

Thus spatial differentiation of clothing insulation required for standing man is greater in the summer season than in the winter one. Including mountains stations this differentiation amounts of 1.4 clo in January and of 2.1 clo in July. Mean annual **Icl** values increase from the south to the north-east of Poland (Fig. 4). It suggests, that bioclimatic conditions of Poland are formed mainly under the influence of continental features of climate (i.e. the frequency of cool air masses).

When man is walking with the speed of 5 km per hour, the metabolic heat production increases to 174 $W \cdot m^{-2}$. The thermal comfort of walking man was kept by less insulated clothing (2-3 clo in January, 0.8-1.0 clo in July) than of standing person. In January on the whole territory of Poland an ordinary summer clothing, with additional pieces increasing thermal insulation, or spring/autumn clothing is necessary for keeping the thermal comfort of walking man. In January, **Icl** varied from 1.2 clo in the mountain basins to 1.8 on the Tatra and Sudety peaks (Fig. 5).

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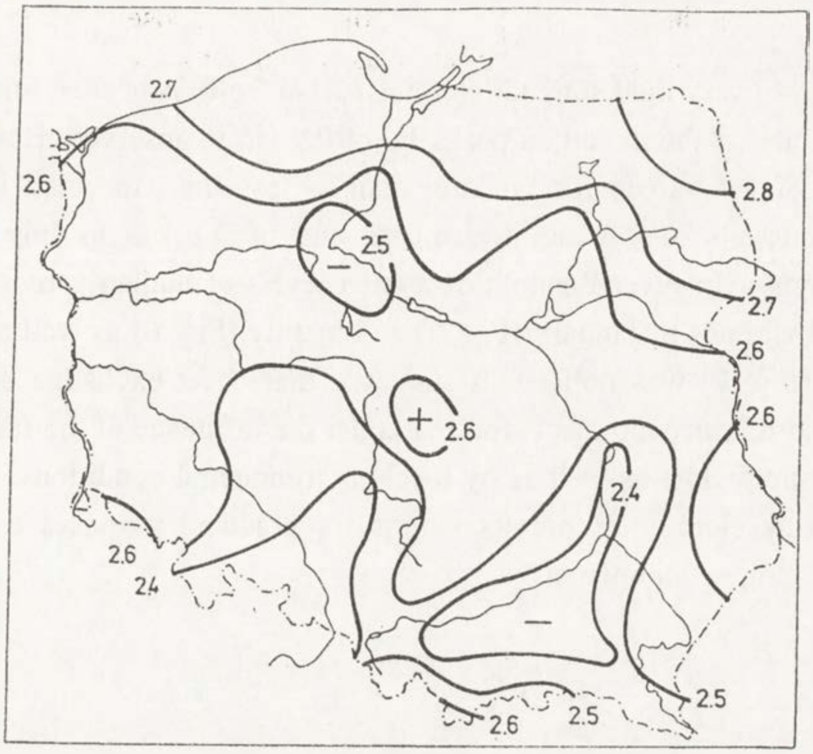

Fig. 4. Insulation of clothing (**Icl** in clo) required for thermal comfort of standing man ($M=70\ W \cdot m^{-2}$), MEAN ANNUAL values (1961-1970), 13°° official time

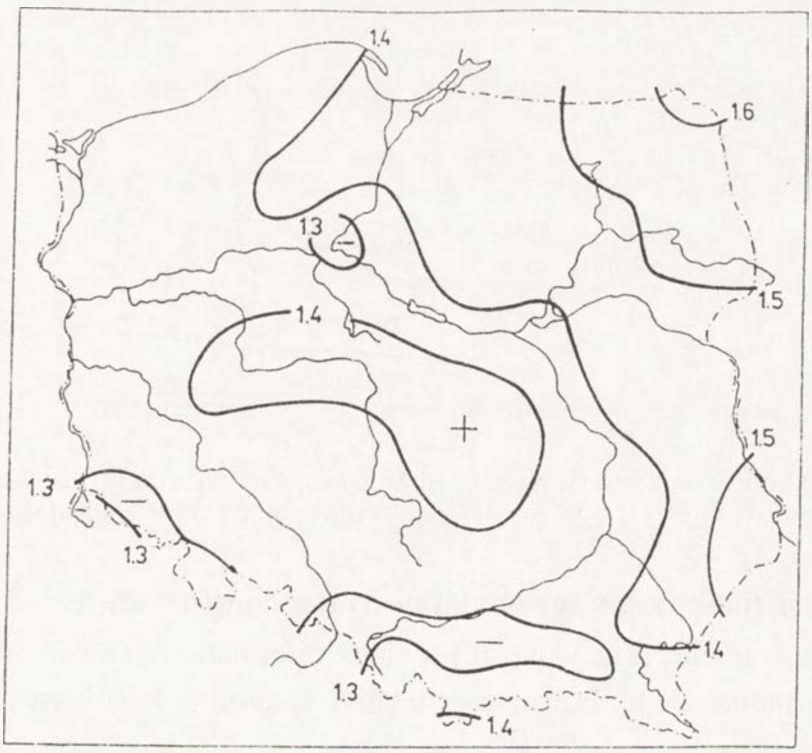

Fig. 5. Insulation of clothing (**Icl** in clo) required for thermal comfort of walking man ($M=174\ W \cdot m^{-2}$), JANUARY, mean values (1961-1970), 13°° official time

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In July (Fig. 6) very light summer clothing (0.1-0.5 clo) is needed for protecting heat balance. Only on the mountain peaks **Icl** of 0.9 clo is observed. Hence spatial differentiation of **Icl** values for walking man is less than for man in standing posture, and amounts of 0.6 clo in January, and of 0.8 clo in July (including mountain stations). However for both examined levels of human activity the same direction of **Icl** isolines in January (Fig. 5) and in July (Fig. 6) as well as for mean annual values (Fig. 7) was noticed. It suggests, that heat exchange between the human body and its surroundings is formed under the influence of the radiative, and advective climatic factors as well as by local environmental conditions. The results obtained provide clothing recommendations for practical purposes e.g. for man working and resting on an open air.

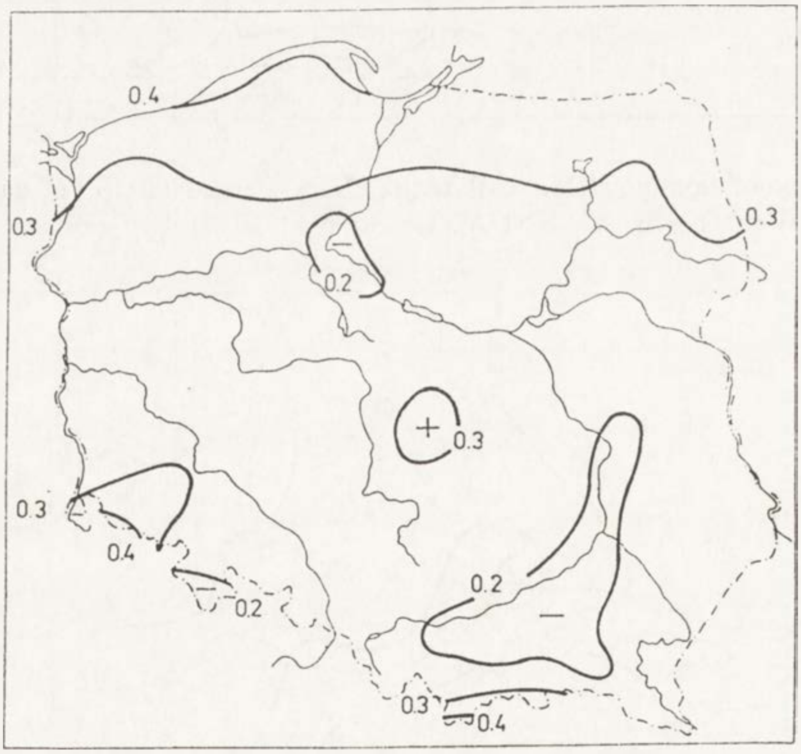

Fig. 6. Insulation of clothing (**Icl** in clo) required for thermal comfort of walking man ($M=174\ W\ m^{-2}$), JULY, mean values (1961-1970), 13°° official time

3. Structure of the human heat balance at the comfort state.

The structure of the heat balance provides information due to ways of heat losses from the human body. It expresses relative amount of heat losses or share of heat fluxes in the heat balance of the human body. The following mean monthly and yearly values were considered:

C/(R+M) - share of sensible (convective) heat loss,

E/(R+M) - share of latent (evaporative) heat loss,

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L/(**R**+**M**) - share of heat loss by long-wave radiation,
Res/(**R**+**M**) - share of heat loss due to respiration.
The sum of those quotients is always 100%.

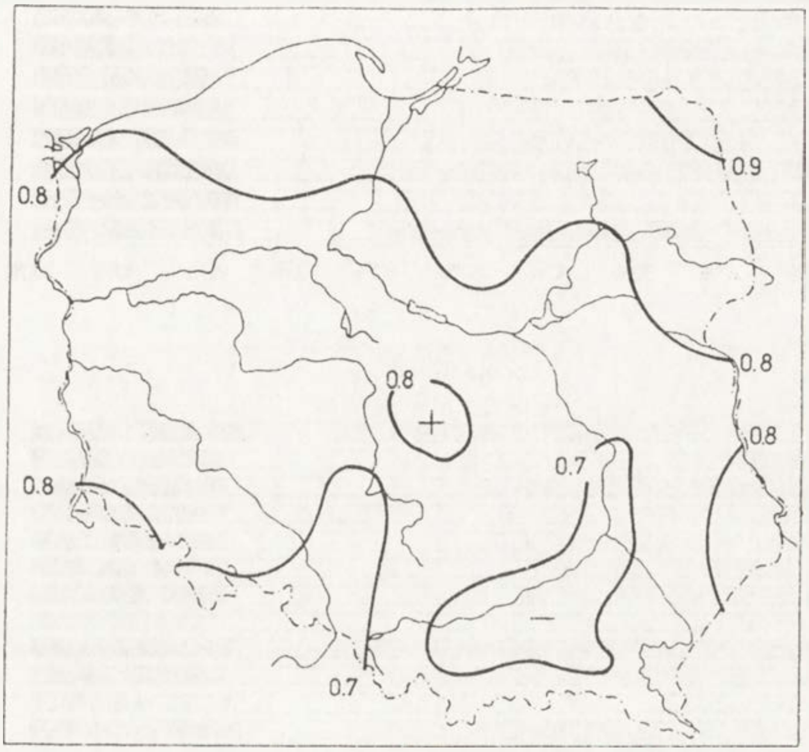

Fig. 7. Insulation of clothing (Icl in clo) required for thermal comfort of walking man (M=174 W m^{-2}), MEAN ANNUAL values, (1961-1970), 13°° official time.

The studies indicate that differentiation of mean annual values of relative heat losses is rather slight on the territory of Poland. It amounts: 14% at convection, 12% at radiation, 7% at evaporation and 3% at respiration (Krawczyk 1993). Three stations representing main geographical units of Poland: Kołobrzeg (Baltic seaside), Topola-Błonie (Lowland), Kasprowy Wierch Mt. (Tatry Mts.) were chosen for illustrating the structure of the human heat balance.

At standing man (Fig. 8) annual maximum of relative values of convective heat losses occurs in the winter reaching 56-58% at the Baltic seaside and on the Polish Lowland and 65% in the Carpathians. The share of evaporative heat losses was the greatest in July amounting 31% in Kołobrzeg, 37% in Topola-Błonie and 25% on Kasprowy Wierch Mt. It was noticed that long-wave radiation and respiration were the less significant fluxes of heat expenditure. They were the less spatially differentiated as well. Radiative heat loss amounted 12% with a slight maximum in the summer season. Heat loss due to respiration was the biggest in January (12% at the seaside and on the lowland, 15% in the mountains).

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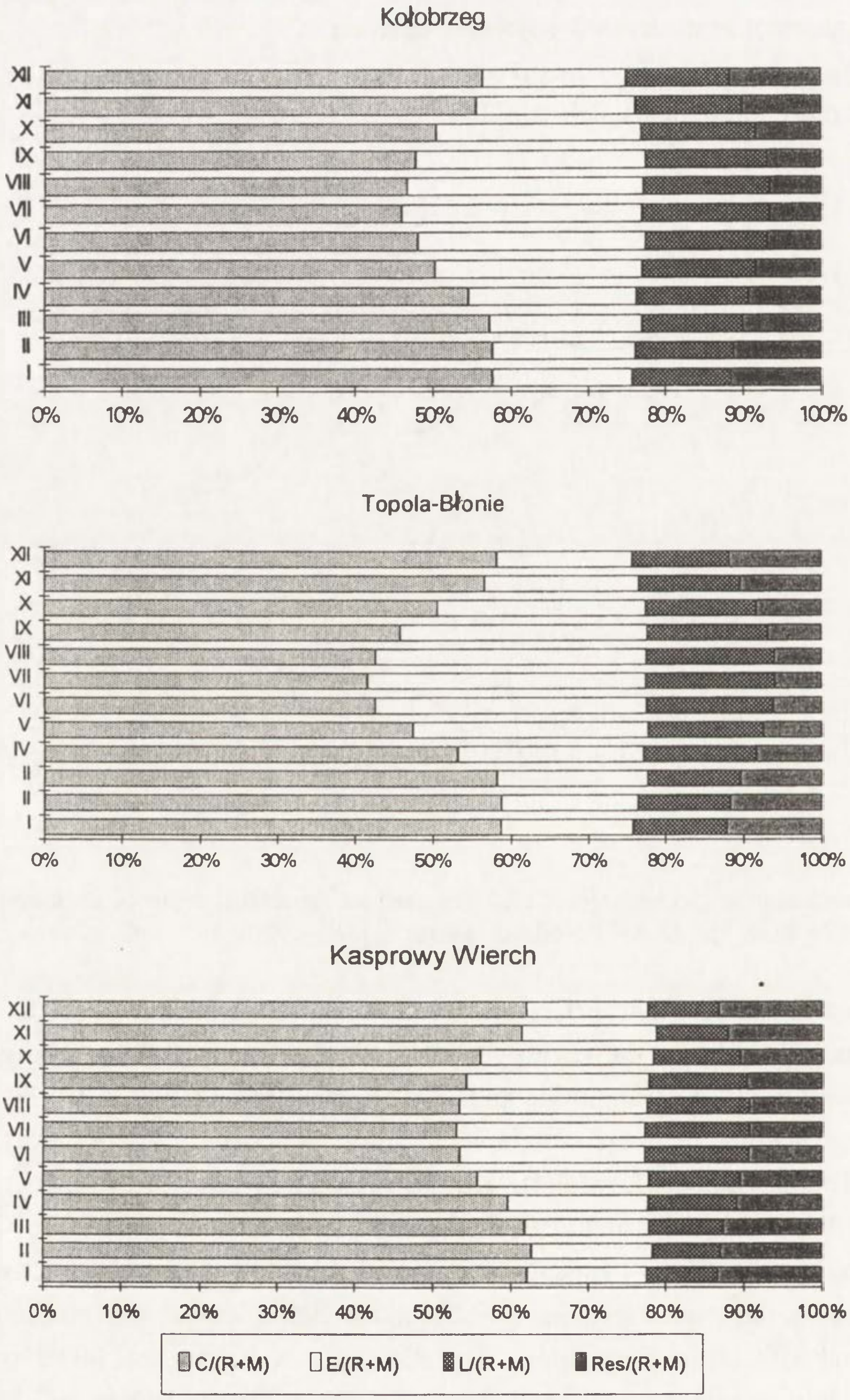

Fig. 8. The structure of the heat balance within thermal comfort of standing man ($M=70\ W \cdot m^{-2}$), mean values (1961-1970), 13°° official time;
C/(R+M) - share of convective heat loss, E/(R+M) - share of evaporative heat loss, L/(R+M) - share of heat loss by long- wave radiation, Res/(R+M) - share of heat loss due to respiration.

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When man is walking with a speed of 5 km per hour (Fig. 9) relative convective heat losses are about 5% higher than for man in standing posture. Share of long-wave radiation increased of about 2-3 % and share of evaporative heat loss is the same for walking and for standing person. However relative heat losses due to respiration decreased slightly. It is related to the method of the calculation of **Res** flux. In Budyko's model it depends only on air temperature and humidity. The model does not take into account an increase of respiration rate during physical work.

4. Final remarks.

1. Seasonal and spatial variability of bioclimatic conditions of Poland were studied with the use of stationary heat balance model. The results of investigations have not only cognitive meaning, but they also provide information useful for many practical purposes, e.g. for recreation, climatotherapy and work activity of man in an open air. All the results presented above should be helpful for many groups of people working and resting outdoor to chose proper clothing.

2. Seasonal and spatial distribution of bioclimatic indices (clothing insulation, structure of the heat balance) indicate relationships between their values and climatic conditions of Poland forming by advective and radiative factors as well as by local-environmental features.

3. It should be stated that the results obtained apply to so called "average man", i.e. without the differentiation of a functioning of thermoregulative system determined by sex, age, and state of health.

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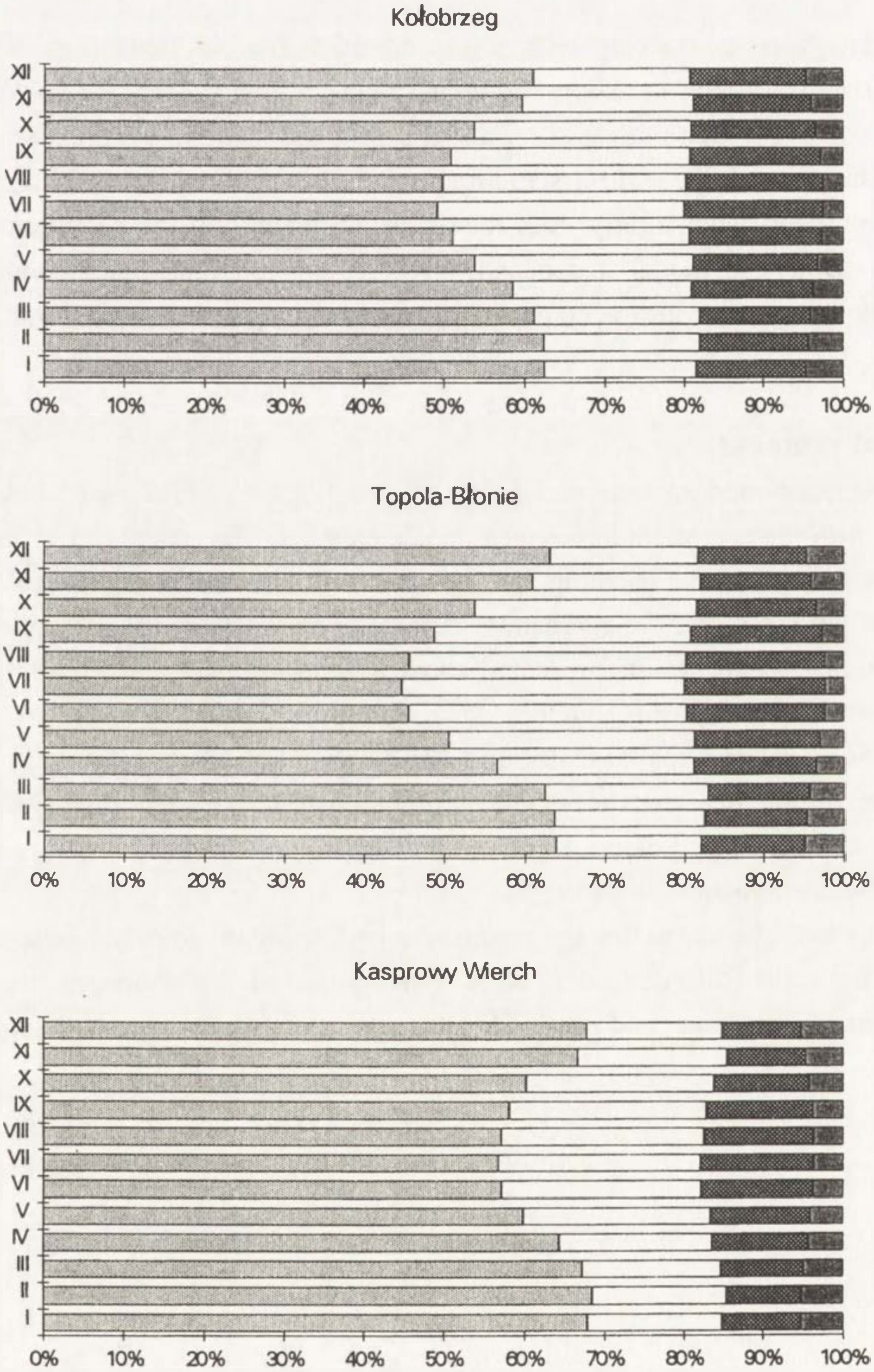

Fig. 9. The structure of the heat balance within thermal comfort of walking man (M=174 W·m^{-2}), mean values for the period of 1961-1970, 13^{oo} official time; explanations as at fig 8.

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NEW CLIMATOLOGICAL-AND-PHYSIOLOGICAL MODEL OF THE HUMAN HEAT BALANCE OUTDOOR (MENEX) AND ITS APPLICATIONS IN BIOCLIMATOLOGICAL STUDIES IN DIFFERENT SCALES

Krzysztof Błażejczyk

Abstract: The paper presents new climatological-and-physiological model of man-environment heat exchange outdoor (**MENEX**). The model considers heat gains due to metabolism and absorbed solar radiation as well as heat losses by convection, evaporation, respiration and long-wave radiation. The resultant value of heat exchange is net heat storage which illustrates heat load in man and his thermal sensations. The **MENEX** model estimates human heat balance in unstationary as well as in stationary conditions and may be used in many branches of bioclimatic research. The model was verified during bioclimatological investigations performed in different climatic zones with varying weather as well as in different types of land use and relief.

Key words: Human heat balance - Heat exchange - Heat load -Bioclimate - MENEX model

1. Introduction

Many different models try to describe relations between heat state of man and thermal factors of his surroundings as well as requirements of heat equilibration. Review of previous models is enclosed into this issue in the paper written by B. Krawczyk.

The aim of this paper is to present new, climatological-and-physiological model of man-environment heat exchange (**MENEX**). The model unites the best features of previous models and may be used both in unstationary and stationary conditions. It may be applied in many areas of bioclimatic research.

2. Principles of the MENEX model

Atmospheric stimuli influence the human organism continuously. Autonomic and behavioural thermoregulative reactions of man lead to adapt an organism to thermal conditions of surroundings. Both, internal and external factors influence direction and intensity of adaptation processes as well as they impact heat balance of man (Fig. 1).

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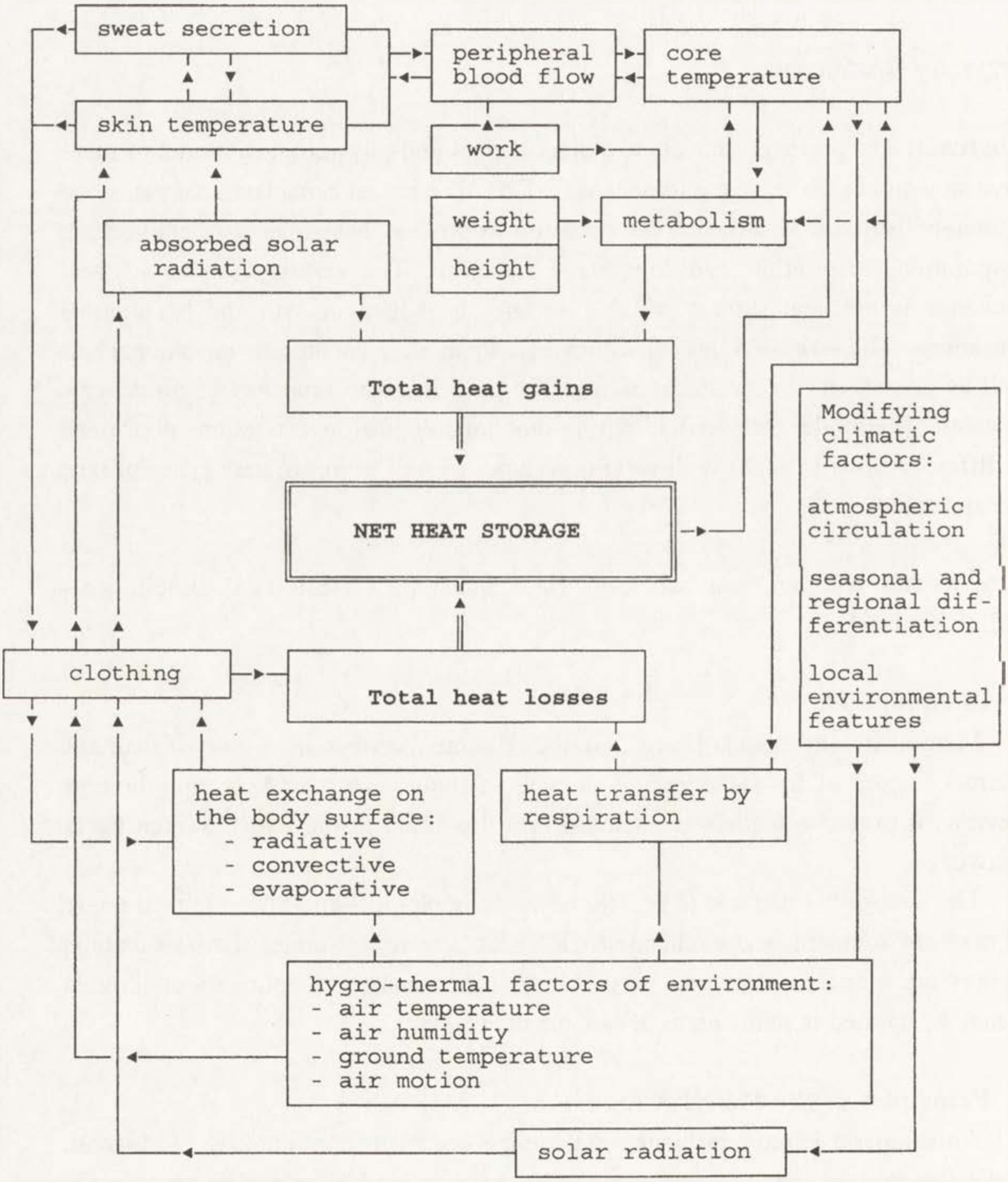

Fig. 1. Relationships between meteorological and physiological factors of man-environment heat exchange

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The main source of heat in man is metabolism. It consists of basal metabolic rate (**BMR**) as well as of metabolic free energy production (**WL**), which deals with human activity and work load. **BMR** depends on sex, age, height and weight of the human body and it varies in adults from about 35 to about 55 $W \cdot m^{-2}$ (Schofield 1985). However **WL** fluctuates from 15 $W \cdot m^{-2}$ at sitting man to about 400 $W \cdot m^{-2}$ at hard physical work (ISO 8996).

The second source of heat in an organism is absorbed solar radiation. Its quantity depends on intensity of solar radiation (direct, diffuse and reflected) as well as on Sun altitude and albedo of clothing (Clark & Cena 1978; Clark & Edholm 1985; Nielsen 1990, 1991; Nielsen et al. 1988).

In specific meteorological situations - when air temperature is higher then skin temperature - slight income of heat by sensible heat transfer (convection) or by long-wave radiation is observed (Błażejczyk 1991, 1993a; Błażejczyk & Krawczyk 1991).

In humans heat is eliminated mainly by convection, evaporation, respiration as well as by long-wave radiation. Intensity of these heat fluxes and direction of their flow (from an organism to surroundings or vice versa) depend on physical characteristics of a near-ground layer of the atmosphere, i.e. its temperature, moisture, density and heat capacity as well as on physical properties of body surface (ed. skin wettedness and skin resistance for heat transfer) and/or clothing (insulation, albedo, permeability). Heat loss due to conduction is insignificant especially at standing or sitting man and is not considered in the model (Parsons 1993).

2.1. General equation of heat balance

The general equation of man-environment heat exchange has the following form (explanation of symbols and units are given in Table 1):

$$\mathbf{BMR} + \mathbf{WL} + \mathbf{R} + \mathbf{C} + \mathbf{E} + \mathbf{L} + \mathbf{Res} = \mathbf{S}. \qquad (1)$$

The resultant quantity of man-environment heat exchange is net heat storage, i.e. changes of body heat content (**S**). Its positive value points to heat accumulation in an organism. Negative **S** value testifies to heat deficit and to heat elimination from the body core. Intensive and continuous heat surplus can involve organism overheating, however heat deficit can affect its overcooling. Intensity of net heat storage correlates also with thermal sensations in man.

The **Man-ENvironment heat EXchange** model is adapted for studies of heat balance of man outdoor (Błażejczyk 1991, 1992, 1993a, b). It takes into account

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Table 1

List of symbols and units

Symbol	Definition	Unit
A	Mean albedo of skin and/or clothing , = 30	%
ap	Air pressure	hPa
BMR	Basal metabolic rate	$W \cdot m^{-2}$
c	Coefficient characterising clouds type (0.2 for Ci and/orCc, 0.3 for Cs, 0.4 for Ac, 0.5 for As, 0.6 for Cu and/or Cb, 0.7 for Sc and/or St, 0.8 for Ns, 0.9 for fog)	nondimen.
C	Heat exchange by convection (i.e. turbulent exchange of sensible heat)	$W \cdot m^{-2}$
d	Coefficient of turbulent diffusion, $= \sqrt{\mathbf{v}+\mathbf{v}'}$	nondimen.
d'	Coefficient of heat resistance of clothing, $= 0.53/\mathbf{Icl_{eff}}$	nondimen.
$\mathbf{e_a}$	Air vapour pressure	hPa
$\mathbf{e_s}$	Vapour pressure at skin surface, $= \exp(0.58 \cdot \mathbf{Ts}+2.003)$	hPa
E	Heat loss by evaporation (i.e. turbulent exchange of latent heat)	$W \cdot m^{-2}$
f	Relative humidity of the air	%
h	Sun altitude	°
hc	Coefficient of sensible heat transfer, $= 0.013 \cdot \mathbf{ap} - 0.04 \cdot \mathbf{Ta} - 0.503$	$W \cdot m^{2} \cdot K^{-1}$
he	Coefficient of latent heat transfer, $= \mathbf{Ta} \cdot (0.00006 \cdot \mathbf{Ta} - 0.00002 \cdot \mathbf{ap} + 0.011) + 0.02 \cdot \mathbf{ap} - 0.773$	$W \cdot m^{2} \cdot hPa^{-1}$
Icl	Basal insulation of clothing	clo
$\mathbf{Icl_{eff}}$	Effective insulation of clothing, $= \mathbf{Icl} \cdot [1 - 0.27 \cdot (\mathbf{v}+\mathbf{v}')^{0.55}]$	clo
Ie*	Coefficient of heat transfer through clothing - for evaporation, $= \mathbf{hc \cdot d'/(hc \cdot d' + hc \cdot d)}$	nondimen.
Irc*	Coefficient of heat transfer through clothing - for convection and radiation, $= \mathbf{hc \cdot d'/(hc \cdot d' + hc \cdot d + 4 \cdot s \cdot \sigma \cdot T^3)}$	nondimen.
$\mathbf{K_{dif}}$	Intensity of diffuse solar radiation	$W \cdot m^{-2}$
$\mathbf{K_{dir}}$	Intensity of direct solar radiation on horizontal plane	$W \cdot m^{-2}$
$\mathbf{K_{ref}}$	Intensity of reflected solar radiation	$W \cdot m^{-2}$
L	Heat exchange by long-wave radiation	$W \cdot m^{-2}$
M	Metabolic heat production	$W \cdot m^{-2}$
MTE	Maximal time of exposure	min
N	Cloudiness	%

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R	Solar radiation absorbed by clothed man	$W \cdot m^{-2}$
Res	Heat loss by respiration	$W \cdot m^{-2}$
S	Net heat storage (i.e. changes of body heat content)	$W \cdot m^{-2}$
T	Air temperature	K
Ta	Air temperature	°C
Tg	Ground temperature	°C
Ts	Mean skin temperature	°C
v	Wind speed	$m \cdot s^{-1}$
v'	Velocity of man motion	$m \cdot s^{-1}$
w	Skin wettedness coefficient (= 1.031/(37.5-**Ts**)-0.065)	nondimen.
	! at **Ts** > 36.5°C **w** = 1	
WL	Metabolic heat production due to work or activity	$W \cdot m^{-2}$
σ	Stefan-Boltzman constant (= $5.67 \cdot 10^{-8}$)	$W \cdot m^{-2} \cdot K^{-4}$

physical parameters of the atmosphere as well as physiological characteristics of subjects.

The model calculates human heat balance outdoor both in unstationary and stationary conditions. It contains 5 options for applying in different branches of bioclimatic research:

- **"full method"** - which precisely characterises and evaluates heat state of man in unstationary conditions; it may be used in microclimatic and topoclimatic scales,
- **"work"** - which evaluates thermal conditions of work outdoor in unstationary situations; it may be used in microclimatic, topoclimatic and regional scales,
- **"forecasting"** - which forecasts thermal conditions in different parts of the day as well as in different sites; it may be used in microclimatic and topoclimatic scales,
- **"general"** - which evaluates general bioclimatic conditions of different places or seasons in stationary conditions; it may be used in regional scale,
- **"simplified method"** - which gives estimated values of man-environment heat exchange and heat load in man; it may be used in topoclimatic scale.

2.2. Input data

For the calculation of detail quantity of individual heat fluxes the following data are necessary:

- meteorological: air temperature, wind speed, air vapour pressure, relative humidity of air, air pressure, ground surface temperature, intensity of solar radiation at horizontal plane (direct, diffuse, reflected), cloudiness, coefficient of cloud type ,

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- physiological: weight, height, work load, mean skin temperature, skin emissivity, skin wettedness, vapour pressure at skin surface, age, sex,
- others: Sun altitude, velocity of man motion, Stefan-Boltzman constant, basic clothing insulation, mean albedo of clothing and/or skin.

With the lack of measurement data of mean skin temperature it may be estimated by using empirical formulas based on its correlation with meteorological parameters (Błażejczyk 1993a; see Appendix 1).

2.3. Calculations

Basal metabolic rate can be standardised due to ISO 8996 (40 $W \cdot m^{-2}$ for females and 44 $W \cdot m^{-2}$ for males) or calculated for individual characteristics of subjects (sex, age, height, weigh) according to Schofield's method (Schofield 1985; see Appendix 1). Metabolic production due to work and activity can be assessed according to ISO 8996 (Table 2).

In studies of the human heat balance outdoor very important is proper estimation of absorbed solar radiation. Its intensity is achieved by recalculation of solar radiation observed on horizontal plane. Most of previous methods used in this purpose a vertical cylinder as an analog model of man. Comparative studies carried out by Błażejczyk et al. (1993) showed that most of them give non realistic values of this heat flux. Thus the new empirical investigations of absorbed solar radiation were undertaken by the author - in co-operation with prof. Ingvar Holmér and ing. Håkan Nilsson from the National Institute of Occupational Health in Solna (Sweden) - with the use of an ellipsoid model of the human body (Błażejczyk et al. 1992). An ellipsoid sensor of PMV meter (Brüel & Kjær, type MM0023) - with axis of 160 and 54 mm - was used in this purpose. The new formula of absorbed solar radiation (**R**) derived from this study has the following form:

$$\mathbf{R} = [\cot \mathbf{h} \cdot (0.25-0.001 \cdot \mathbf{h}) \cdot \mathbf{K}_{dir} + 0.36 \cdot \mathbf{K}_{dif} + (0.49-0.005 \cdot \mathbf{h}) \cdot \mathbf{K}_{ref}] \cdot (1-\mathbf{A}/100) \cdot \mathbf{Irc^*}. \quad (2)$$

Comparison of the relationships between mean skin temperature measured on subjects outdoor and **R** values calculated with the use of above formula as well as assessed for a cylinder model of man shows that new criteria used in the MENEX model better estimates rate of solar radiation absorbed by man than the previous methods (Table 3).

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Table 2

Metabolic heat production (excluding basal metabolism) with different activity (by ISO 8996)

Human activity		**Metabolism** ($W \cdot m^{-2}$)
Metabolism due to body posture		
Sitting		10
Kneeling		20
Standing		25
Standing stooped		30
Metabolism for different type of work		
Hand work		
light		15
average		30
heavy		40
One-arm work		
light		35
average		55
heavy		75
Two-arm work		
light		65
average		85
heavy		105
Trunk work		
light		125
average		190
heavy		280
very heavy		390
Metabolism related to motion speed:		
2-5 $km \cdot h^{-1}$:		
on a flat		110
uphill:	inclination 5°	210
	inclination 10°	360
downhill:	inclination 5°	60
	inclination 10°	50
4 $km \cdot h^{-1}$ with load of:		
	10 kg	125
	30 kg	185
	50 kg	285

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Table 3

Correlation coefficients of mean skin temperature and absorbed solar radiation calculated for an ellipsoid and with the use of previous methods

Author of a method	Correlation coefficient
Budyko & Tsytsenko (1960)	0.69
Breckenridge & Goldman (1971,1977)	0.69
Lee (1980)	0.51
Terjung & Louie (1971)	0.67
Morgan & Baskett (1974)	0.64
Tuller (1975)	0.57
Höppe (1982)	0.62
Nielsen et al. (1988)	0.67
de Freitas & Ryken (1989)	0.61
Krys & Brown (1990)	0.68
new criteria for an ellipsoid	**0.74**

For the calculation of the quantity of individual heat fluxes modified equations of Budyko and Tsytsenko (1960) were used. The author has adapted Budyko's formulas taking into consideration results of latest studies of the human heat balance. New, modified formulas of heat exchange by evaporation (**E**), convection (**C**), long-wave radiation (**L**) and respiration (**Res**) have the following forms:

$$\mathbf{E} = \mathbf{he} \cdot \mathbf{d} \cdot (\mathbf{e_a} - \mathbf{e_s}) \cdot \mathbf{w} \cdot \mathbf{Ie^*} - [0.42 \cdot (\mathbf{BMR} + \mathbf{WL} - 58) - 5.04], \quad (3)$$

$$\mathbf{C} = \mathbf{hc} \cdot \mathbf{d} \cdot (\mathbf{Ta} - \mathbf{Ts}) \cdot \mathbf{Irc^*}, \quad (4)$$

$$\mathbf{L} = [2 \cdot \mathbf{s} \cdot \sigma \cdot \mathbf{T}^3 \cdot (\mathbf{Tg} - \mathbf{Ta}) - 0.5 \cdot \mathbf{s} \cdot \sigma \cdot \mathbf{T}^4 \cdot (0.254 - 0.005 \cdot \mathbf{e_a}) \cdot (1 - \mathbf{c} \cdot \mathbf{N}/100) + 4 \cdot \mathbf{s} \cdot \sigma \cdot \mathrm{T}^3 \cdot (\mathbf{Ta} - \mathbf{Ts})] \cdot \mathbf{Irc^*}, \quad (5)$$

$$\mathbf{Res} = \mathbf{Ta} \cdot (0.0005 \cdot \mathbf{f} + 0.112) + (0.013 \cdot \mathbf{f} - 9.653) + 0.147. \quad (6)$$

Numerical constants and coefficients were taken from Fanger (1970) - equation (3) -, Budyko and Tsytsenko (1960) - equation (5) - and Liopo and Tsytsenko (1971) - equation (6).

Coefficients of heat transfer through clothing (**Ie***, **Irc***) used in equations (2), (3), (4) and (5) include reduction effect of wind on total clothing insulation (Fourt & Hollies 1970; Havenith et al. 1990; Holmér et al. 1992; Nilsson et al. 1992).

The model defines also maximal time of exposure (**MTE**) to a given ambient conditions i.e. the time when changes of core temperature do not exceed ±2°C. That event can occur when total change of body heat content reaches of 600 kJ (Clark et al. 1980; Smolander 1987). Thus maximal time of exposure is assessed as follows:

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$$\mathbf{MTE} = 5400/|\mathbf{S}|. \quad (7)$$

With a lack of measured data of solar radiation intensity its quota absorbed by man may be estimated with the use of simplified empirical formulas (Błażejczyk 1993a; see Appendix 1). They have different forms depending on clouds amount and their type and they include coefficient dealing with albedo of clothing. The coefficient was achieved empirically during Polish-Swedish investigations mentioned above. It was noticed that so called absorbance index (**Abs**), which illustrates a ratio of absorbed solar radiation observed on covered ellipsoid to its standard value measured on uncovered ellipsoid in still air, varied from about 0.2 at white fabric to about 1.6 at black cover (Fig. 2).

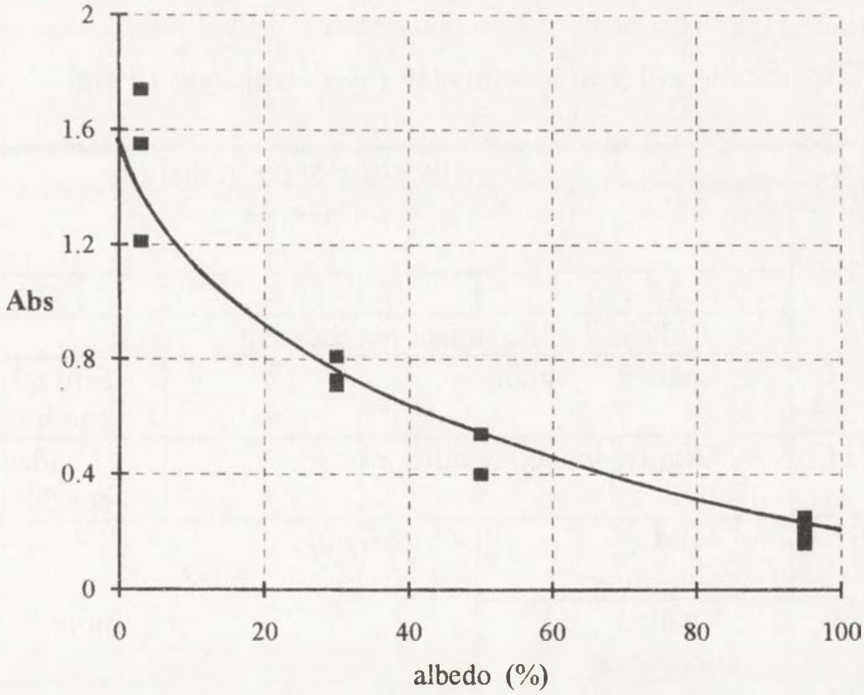

Fig. 2. Absorbance index (**Abs**) at different albedo of fabric

In simplified option of the **MENEX** model - the intensity of heat fluxes is assessed by the use of empirical equations based on their relationships with air temperature and wind speed. Equations have different forms due to environmental features of study site. Heat exchange calculated by simplified method refers to "standard" man, standing in upright posture and wearing clothing with insulation of 0.8-1.5 clo.

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Calculation procedures and detail equations for all options of the **MENEX** model are given in Appendix 1.

2.4. Output data

The calculations afford values of individual heat fluxes (absorbed solar radiation, convection, evaporation, respiration, long-wave radiation), water loss, maximal time of exposure as well as characteristics of heat load of man. Predicted thermal sensations of man in studied environmental conditions may be assessed as well.

Heat load (**HL**) in man is assessed by combination of net heat storage and absorbed solar radiation. **HL** evaluates thermal conditions of various environments (Table 4).

Table 4

Classification of heat load in man (by Błażejczyk, 1993a)

Net heat storage ($W \cdot m^{-2}$)	Absorbed solar radiation ($W \cdot m^{-2}$)		
	≤ 15.0	15.1 - 30.0	≥30.1
≥ 90.1	Hazard of organism overheating		
45.1 — 90.0	Loaded conditions		Strongly loaded conditions
20.1 — 45.0	Slightly loaded conditions		Loaded conditions
-20.0 — 20.0	Mild conditions	Slightly loaded conditions	
-45.0 — -19.9	Loaded conditions		
-90.0 — -44.9	Strongly loaded conditions	Loaded conditions	
≤ -90.1	Hazard of organism overcooling		

Thermal sensations of man outdoor are assessed by resultant value of net heat storage (Table 5). General evaluation of bioclimate in stationary conditions may be achieved by index value of net heat storage or by index value of skin temperature, which is required for heat balance of an organism (Table 6).

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Table 5

Thermal sensations of man at different net heat storage (by Błażejczyk 1993a)

Thermal sensations	Net heat storage ($W \cdot m^{-2}$)
cold	< -15.0
cool	-15.0 — -5.1
neutral	-5.0 — 15.0
warm	15.1 — 35.0
hot	35.1 — 55.0
very hot	> 55.0

Table 6

Evaluation of bioclimatic conditions based on index values of net heat storage and skin temperature (by de Freitas 1990)

Bioclimatic conditions	Index value of: net heat storage ($W \cdot m^{-2}$)	Index value of: skin temperature (°C)
very cold	≤ -232.0	≤ 21.0
cold	-231.9 — -185.0	21.1 — 25.9
cool	-184.9 — -111.0	26.0 — 29.0
temperate cool	-110.9 — -50.0	29.1 — 30.8
comfortable	-49.9 — 16.0	30.9 — 32.2
temperate warm	16.1 — 83.0	32.3 — 33.3
warm	83.1 — 161.0	33.4 — 34.4
hot	161.1 — 307.0	34.5 — 35.2
very hot	≥ 307.1	≥ 35.3

3. Applications of the MENEX model

The **MENEX** model may be applied for estimation of the human heat balance in different environmental conditions with varying work load and with specified properties of clothing. Figure 3 illustrates daily course of the fluxes of man-environment heat exchange during days with opposite weather conditions. In cloudy, windy and temperate warm day convective heat exchange was the biggest flux of heat loss; net heat storage oscillated about zero and mild heat load in man occurred. In sunny, calm and hot day evaporative heat loss predominated and heat income by convection was noticed. Net heat storage had high positive

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values. Thermal conditions were strongly loaded and even hazard of organism overheating occurred.

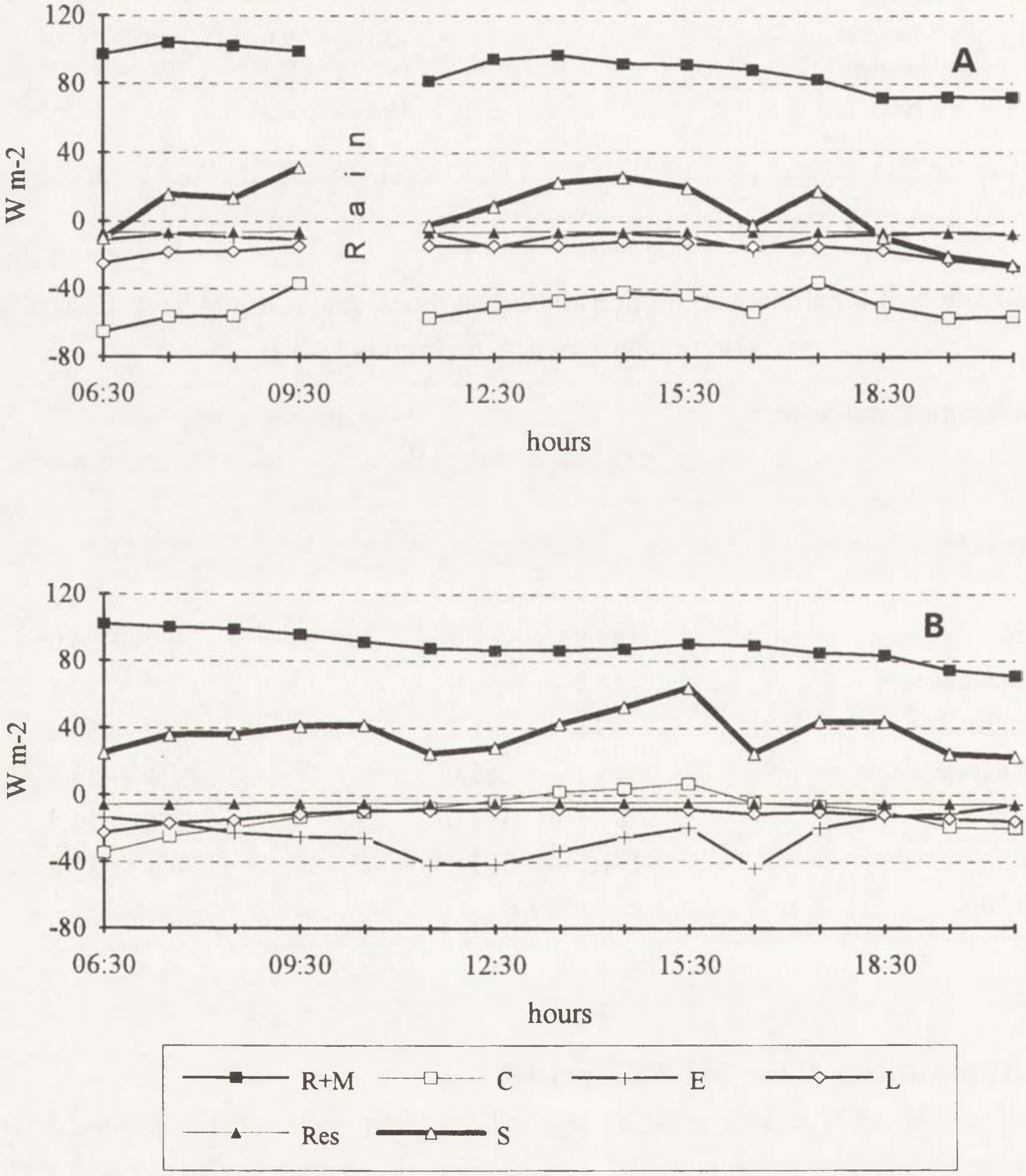

Fig. 3. Daily course of heat exchange fluxes during temperate warm, cloudy and windy day (A - 13 July 1989) as well as during hot, sunny and calm day (B - 7 July 1989); an example from Northeast Poland

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The **MENEX** model may be also used in comparative studies of spatial distribution of thermal conditions in different types of terrain in similar meteorological situations. Table 7 contains mean values of particular heat fluxes in selected types of mountain landscape observed during sunny and cloudy days.

Table 7

Characteristics of the human heat balance in different types of terrain during sunny and cloudy days; an example from South Poland (by Błażejczyk 1993b)

Characteristic	Sunny days (**N** ≤ 50%)			Cloudy days (**N** ≥ 90%)		
	Ridge	Wide valley	Narrow valley	Ridge	Wide valley	Narrow valley
R ($W \cdot m^{-2}$)	45.6	45.0	46.5	15.1	15.3	16.3
C ($W \cdot m^{-2}$)	-65.4	-54.1	-47.3	-50.8	-43.0	-38.5
L ($W \cdot m^{-2}$)	-29.3	-29.7	-31.8	-26.9	-27.1	-28.8
E ($W \cdot m^{-2}$)	-39.9	-35.7	-32.4	-15.4	-15.5	-12.9
Res ($W \cdot m^{-2}$)	-6.1	-6.1	-6.1	-6.1	-6.0	-6.0
S ($W \cdot m^{-2}$)	-25.1	-10.7	-0.9	-14.1	-6.3	0.1
MTE (min)	260	244	414	874	934	n.l.

n.l. - no time limit

Spatial distribution of heat load in man in a local scale is presented on biotopoclimatic maps. Figure 4 shows a fragment of biotopoclimatic map of the Lake District of Northeast Poland. On a relatively small area with differentiated orography and land use the great variability of heat load in man is observed.

With evaluation of thermal conditions of work outdoor the **MENEX** model defines clothing properties (colour, insulation) required for keeping thermal comfort of man. Maximal time of exposure, maximal work load, water loss and permitted work load in given meteorological conditions may be assessed as well (Table 8).

The **MENEX** model may be also applied for forecasting of thermal conditions. It defines predicted heat load in man as well as essential properties of clothing in different meteorological conditions and with different work load (Table 9).

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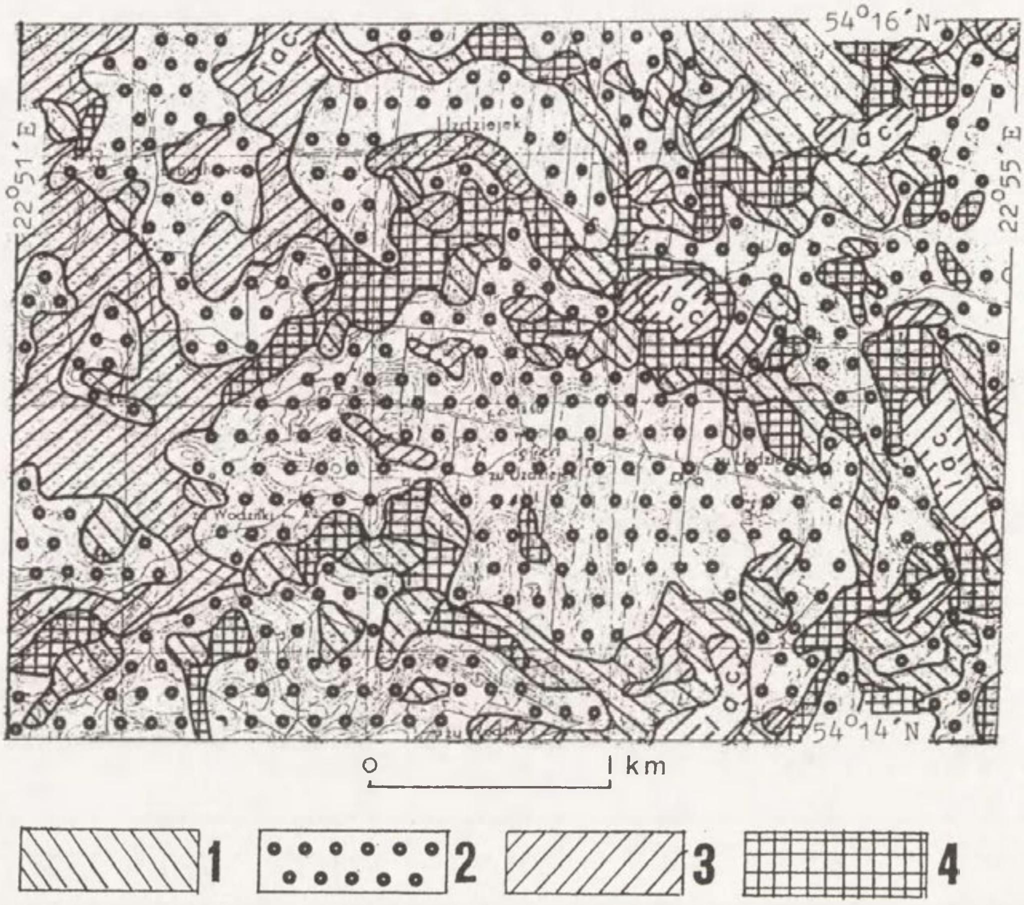

Fig. 4. Heat load in man - a fragment of biotopoclimatic map of Northeast Poland:
1 - mild, 2 - slight, 3 - average, 4 - strong

Table 8

Predicted characteristics of heat load in man during work outdoor

Characteristic	Kind of work:							
	static		dynamic		static		dynamic	
	Place of work:							
	sunny	shaded	sunny	shaded	sunny	shaded	sunny	shaded
	Air temperature of 0°C				Air temperature of 25°C			
With work load of 105 W·m^{-2}:								
MTE (min)	1280	2990	4300	6930	144	162	163	182
Icl* (clo)	1.90	1.95	1.97	2.00	0.56	0.61	0.63	0.67
With work load of 205 W·m^{-2}:								
MTE (min)	87	90	91	94	57	59	59	62
Icl* (clo)	1.15	1.18	1.20	1.23	0.27	0.30	0.33	0.36
Permitted work load (in W·m^{-2}) with clothing insulation of:								
1.0 clo	235	245	252	259	40	47	48	55
2.0 clo	97	102	102	106	-	-	-	-

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Table 9

Characteristics of the human heat balance using in forecasting of thermal conditions

Parameter of heat exchange	Place of stay: Sunny: Windy		Sunny: Calm		Shaded: Windy		Shaded: Calm	
	Activity level ($W \cdot m^{-2}$): 25	70	25	70	25	70	25	70
	Morning hours:							
R ($W \cdot m^{-2}$)	25	25	29	29	9	9	10	10
S ($W \cdot m^{-2}$)	-24	2	-14	12	-31	-4	-24	3
Main heat flux	**C**	**C**	**C/L**	**C/L**	**C**	**C**	**C/L**	**C/L**
Icl* (clo)	2.5	1.7	2.3	1.4	2.9	1.9	2.8	1.8
	Noon hours:							
R ($W \cdot m^{-2}$)	32	32	50	50	11	11	18	18
S ($W \cdot m^{-2}$)	-3	24	28	54	1	27	15	42
Main heat flux	**E**	**E**	**E**	**E**	**C**	**E**	**C/E**	**E**
Icl* (clo)	1.0	0.7	0.9	0.9	1.4	0.9	1.0	0.8

Icl* - clothing insulation required for heat equilibrium with constant skin temperature of 33°C,

C/L and **C/E** - point to equal intensity of marked heat fluxes.

General evaluation of different regions or seasons was achieved by the use of the **MENEX** model as well. Characteristics of the human heat balance are calculated for stationary conditions of man-environment heat exchange, i.e. when heat gains are equal to heat losses. It bases on mean (daily, monthly, seasonally or yearly) values of meteorological parameters. Index values of skin temperature (**Ts***) or clothing insulation (**Icl***) required for keeping heat equilibrium of the human organism are the balancing factors. Evaluation of bioclimatic conditions may be also achieved by index value of net heat storage (**S***), which is calculated for constant skin temperature, insulation and work load. Table 10 contains some bioclimatic characteristics of the human heat balance in selected sites of Poland and Bulgaria.

4. Conclusions

Heat exchange between man and his surroundings is one of the principle processes of an organism. Its intensity depends both on internal factors (metabolism, peripheral blood flow, sweating) as well as on meteorological parameters (solar radiation, air temperature, humidity of air and air motion). Physiological processes of an organism aim at keeping heat equilibrium and constant core temperature.

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Table 10

Indices of the human heat balance characterising bioclimatic conditions on the Polish Baltic coast (Kołobrzeg) and Bulgarian coast of Black Sea (Varna) in the period 1961-1970.

Index	Kołobrzeg				Varna			
	Jan.	Apr.	June	Oct.	Jan.	Apr.	June	Oct.
With activity level of 25 $W \cdot m^{-2}$								
Ts* (°C)	10.0	19.4	32.0	24.0	13.6	27.5	33.7	30.9
Icl* (clo)	4.7	3.6	1.4	2.9	4.3	2.4	0.7	1.7
S* ($W \cdot m^{-2}$)	-183	-128	-16	-92	-160	-69	+17	-33
With activity level of 75 $W \cdot m^{-2}$								
Ts* (°C)	15.5	24.3	33.5	28.2	19.0	30.5	34.6	32.8
Icl* (clo)	3.2	2.4	0.8	1.9	2.8	1.6	0.4	1.0
S* ($W \cdot m^{-2}$)	-154	-99	+13	-63	-131	-40	+46	-4

Ts* - index value of skin temperature necessary for heat equilibrium with constant clothing insulation of 1 clo,

S* - index value of net heat storage with constant skin temperature of 33°C and clothing insulation of 1 clo.

The **MENEX** model which has been proposed in this paper affords possibilities for studying the human heat balance outdoor in different branches of bioclimatic and thermophysiological research. It may be used both in unstationary and stationary conditions of man-environment heat exchange.

The **MENEX** model may be applied in studies of heat load in man (with varying work load) in different weather conditions, in research of its spatial distribution in different types of terrain as well as for general evaluation of bioclimatic conditions. The model may be also used for forecasting of thermal conditions as well as for assessing of thermal conditions of work outdoor. The model was tested in bioclimatological investigations performed in different climatic zones, weather conditions and types of terrain.

The special computer program of the **MENEX** model was developed by the author (Appendix 1). The program may be used for non commercial purposes after contact with the author (dr. K. Błażejczyk, IGiPZ PAN, Krakowskie Przedmieście 30, PL-00-927 Warszawa, Poland, fax. +48-22-267-267).

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Appendix 1

PROGRAM MENEX_Model;

{ Computer program of the Man-Environment Heat Exchange Model (MENEX) written in TURBO PASCAL 6.0 can be compiled at IBM/PC or compatible computers. The program calculates the human heat balance outdoor, with different activity and clothing. Program is adapted for stationary and unstationary conditions of heat exchange. It may be used with evaluation and forecasting of heat load in different weather situations and work load as well as with evaluation of general and local bioclimatic conditions. The MENEX model was developed in the Institute of Geography and Spatial Organization, Krakowskie Przedmieście 30, 00-927 Warszawa, Poland by dr. K. Błażejczyk }

```
USES  Crt;
VAR
Ta,Ts,ap,v,f,ea,Tg,Icl,CLO,M,a,v0,v1,Ta1,vu,sol,Rp,pora,dat,Dir,Dif,Ref,h,h1,h
2,N,cl,sr, sex,sex1,age,BMR,Ht,Wt,WL,sw,
hc,he,Irc,Ie,w,es,s1,s2,ctg,cn,Ts0,Ts2,Bil,ph,Resp,alb,
R1,R,C,E,L,Res,S,MTE,Cu,Eu,Lu,Su,Cp,Ep,Lp,godz: Real;
answer,ask,Ins,OK:Char;
dane:String[20];

PROCEDURE InputMeteo; { Input of full meteorological data }
BEGIN
  Write('Air temperature          (°C):     '); ReadLn(Ta);
  Write('Relative humidity of air (%):      '); ReadLn(f);
  Write('Vapour pressure          (hPa):    '); ReadLn(ea);
  Write('Wind speed               (m/s):    '); ReadLn(v);
  Write('Air pressure             (hPa):    '); ReadLn(ap);
  Write('Ground temperature       (°C):     '); ReadLn(Tg);
  Write('Cloudiness               (%):      '); ReadLn(N);
  Write('Cloud type : '); WriteLn;
  Writeln('Cirrocumulus-Cirrus [2]':30,'Cirrostratus [3]':30);
  Writeln('Altocumulus [4]':30,'Altostratus [5]':30);
  Writeln('Cumulus-Cumulonimbus [6]':30,'Stratocumulus-Stratus [7]':30);
  Writeln('Nimbostratus [8]':30,'fog  [9]  ':30);
  Write('clear sky [0]':30,'  '); ReadLn(cl); Writeln;
END;
```

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```
PROCEDURE InputMetProg; { Input of simplified meteorological data }
BEGIN
 Write('Air temperature          (°C):      '); ReadLn(Ta);
 Write('Relative humidity of air (%):       '); ReadLn(f);
 Write('Vapour pressure          (hPa):     '); ReadLn(ea);
 Write('Wind speed               (m/s):     '); ReadLn(v);
 Write('Cloudiness               (%):       '); ReadLn(N);
 Write('Cloud type : '); WriteLn;
 Writeln('Cirrocumulus-Cirrus [2]':30,'Cirrostratus [3]':30);
 Writeln('Altocumulus [4]':30,'Altostratus [5]':30);
 Writeln('Cumulus-Cumulonimbus [6]':30,'Stratocumulus-Stratus [7]':30);
 Writeln('Nimbostratus [8]':30,'fog  [9]  ':30);
 Write('clear sky [0]':30,'   '); ReadLn(cl);
 Tg:=Ta; ap:=1000; Writeln;
END;

PROCEDURE InputPhysio; { Input of individual physiological data }
BEGIN
 Write('Mean skin temperature (°C) - (0 when lack of data): ');
  ReadLn(Ts0);
 Write('Sex:       man [1],      woman [2] :           '); ReadLn(sex);
 Write('Age                                 (years):       '); ReadLn(age);
 Write('Height                              (m):       '); ReadLn(Ht);
 Write('Weight                              (kg):      '); ReadLn(Wt);
 Write('Work load                          (W/m2):        '); ReadLn(WL);
 Write('Clothing insulation            (clo):        '); ReadLn(Icl);
 Write('Mean albedo of clothing         (%):       '); ReadLn(a);
 Write('Velocity of subject motion     (m/s):      '); ReadLn(v0);
 WriteLn('Date \ Hour \ Study place (to 20 characters):  '); ReadLn(dane);
WriteLn;
END;

PROCEDURE InputStandard; { Input of standard physiological data }
BEGIN
 WriteLn('Mean skin temperature (°C) - (0 when lack of data): '); ReadLn(Ts0);
 Write('Sex:                  man [1],   woman [2] :    '); ReadLn(sex1);
 Write('Work load                            (W/m2):    '); ReadLn(WL);
 Write('Clothing insulation                  (clo):     '); ReadLn(Icl);
```

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```
 Write('Mean albedo of clothing          (%):    '); ReadLn(a);
 Write('Velocity of subject motion     (m/s):    '); ReadLn(v0);
 WriteLn; WriteLn('Date \ Hour \ Study place (to 20 characters):  ');
ReadLn(dane);
 WriteLn;
END;

PROCEDURE InputSolar; { Input of full data of solar radiation }
BEGIN
 Write('Solar radiation                    (W/m2):      '); WriteLn;
 Write('  - Direct (-1 when lack of data):           '); ReadLn(Dir);
 Write('  - Diffuse :                                    '); ReadLn(Dif);
 Write('  - Reflected :                                  '); ReadLn(Ref);
 Write('Sun altitude    - (degree):   '); Read(h1);
 Write('                  - (minutes): '); ReadLn(h2); WriteLn;
 WriteLn('Location of study place: sunny [1] ');
 Write('                          shaded [2] '); ReadLn(sol); WriteLn;
 WriteLn('Physiological data:  individual [1] ');
 Write('                              standard [2] '); ReadLn(ph);
 IF (ph=1) THEN InputPhysio ELSE InputStandard;
END;

PROCEDURE InputProg; { Input of estimated data of solar radiation }
BEGIN
 WriteLn('Season: ');
 WriteLn('spring [1]':20,'summer [2]':20);
 Write('  autumn [3]':20,'   winter [4]':20,'  '); ReadLn(pora);
 WriteLn('Time of the day: ');
 WriteLn('  before noon or afternoon hours [1]':40);
 WriteLn('                          noon hours [2]':40);
 Write('                       evening hours [3]':40,'  '); ReadLn(godz); WriteLn;
 WriteLn('Location of study place: sunny [1] ');
 WriteLn('                                  shaded [2] '); ReadLn(sol);
 WriteLn('Physiological data:   individual [1] ');
 Write('                                  standard [2] '); ReadLn(ph);
 IF (ph=1) THEN InputPhysio ELSE InputStandard;
END;
```

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```
PROCEDURE ParamProg; { Estimated values of absorbed solar radiation }
BEGIN
  IF ((pora=1) OR (pora=3)) AND (godz=1) THEN h:=20;
  IF ((pora=1) OR (pora=3)) AND (godz=2) THEN h:=40;
  IF ((pora=1) OR (pora=3)) AND (godz=3) THEN h:=5;
  IF (pora=2) AND (godz=1) THEN h:=30;
  IF (pora=2) AND (godz=2) THEN h:=50;
  IF (pora=2) AND (godz=3) THEN h:=10;
  IF (pora=4) AND (godz=1) THEN h:=10;
  IF (pora=4) AND (godz=2) THEN h:=30;
  IF (pora=4) AND (godz=3) THEN h:=0;
  cn:=(N/100)*(cl/10);
  IF (h<2) THEN R1:=0;
  IF a>30 THEN alb:=(1-(a-30)*0.012);
  IF a<30 THEN alb:=(1+(30-a)*0.022);
  IF a=30 THEN alb:=1;
  IF (h>2) THEN
  BEGIN
     IF (sol=1) AND (cn<0.31) THEN R1:=((LN(h)-1.1)/0.015)*alb;
     IF (sol=1) AND (cn>0.3) AND (cn<0.61)  THEN
       R1:=(EXP(0.051*h+2.34))*alb;
     IF (sol=1) AND (cn>0.6) THEN R1:=(2.21*h-6.8)*alb;
     IF (sol=2) AND (cn<0.31) THEN R1:=((LN(h)-1.1)/0.015)*0.35;
     IF (sol=2) AND (cn>0.3) AND (cn<0.6) AND (N<90) THEN
       R1:=(EXP(0.051*h+2.34))*0.58;
     IF ((sol=2) AND (cn>0.3) AND (cn<0.6) AND (N>=90)) OR
       ((sol=2) AND (cn>=0.6)) THEN R1:=(2.21*h-6.8)*0.83;
  END;
END;

PROCEDURE Parameters; { Calculation of absorbed solar radiation }
BEGIN
  h:=h1+h2/60;
  IF (h<3) THEN ctg:=0 ELSE ctg:=COS(h*PI/180)/SIN(h*PI/180);
  cn:=(N/100)*(cl/10);
  IF a>30 THEN alb:=(1-(a-30)*0.012);
  IF a<30 THEN alb:=(1+(30-a)*0.022);
  IF a=30 THEN alb:=1;
```

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```
  IF (h<2) THEN Rp:=0 ELSE
    Rp:=(0.36*Dif+(0.49-0.005*h)*Ref+ctg*(0.25-0.001*h)*Dir)*(1-a/100 );
  IF (Dir>=0) AND (sol=1) THEN R1:=Rp;
  IF (Dir>=0) AND (sol=2) THEN
  BEGIN
      IF (cn<0.31) THEN R1:=Rp*0.35;
      IF (cn>0.3) AND (cn<0.6) AND (N<90) THEN R1:=Rp*0.58;
      IF (cn>=0.6) OR ((cn>0.3) AND (cn<0.6) AND (N>=90)) THEN
        R1:=Rp*0.83;
  END;
  IF (Dir<0) AND (h<2) THEN R1:=0;
  IF (Dir<0) AND (h>=2) THEN
  BEGIN
    IF (cn<0.31) AND (sol=1) THEN R1:=((LN(h)-1.1)/0.015)*alb;
    IF (cn>0.3) AND (cn<0.61) AND (sol=1) THEN
      R1:=(EXP(0.051*h+2.34))*alb;
    IF (cn>0.6) AND (sol=1) THEN R1:=(2.21*h-6.8)*alb;
    IF (cn<0.31) AND (sol=2) THEN R1:=((LN(h)-1.1)/0.015)*0.35;
    IF (cn>0.3) AND (cn<0.6) AND (N<90) AND (sol=2) THEN
      R1:=(EXP(0.051*h+2.34))*0.58;
    IF ((sol=2) AND (cn>=0.6)) OR ((sol=2) AND
     (cn>0.3) AND (cn<0.6) AND (N>=90)) THEN R1:=(2.21*h-6.8)*0.83;
  END;
END;

PROCEDURE Skin; { Skin temperature }
BEGIN
  IF (dat=1) THEN sol:=1;
  IF (Ts0>0) AND (sol=1) THEN Ts:=Ts0;
  IF (Ts0>0) AND (sol=2) THEN Ts:=Ts0*0.96;
  IF (Ts0=0) AND (Dir>=0) THEN
      Ts2:=26.4+0.04*(Dir+Dif)+0.09*Ta+0.08*ea-0.1*v;
  IF ((Ts0=0) AND (Dir<0)) OR ((Ts0=0) AND ((dat=3) OR (dat=4))) THEN
  BEGIN
    IF (h<5) OR (R1<30) THEN Ts2:=0.293*Ta+0.0012*f-0.077*v+26;
    IF (R1>=30) AND (v<=4) THEN
      Ts2:=0.294*Ta+0.001*f+1.12*(1-N/100)-0.08*v+26.03;
    IF (R1>=30) AND (v>4) THEN
```

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```
    Ts2:=0.267*Ta+0.001*f+1.1*(1-N/100)-0.074*v+25.1;
  END;
  IF (Ts0=0) AND (sol=2) THEN Ts:=Ts2*0.96+((Icl-1)*0.6);
  IF (Ts0=0) AND (sol=1) THEN Ts:=Ts2+((Icl-1)*0.6);
END;

PROCEDURE Metabolism; { Calculation of basal metabolic rate }
BEGIN
  IF (sex1=1) THEN BMR:=44;
  IF (sex1=2) THEN BMR:=40;
  IF (sex=1) AND (age<=3) THEN
BMR:=(0.0007*Wt+6.349*Ht-2.584)/0.14688;
  IF (sex=2) AND (age<=3) THEN BMR:=(0.068*Wt+4.281*Ht-1.73)/0.14688;
  IF (sex=1) AND (age>3) AND (age<10) THEN
    BMR:=(0.082*Wt+0.545*Ht+1.736)/0.14688;
  IF (sex=2) AND (age>3) AND (age<10) THEN
    BMR:=(0.071*Wt+0.677*Ht+1.553)/0.14688;
  IF (sex=1) AND (age>=10) AND (age<18) THEN
    BMR:=(0.068*Wt+0.574*Ht+2.157)/0.14688;
  IF (sex=2) AND (age>=10) AND (age<18) THEN
    BMR:=(0.035*Wt+1.948*Ht+0.411)/0.14688;
  IF (sex=1) AND (age>=18) AND (age<30) THEN
    BMR:=(0.063*Wt-0.042*Ht+2.953)/0.14688;
  IF (sex=2) AND (age>=18) AND (age<30) THEN
    BMR:=(0.057*Wt+1.184*Ht+0.411)/0.14688;
  IF (sex=1) AND (age>=30) AND (age<60) THEN
    BMR:=(0.048*Wt-0.011*Ht+3.67)/0.14688;
  IF (sex=2) AND (age>=30) AND (age<60) THEN
   BMR:=(0.034*Wt+0.006*Ht+3.53)/0.14688;
  IF (sex=1) AND (age>=60) THEN
    BMR:=(0.038*Wt+4.068*Ht-3.491)/0.14688;
  IF (sex=2) AND (age>=60) THEN
    BMR:=(0.033*Wt+1.917*Ht+0.074)/0.14688;
END;
```

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```
PROCEDURE Storage; { Calculation of net heat storage }
BEGIN
 IF (v=0) THEN v:=0.3; v1:=v+v0;
 hc:=0.013*ap-0.04*Ta-0.503;
 he:=Ta*(0.00006*Ta-0.00002*ap+0.011)+0.02*ap-0.773;
 s1:=0.056*Ta+4.48;
 s2:=0.95*0.000000057*((273+Ta)*(273+Ta)*(273+Ta)*(273+Ta));
 M:=BMR+WL;
 CLO:=Icl*(1.0-0.27*EXP(0.55*LN(v1)));
 Irc:=(hc*(0.53/CLO))/((hc*(0.53/CLO))+(hc*SQRT(v1))+s1);
 Ie:=(hc*(0.53/CLO))/(hc*(0.53/CLO)+hc*SQRT(v1));
 es:=EXP(0.058*Ts+2.003);
 IF Ts>36 THEN w:=1 ELSE w:=1.031/(37.5-Ts)-0.065;
 R:=R1*Irc;
 C:=hc*SQRT(v1)*(Ta-Ts)*Irc;
 E:=he*SQRT(v1)*(ea-es)*w*Ie-(0.42*(M-58)-5.04);
L:=(0.5*s1*(Tg-Ta)-0.5*s2*(0.254-0.005*ea)*(1-cn)+s1*(Ta-Ts))*Irc ;
 Res:=Ta*(0.0005*f+0.112)+(0.013*f-9.653)+0.147;
 S:=M+R+C+E+L+Res;
 IF (S>-0.55) AND (S<0.55) THEN MTE:=12000 ELSE MTE:=5400/ABS(S);
 sw:=E/-0.385; WriteLn;
END;

PROCEDURE ResultFlux; { Output data - fluxes }
BEGIN
ClrScr;
 Write('Study place : ',dane); WriteLn; WriteLn;
 Write('Values of particular heat fluxes:  '); WriteLn; WriteLn;
 WriteLn('Absorbed solar radiation     * ',R:3:1,' W/m2');
 WriteLn('Convection                   * ',C:3:1,' W/m2');
 WriteLn('Evaporation                  * ',E:3:1,' W/m2');
 WriteLn('Long-wave radiation          * ',L:3:1,' W/m2');
 WriteLn('Respiration                  * ',Res:2:1,' W/m2'); WriteLn;
 WriteLn('Net heat storage             * ',S:3:1,' W/m2'); WriteLn;
 WriteLn('Mean skin temperature        * ',Ts:2:1,' °C');
 WriteLn('Clothing insulation          * ',Icl:2:1,' clo');
 WriteLn('Metabolism                   * ',M:3:0,' W/m2'); WriteLn;
 WriteLn('Water loss                   * ',sw:4:0,' g/h'); WriteLn;
END;
```

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```
PROCEDURE ResultMTE; { Output data - maximal time of exposure }
BEGIN
  IF MTE<12000 THEN
    Write('Maximal time of exposure      * ',MTE:5:0,' min');
  IF MTE=12000 THEN
    Write('Maximal time of exposure:   * without time limit');
  WriteLn; WriteLn;
END;

PROCEDURE ResultLoad; { Output data - heat load }
BEGIN
  Write('<> Thermal conditions - ');
  IF (S>=-20) AND (S<=20) AND (R<=15) THEN Write('mild <>');
  IF (S>=-45) AND (S<-20) AND (R>15) OR (S>20) AND (S<=45) AND
    (R<=30) OR (S>=-20) AND (S<=20) AND (R>15) THEN
    Write('slightly loaded <>');
  IF (S<-45) AND (S>-90) AND (R>15) OR (S>20) AND (S<=45) AND (R>30)
    OR (S>45) AND (S<90) AND (R<=30) OR (S<-20) AND (S>=-45) AND
    (R<=15) THEN Write('loaded <>');
  IF (S>45) AND (S<=90) AND (R>30) OR (S<-45) AND (S>=-90) AND
    (R<=15) THEN Write('strongly loaded <>');
  IF (S>90) THEN Write('with overheating hazard <>');
  IF (S<-90) THEN Write('with overcooling hazard <>'); WriteLn;
END;

PROCEDURE ResultSens; { Output data - thermal sensations }
BEGIN
  Write('* Predominate thermal sensations - ');
  IF (S<-15) THEN Write('cold *');
  IF (S>=-15) AND (S<-5) THEN Write('cool *');
  IF (S>=-5) AND (S<=15) THEN Write('neutral *');
  IF (S>15) AND (S<=35) THEN Write('warm *');
  IF (S>35) AND (S<=55) THEN Write('hot *');
  IF (S>55) THEN Write('very hot *'); WriteLn; WriteLn;
END;
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PROCEDURE ResultBal; {Output data - general evaluation of bioclimate}
BEGIN
 WriteLn; WriteLn;
 Write('* Bioclimatic conditions - ');
 IF (Bil=1) THEN
 BEGIN
    IF (Ts<21.1) THEN Write('very cold *');
    IF (Ts>=21.1) AND (Ts<26) THEN Write('cold *');
    IF (Ts>=26) AND (Ts<29) THEN Write('cool *');
    IF (Ts>=29.1) AND (Ts<30.9) THEN Write('temperate cool *');
    IF (Ts>=30.9) AND (Ts<32.3) THEN Write('neutral *');
    IF (Ts>=32.3) AND (Ts<33.4) THEN Write('temperate warm *');
    IF (Ts>=33.4) AND (Ts<34.5) THEN Write('warm *');
    IF (Ts>=34.5) AND (Ts<35.2) THEN Write('hot *');
    IF (Ts>=35.2) THEN Write('very hot *');
 END;

 IF (Bil=2) THEN
 BEGIN
    IF (S<-282) THEN Write('very cold *');
    IF (S>=-282) AND (S<-185) THEN Write('cold *');
    IF (S>=-185) AND (S<-111) THEN Write('cool *');
    IF (S>=-111) AND (S<-50) THEN Write('temperate cool *');
    IF (S>=-50) AND (S<16) THEN Write('neutral *');
    IF (S>=16) AND (S<83) THEN Write('temperate warm *');
    IF (S>=83) AND (S<161) THEN Write('warm *');
    IF (S>=161) AND (S<307) THEN Write('hot *');
    IF (S>=307) THEN Write('very hot *'); WriteLn; WriteLn;
 END;
END;

PROCEDURE Next;
BEGIN
 Write('Another calculation ?  Y \ N  '); ReadLn(answer);
END;
```

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```
PROCEDURE Balance; { Balancing of heat exchange for stationary conditions
                     by the change of skin temperature, clothing parameters
                     or work load }
BEGIN
  WriteLn; WriteLn;
  WriteLn('Do you want to change skin temperature,');
  Write('clothing characteristics or work load ?  Y \ N '); ReadLn(ask);
  IF (ask='N') OR (ask='n') THEN NEXT;
  WHILE (ask='Y') OR (ask='y') DO BEGIN
    Write('New skin temperature     (',Ts:2:1,')  '); ReadLn(Ts0);
    Write('New clothing insulation (',Icl:1:1,')  '); ReadLn(Icl);
    Write('New albedo of clothing    (',a:2:0,')  '); ReadLn(a);
    Write('New work load            (',WL:3:0,')  '); ReadLn(WL); WriteLn;
    WriteLn('Evaluation of bioclimate by: ');
    WriteLn('- index value of mean skin temperature - [1] ');
    Write('  -      index value of net heat storage - [2] '); ReadLn(Bil);
    Parameters; Skin; Storage; ResultFlux; ResultBal;
    WriteLn('Do you want to change skin temperature,');
    Writeln('clothing characteristics or work load ?  Y \ N '); ReadLn(ask);
    IF (ask='N') OR (ask='n') THEN NEXT;
    END;
END;

PROCEDURE Work; {Calculations of heat load during work outdoor }
BEGIN
  WriteLn; WriteLn;
  WriteLn('Do you want to define characteristics required  ');
  Write('for heat equilibrium of the organism ?   - Y \ N '); ReadLn(ask);
WriteLn;
  WHILE (ask='Y') OR (ask='y') do BEGIN
    Write('New skin temperature    (',Ts:2:1,')  '); ReadLn(Ts0);
    Write('New clothing insulation (',Icl:1:1,')  '); ReadLn(Icl);
    Write('New albedo of clothing    (',a:2:0,')  '); ReadLn(a);
    Write('New work load            (',WL:3:0,')  '); ReadLn(WL);
    Write('Increase/reduction of wind speed (',v:2:1,')  '); ReadLn(v);
    WriteLn('Using of shaded screens : ');
    Write('      no [1] ,    yes [2] '); ReadLn(sol);
    ParamProg; Skin; Storage; ResultFlux; ResultMTE; ResultLoad; WriteLn;
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```
   WriteLn('Do you want to define characteristics required  ');
   Write('for heat equilibrium of the organism ?   - Y \ N '); ReadLn(ask);
   IF (ask='N') OR (ask='n') THEN Next;
   END;
END;

PROCEDURE Prognoza; {Forecasting of thermal conditions and heat load}
BEGIN
  WriteLn; WriteLn;
  WriteLn('Do you want to define characteristics required  ');
  Write('for heat equilibrium of the organism ?   - Y \ N '); ReadLn(Ins);
WriteLn;
  IF (Ins='N') OR (Ins='n') THEN Next;
  WHILE (Ins='Y') OR (Ins='y') do BEGIN
   Write('New clothing insulation  (',Icl:2:0,')  '); ReadLn(Icl);
   Write('New albedo of clothing    (',a:2:0,')  '); ReadLn(a);
   Write('New work load           (',WL:3:0,')  '); ReadLn(WL);
   Write('New wind speed            (',v:2:1,')  '); Readln(v);
   WriteLn('Change of place of stay:');
   Write('sunny [1]':20,'shaded [2]':20,'  '); Readln(sol);
   ParamProg; Skin; Storage; ResultFlux; ResultMTE;
   ResultLoad; ResultSens; WriteLn; WriteLn;
   WriteLn('Do you want to define characteristics required  ');
   Write('for heat equilibrium of the organism ?   - Y \ N '); ReadLn(Ins);
   IF (Ins='N') OR (Ins='n') THEN Next;
   END;
END;

PROCEDURE Menu;
BEGIN
ClrScr;
  WriteLn('MENEX - Man-Environment Heat Exchange Model');
  WriteLn('                    version 1.1  ');
  WriteLn; WriteLn;
  WriteLn('Choose on the one of the following options: '); WriteLn;
  WriteLn('Unstationary conditions (full method)  - [1]  ');
  WriteLn('General evaluation of bioclimate           - [2]  ');
  WriteLn('Forecasting of thermal conditions          - [3]  ');
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 WriteLn('Evaluation of heat load during work      - [4]  ');
 WriteLn('Simplified method                        - [5]  ');
 Write('Quit                                       - [6]  '); ReadLn(dat); WriteLn;
END;

PROCEDURE Simplified;  { Calculation of heat balance by simplified method }
BEGIN
  WriteLn('This option calculates estimated values of man-environment heat
  WriteLn('exchange (with accuracy of 80-90%) for standing or light working ');
  WriteLn('working man, wearing normal business suit with insulation ');
  WriteLn(' of 0.7-1.5 clo and albedo of 30%.This option can be used with air ');
  WriteLn('temperature of 0-35°C and wind speed ≤10 m/s.'); WriteLn;
  Write('Continue ?   -  Y \ N '); ReadLn(OK); WriteLn;
  IF (OK='Y') OR (OK='y') THEN
  BEGIN
    Write('Air temperature              (°C):  '); ReadLn(Ta1);
    Write('Wind speed                   (m/s):  '); ReadLn(vu);
    Write('Realative humidity of air (%):  '); ReadLn(f);
    WriteLn; WriteLn;
    WriteLn('Examined conditions: setlements-beach [1] ');
    WriteLn('                                   open area [2] ');
    WriteLn('        sun elevation < 5° over the horizon [3] ');
    WriteLn('                                 forest-park [4] '); ReadLn(sr);
WriteLn;
    Write('Study place : '); ReadLn(dane);
    Res:=Ta1*(0.0005*f+0.112)+(0.013*f-9.653)+0.147;
    IF (sr<3) AND (vu<=4) THEN
    BEGIN
      Cu:=2.39*Ta1-2.91*vu-74.18;
      Lu:=0.95*Ta1+3.14*vu-44.61;
      Eu:=-0.87*Ta1-1.46*vu-0.77;
      Su:=2.76*Ta1-4.77*vu-29.78;
    END;

    IF (sr<3) AND (vu>4) THEN
    BEGIN
      Cu:=2.4*Ta1-2.9*vu-84.2;
      Lu:=0.9*Ta1+3.1*vu-43.6;
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  Eu:=14.2-1.37*Ta1-2.46*vu;
  Su:=2.3*Ta1-0.5*vu-35.32;
END;

IF (sr>2) THEN
BEGIN
  Cu:=2.36*Ta1-8.24*vu-66.2;
  Lu:=0.77*Ta1+5.63*vu-43.02;
  Eu:=-0.32*Ta1-4.1*vu-5.51;
  Su:=3.34*Ta1-1.48*vu-51.16;
END;

Cp:=100*Cu/(Cu+Lu+Eu+Res);
Lp:=100*Lu/(Cu+Lu+Eu+Res);
Ep:=100*Eu/(Cu+Lu+Eu+Res);
Resp:=100*Res/(Cu+Lu+Eu+Res);
ClrScr;
Write('Study place : ',dane); WriteLn; WriteLn;
WriteLn('Convection          * ',Cu:3:1,' W/m2  (',Cp:2:1,' %)');
WriteLn('Evaporation         * ',Eu:3:1,' W/m2  (',Ep:2:1,' %)');
WriteLn('Long-wave radiation   * ',Lu:3:1,' W/m2  (',Lp:2:1,' %)');
WriteLn('Respiration         * ',Res:2:1,' W/m2 (',Resp:2:1,' %)');
WriteLn; WriteLn;
WriteLn('Net heat storage     * ',Su:3:1,' W/m2'); WriteLn; WriteLn;
Write('<> Thermal conditions - ');
IF (sr>2) AND (Su>=-20) AND (Su<=20) THEN Write('mild <>');
IF (sr<=2) AND (Su>-45) AND (Su<=20) OR
  (sr>=2) AND (Su>20) AND (Su<=45) THEN Write('slightly loaded <>');
IF (sr<3) AND (Su>=-90) AND (Su<=-45) OR (sr=1) AND (Su>20) AND
  (Su<=45) OR (sr>=2) AND (Su>45) AND (Su<=90) OR (sr>=3) AND
  (Su<=-20) AND (Su>=-45) THEN Write('loaded <>');
IF (sr=1) AND (Su>45) AND (Su<=90) OR (sr>=3) AND (Su<-45) AND
  (Su>=-90) THEN Write('strongly loaded <>');
IF (Su<-90) THEN Write('with overcooling hazard <>');
IF (Su>90) THEN Write('with overheating hazard <>'); WriteLn; WriteLn;
Write('* Predominated thermal sensations - ');
IF (Su<-15) THEN Write('cold *');
IF (Su>=-15) AND (Su<-5) THEN Write('cool *');
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  IF (Su>=-5) AND (Su<=15) THEN Write('neutral *');
  IF (Su>15) AND (Su<=35) THEN Write('warm *');
  IF (Su>35) AND (Su<=55) THEN Write('hot *');
  IF (Su>55) THEN Write('very hot *'); WriteLn; WriteLn; Next;
  END;
END;

PROCEDURE UnStationary; { Heat balance for unstationary conditions }
BEGIN
 WriteLn('This option calculates exact values of man-environment heat');
 WriteLn('exchange in unstationary conditions, i.e. with temporary');
 WriteLn('fluctuations of meteorological and physiological parameters');
 WriteLn; Write('Continue ?   -  Y \ N '); ReadLn(OK); WriteLn;
 IF (OK='Y') OR (OK='y') THEN
 BEGIN
 ClrScr;
  InputMeteo; InputSolar; Parameters; Skin; Metabolism; Storage;
  ResultFlux; ResultMTE; ResultLoad; ResultSens; Next;
 END;
END;

PROCEDURE General; { Heat balance for stationary conditions }
BEGIN
 WriteLn('This option calculates man-environment heat exchange in  ');
 WriteLn('stationary conditions, i.e. with mean values of  meteorological ');
 WriteLn('and physiological parameters which are necessary for heat');
 WriteLn('equilibrium of the organism.');
 WriteLn('Continue ?   -  Y \ N '); ReadLn(OK); WriteLn;
 IF (OK='Y') OR (OK='y') THEN
 BEGIN
 ClrScr;
  WriteLn('Evaluation of bioclimate by: ');
  WriteLn('- index value of mean skin temperature - [1] ');
  Write('-      index value of net heat storage - [2] '); ReadLn(Bil);
  WriteLn; InputMeteo; InputSolar; Parameters; Skin; Metabolism;
  Storage; ResultFlux; ResultBal; Balance;
 END;
END;
```

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```
PROCEDURE Forecasting; { Forecasting of thermal conditions }
BEGIN
  WriteLn('This option completes standard weather forecasting in additional ');
  WriteLn('characteristics of heat load in man in different locations and time  ');
  WriteLn('of the day with temporary fluctuations of meteorological and  ');
  WriteLn('physiological parameters. ');
  WriteLn('Continue ?   -  Y \ N '); ReadLn(OK); WriteLn;
  IF (OK='Y') OR (OK='y') THEN
  BEGIN
  ClrScr;
    InputMetProg; InputSolar; ParamProg; Skin; Metabolism; Storage;
    ResultFlux; ResultMTE; ResultLoad; ResultSens; Prognoza;
  END;
END;

PROCEDURE WorkLoad; { Estimation of heat load during work outdoor }
BEGIN
  WriteLn('This option calculates heat load in man during work outdoor. ');
  WriteLn('Maximal work load as well as maximal time of exposure in given ');
  WriteLn('meteorological conditions can be also estimated.'); WriteLn;
  Write('Continue ?   -  Y \ N '); ReadLn(OK); WriteLn;
  IF (OK='Y') OR (OK='y') THEN
  BEGIN
  ClrScr;
    InputMetProg; InputSolar; ParamProg; Skin; Metabolism; Storage;
    ResultFlux; ResultMTE; ResultLoad; Work;
  END;
END;

{ Main Program }
BEGIN
  answer:='y';
  WHILE (answer='Y') OR (answer='y') DO BEGIN
    Write(Chr(12)); ClrScr;
    Menu;
      IF (dat=1) THEN UnStationary;
      IF (dat=2) THEN General;
      IF (dat=3) THEN Forecasting;
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    IF (dat=4) THEN WorkLoad;
    IF (dat=5) THEN Simplified;
    IF (dat=6) THEN Exit;
    IF (answer='N') OR (answer='n') THEN
    WriteLn('Thank you for work with MENEX program, see next time');
  END;
END.
```

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BIOKLIMATYCZNE BADANIA BILANSU CIEPLNEGO CZŁOWIEKA

Streszczenie

Przedmiotem badań współczesnej bioklimatologii jest proces wymiany ciepła zachodzący pomiędzy ciałem człowieka a środowiskiem atmosferycznym i podłożem. Zrównoważona wymiana ciepła stanowi bowiem niezbędny warunek utrzymania temperatury wewnętrznej na stałym poziomie, a zatem zachowania zdrowia i dobrego samopoczucia człowieka. Prekursorami tego kierunku badawczego byli H. Pfleiderer i K. Büttner (Büttner 1938).

Bilansowanie zysków i strat ciepła na powierzchni ciała człowieka stanowi kompleksowy sposób oceny jego stanu cieplnego, kształtującego się pod wpływem zarówno czynników meteorologicznych jak i fizjologicznych, a także aktywności fizycznej i rodzaju odzieży. Wyznaczając poszczególne składniki bilansu cieplnego wykorzystuje się prawa przenoszenia energii oraz przyjmuje założenie, że powierzchnia ciała człowieka podlega takim samym procesom wymiany ciepła jak każda powierzchnia fizyczna (Bligh i Johnson 1973; Parsons 1993; Terjung 1970, 1974).

W pracy zaprezentowano wyniki badań z zakresu bioklimatologii, prowadzonych w Zakładzie Klimatologii Instytutu Geografii i Przestrzennego Zagospodarowania PAN w Warszawie, w których posługiwano się metodą bilansu cieplnego człowieka. Prace te oparte były na różnych modelach wymiany ciepła i dotyczyły różnych skal przestrzennych.

Przeglądu różnych modeli bilansu cieplnego człowieka dokonała B. Krawczyk. Autorka klasyfikuje je z uwagi na przydatność w badaniach prowadzonych w skali mikroklimatycznej, topoklimatycznej i regionalnej.

Druga praca prezentuje typologię bioklimatyczną Polski wykonaną na podstawie analizy bilansu cieplnego człowieka (B. Krawczyk). Wykorzystano w tym celu zmodyfikowany przez autorkę model M.I. Budyko. Typy bioklimatu Polski wydzielono na podstawie charakterystyki termoizolacyjnych właściwości niezbędnej dla zachowania równowagi cieplnej organizmu.

Trzecia praca przedstawia nowy model bilansu cieplnego człowieka (**MENEX**), przydatny do badania wymiany ciepła pomiędzy człowiekiem a otoczeniem w zmieniających się warunkach meteorologicznych, przy różnej aktywności człowieka i różnych właściwościach odzieży (K. Błażejczyk). Przy konstruowaniu modelu

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oparto się na wynikach badań własnych autora oraz na licznych, publikowanych pracach z zakresu termofizjologii i bioklimatologii. Wykorzystano także niepublikowane wyniki badań związanych z pochłanianiem promieniowania słonecznego przez nowy analog ciała całowieka (pionowo usytuowaną elipsoidę), prowadzonych w ramach współpracy pomiędzy Instytutem Geografii i Przestrzennego Zagospodarowania PAN w Warszawie, a Narodowym Instytutem Medycyny Pracy w Solnej (Szwecja). Uzupełnieniem opisu modelu **MENEX** jest jego program komputerowy, napisany w języku TURBO PASCAL 6.0. Program jest dostosowany do kompilacji na komputerach klasy IBM.

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