MENEX_2005

– the updated version of man-environment heat exchange model

Krzysztof Blazejczyk

Introduction

The Man-ENvironment heat EXchange model (**MENEX_2005**) can be assessed in various applications: bioclimatic (i.e. recreation and tourism, climatotherapy, human health, urban studies), thermophysiological (work condition, controlling of thermoregulation system etc.), spatial design of landscapes, residential and recreational areas.

The principles of the MENEX model was published in 1994 (Blazejczyk 1994). Its modified version that incorporated new models to assess absorbed solar radiation (Blazejczyk 1998, 2004a) was developed in 2002 and was published in several papers (Blazejczyk 1999, 2004b, 2005). The last modifications, proposed new output variables (Physiological Subjective Temperature, Dehydration Risk as well as Overheating and Overcooling Risks) and dealing with the calculation of mean radiant temperature were made in 2005.

Principles of the model

General equation of man environment heat exchange has the following form:

$M + Q + C + E + Res + Kd = S.$

where: M is metabolic heat production (both, basic metabolic rate and metabolic energy production due to activity and work load). Q is radiation balance of man, C – heat exchange by convection, E – heat loss by evaporation, Res – heat loss by respiration and S – is net heat storage, i.e. changes in body heat content. All fluxes are expressed in W m^{-2}. The heat exchange by conduction (Kd) is not considered in the model due to its insignificant values. The graphical presentation of man-environment heat exchange is done on figure 1.

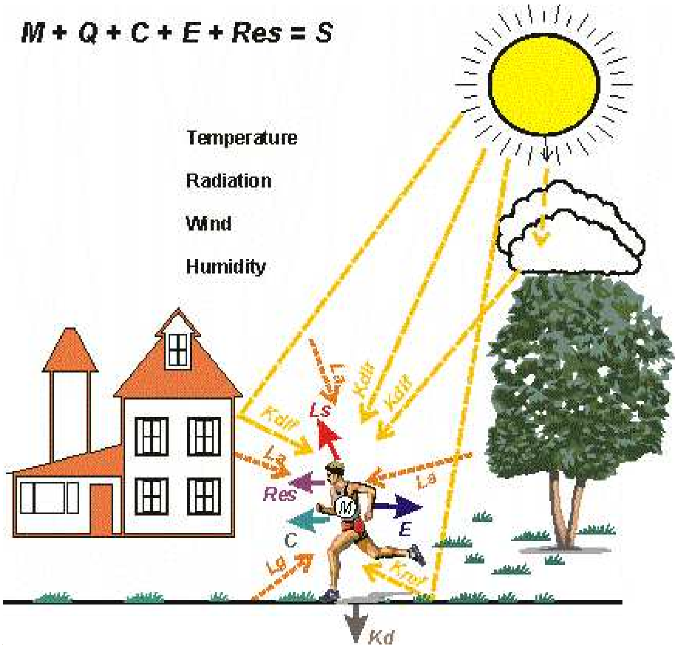

Fig. 1. Components of the human heat balance

INPUT DATA

Meteorological:

air temperature (*t*, °C),

wind speed (*v*, m/s),

air vapour pressure (*e*, hPa),

relative humidity of air (*f*, %),

air pressure (*p*, hPa),

ground surface temperature (*Tg*, °C),

solar radiation: direct (*Kdir*), diffuse (*Kdif*) and reflected (*Kref* - in W·m^{-2}),

cloudiness (*N*, %),

Sun altitude (*hSl*, °),

mean radiant temperature (optionally) (*Mrt*, °C).

Physiological:

mean skin temperature (*Ts*, °C),

skin wettedness (*w*, dimensionless),

metabolic heat production (*M*, W·m^{-2}),

clothing insulation (*Icl*, clo),

albedo of clothing (*ac*, %),

velocity of man motion (*v'*, m·s^{-1}).

Some physiological parameters (*Ts, Icl, w*) are estimated with the use of empirical equations and for some of them default values are assumed (*M*=135 W·m^{-2}, *ac*=30%, *v'*=1.1 m·s^{-1}).

CALCULATIONS

The MENEX_2005 model solves the human heat balance equation is two steps.

In the **first step** the basic values of the human heat balance components that arise just after the contact with ambient conditions are calculated. The signals from temperature receptors activate physiological reactions of an organism to keep homeothermy. In the cold, adaptation processes do not change significantly skin temperature and skin receptors register actual skin temperature that is influenced by ambient conditions. However, in the warm, intensive sweat evaporation lead during 15-20 minutes to cooling of skin surface (0.066°C for each 1 $W \cdot m^{-2}$ of evaporation, Fanger 1970) and thermal receptors register new, low skin temperature (Ts_R). In this case adaptation processes of intensive heat expenditure from the body core are regulated by thermal receptors in the nervous system.

The **second step** in calculations is to solve human heat balance equation taking into consideration skin temperature that is effected by thermoregulation processes (Ts_R). The resultant heat balance components represent heat exchange level after 15-20 minutes of adaptation processes.

Basic values of human heat balance components

Metabolic heat production (M) can be assessed according to ISO 8996. For standard applications M=135 $W \cdot m^{-2}$ (man walking with the speed of 4 km/hour) should be taken for calculations (Jendritzky et al. 2002).

Radiation balance in man (Q):

$Q = R + L$,

where: R – is absorbed solar radiation ($W \cdot m^{-2}$),

L - net long-wave radiation in man ($W \cdot m^{-2}$).

The net long-wave radiation is a balance of heat exchange by thermal radiation between human body (Ls) and the atmosphere (La) as well as between human body and the ground (Lg) as follows:

$L = (0.5 \cdot Lg + 0.5 \cdot La – Ls) \cdot Irc$

$Lg = s \cdot \sigma \cdot (273+Tg)^4$,

$La = s \cdot \sigma \cdot (273+t)^4 \cdot (0.82–0.25 \cdot 10^{(-0.094 \cdot e)})$,

$Ls = s_h \cdot \sigma \cdot (273+Ts)^4$,

where: σ – Stefan-Boltzman constant (= $5.667 \cdot 10^{-8}$, $W \cdot m^2 \cdot K^{-4}$)

s – emissivity coefficient (= 0.97 for natural objects)

s_h – emissivity coefficient (= 0.95 for human body)

Irc – coefficient reducing convective and radiative heat transfer due to clothing (dimensionless):

$Irc = hc'/(hc'+hc+21.55\cdot10^{-8}\cdot T^{3}$

hc – coefficient of convective and radiative heat transfer ($K\cdot W^{-1}\cdot m^{-2}$):

$hc = (0.013\cdot p–0.04\cdot t–0.503)\cdot(v+v')^{0.4\,)}$

hc' – coefficient of heat transfer through clothing ($K\cdot W^{-1}\cdot m^{-2}$):

$hc' = (0.013\cdot p–0.04\cdot t–0.503)\cdot0.53/\{Icl\cdot[1–0.27\cdot(v+v')^{0.4}]\}$

T – air temperature (K),

Icl – clothing insulation (clo):

$Icl = 1.691–0.0436\cdot t$

(at t <-30°C Icl = 3.0 clo, and at t > 25°C Icl = 0.6 clo).

Tg – ground surface temperature (ºC):

- for N>=80% $Tg = t$
- for N<80% and t>=0 $Tg = 1.25\cdot t$
- for N<80% and t <0 $Tg = 0.9\cdot t$

Ts – mean skin temperature (ºC):

$Ts = (26.4+0.02138\cdot Mrt+0.2095\cdot t–0.0185\cdot f–0.009\cdot v)+0.6\cdot(Icl–1)+0.00128\cdot M$

Mrt – mean radiant temperature (ºC):

$Mrt = [(R/Irc+Lg+La)/(s_h\cdot\sigma)]^{0.25}–273$

Depending on insolation data absorbed solar radiation (R) can be assessed in four different ways. When we use measured data of separate solar radiation fluxes the **SolDir** or **SolGlob** models can be applied (Błażejczyk 2004b). **SolDir** model can be applied when we have data of direct ($Kdir$) as well as diffuse ($Kdif$) and reflected ($Kref$) solar radiation fluxes. Depending on Sun altitude (h) absorbed solar radiation is calculated as follows:

- for hSl <= 5°

$R = [1.4\cdot Kdir\cdot e^{(-0.51+0.368\cdot hSl)}+(Kdif+Kref)\,(0.0013 + 0.033\cdot LN(hSl))]\cdot(1–0.01\cdot ac)\cdot Irc$

- or for hSl > 5°

$R = [Kdir\cdot(18.816/hSl - 0.235)+(Kdir+Kref)\cdot(0.0013 + 0.033\cdot LN(hSl))]\cdot(1–0.01\cdot ac)\cdot Irc$

At majority of meteorological stations only global solar radiation ($Kglob=Kdir+Kdif$) is measured and general information about cloudiness (N) is provided. In this case we can use **SolGlob** model to assess absorbed solar radiation. The equations have various forms depending on solar elevation (hSl) and $Kglob/Kt$ ratios:

- for hSl <= 12°,

$R = (0.0014 \cdot Kglob^2 + 0.476 \cdot Kglob - 3.8) \cdot (1 - 0.01 \cdot ac) \cdot Irc$

- for hSl > 12° and $Kglob/Kt$ ratio <= 0.8

$R = 0.2467 \cdot Kglob^{0.9763} \cdot (1 - 0.01 \cdot ac) \cdot Irc$

- for hSl > 12° and $Kglob/Kt$ ratio of more then 0.8 up to 1.05

$R = 3.6922 \cdot Kglob^{0.5842} \cdot (1 - 0.01 \cdot ac) \cdot Irc$

- for hSl > 12° and $Kglob/Kt$ ratio of more then 1.05 up to 1.2

$R = 43.426 \cdot Kglob^{0.2326} \cdot (1 - 0.01 \cdot ac) \cdot Irc$

- for hSl > 12° and $Kglob/Kt$ ratio more then 1.2

$R = 8.9281 \cdot Kglob^{0.4861} \cdot (1 - 0.01 \cdot ac) \cdot Irc.$

where $Kt = -0.0015 \cdot hSl^3 + 0.1796 \cdot hSl^2 + 9.6375 \cdot hSl - 11.9$

Relatively frequent we do not have any data of solar radiation intensity and cloudiness data are only available. For such situations **SolAlt** model can be used:

- for hSl <= 4°

$R = (1.642 + 0.254 \cdot hSl)^2 \cdot (1 - 0.01 \cdot ac) \cdot Irc$

- for hSl > 4° and N <= 20%

$R = (103.573 \cdot \mathrm{LN}(hSl) - 140.6) \cdot (1 - 0.01 \cdot ac) \cdot Irc$

- for hSl > 4° and N = 21-50%

$R = 1.4 \cdot e^{(5.383 - 16.072/hSl)} \cdot (1 - 0.01 \cdot ac) \cdot Irc$

- for hSl > 4° and N = 51-80%

$R = 1.4 \cdot e^{(5.012 - 11.805/hSl)} \cdot (1 - 0.01 \cdot ac) \cdot Irc$

- for h > 4° and N > 80% as well as for shaded sites

$R = 0.9506 \cdot hSl^{1.039} \cdot (1 - 0.01 \cdot ac) \cdot Irc.$

In some applications mean radiant temperature (Mrt, °C) is used as a measure of radiation impacts of environment on man. In this case the R value can be calculated using **SolMrt** model as follows:

$R = \{[s_h \cdot \sigma \cdot (273 + Mrt)^4] - [s \cdot \sigma \cdot (273 + t)^4]\} \cdot Irc.$

In some data bases radiation features of actual weather are expressed by visibility (*vis*). In this case **SolVis** model can be applied to assess absorbed solar radiation:

- for *vis* < 5000 m

$R = (0.815 \cdot hSl + 16.504) \cdot Irc$

- for *vis* between 5000 m and 20000 m

$R = (23.216 \cdot e^{(0.0268 \cdot hSl)}) \cdot Irc$

- for *vis* between 20000 m and 30000 m

$R = 45.368 \cdot (e^{(0.0144 \cdot hSl)}) \cdot Irc$

- for *vis* > 30000 m

$R = 22.626 \cdot (e^{(0.02674 \cdot hSl)}) \cdot Irc$

Evaporative heat loss:

$E = he \cdot (e - es) \cdot w \cdot Ie - [0.42 \cdot (M - 58) - 5.04]$

where: *es* – saturated vapour pressure at skin temperature (hPa):

$es = e^{(0.058 \cdot Ts + 2.003)}$,

w – skin wettedness coefficient (dimensionless):

$w = 1.031/(37.5 - Ts) - 0.065$,

(at $Ts > 36.5°C$ $w = 1.0$ and at $Ts < 22°C$ $w = 0.001$),

he – coefficient of evaporative heat transfer ($hPa \cdot W^{-1} \cdot m^{-2}$):

$he = [t \cdot (0.00006 \cdot t - 0.00002 \cdot p + 0.011) + 0.02 \cdot p - 0.773)] \cdot 0.53/\{Icl \cdot [1 - 0.27 \cdot (v + v')^{0.4}]\}$,

Ie – coefficient reducing evaporative heat transfer due to clothing (dimensionless):

$Ie = hc'/(hc' + hc)$,

Convective heat exchange:

$C = hc \cdot (t - Ts) \cdot Irc$

Respiratory heat loss:

$Res = 0.0014 \cdot M \cdot (t - 35) + 0.0173 \cdot M \cdot (0.1 \cdot e - 5.624)$

Resultant values of the human heat balance components

In the second run the MENEX_2005 model takes into consideration M, R and Res values that were calculated during the first run. However, the resultant values of another fluxes are calculated as follows:

$S_R=M+Q_R+E_R+C_R+Res$

where S_R - is resultant value of net heat storage (W·m^{-2}) that calculated taking into consideration Ts_R values:

$Ts_R = Ts + dTs$,

$dTs = (E+50)\ 0.066$ (for $E<-50$ W·m^{-2})

or $dTs = 0$ (for $E>=-50$ W·m^{-2})

If Ts_R is <22°C we assume Ts_R=22°C

$C_R = hc\cdot(iMrt-Ts_R)\cdot Irc$

$iMrt$ – inner mean radiant temperature (under clothing):

$iMrt = \{R+(La+Lg)\cdot Irc+0.5\cdot Ls]/(s_h\cdot\sigma)\}^{0.25}–273$

$E_R = he\cdot \mathrm{SQRT}(v+v')\cdot(e^*–es_R)\cdot w_R\cdot Ie–[0.42\cdot(M–58)–5.04]$

e^* – vapour pressure under clothing (hPa):

$e^* = 6.12\cdot10^{[7.5\cdot iMrt/(237.7+iMrt)]}\cdot0.01f$

es_R – saturated vapour pressure at resultant skin temperature (hPa):

$es_R = \mathrm{e}^{(0.058\cdot TsR+2.003)}$,

w_R– skin wettedness at resultant skin temperature:

$w_R = 1.031/(37.5–Ts_R)-0.065$,

(at $Ts_R > 36.5$°C $w_R = 1.0$ and at $Ts_R <22$°C $w_R = 0.001$)

$Q_R = R+L_R$,

$L_R = (0.5\cdot Lg+0.5\cdot La–Ls_R)\cdot Irc$

$Ls_R = s_h\cdot\sigma\cdot(273+Ts_R)^4$,

OUTPUT DATA

The calculations afford values of particular heat fluxes (absorbed solar radiation, convection, evaporation, respiration, long-wave radiation) as well as some thermophysiological indices: Subjective temperature (*STI*, °C), Physiological Strain (*PhS*, dimensionless), Heat Load in man (*HL*, dimensionless), Physiological Subjective Temperature (*PST*, ºC), Water Loss (*SW*, g/hours), Dehydration Risk (*DhR*, descriptive scale), Overheating Risk (*OhR*, minutes), Overcooling Risk (*OcR*, minutes).

Subjective Temperature (*STI*, °C) is an index that illustrates thermal load subjectively felt by man caused by ambient environment before the activation of adaptation processes. The *STI* depends both, on ambient conditions (temperature, solar radiation, wind, humidity) as well as on man-environment heat exchange. *STI* represents thermal load formed in the air layer surrounded the outer layer of clothing. Thermal impacts of environment are expressed by mean radiant temperature (*Mrt*). Physiological response of an organism is represented by net heat storage (S). *STI* is calculated as follows:

$$STI = Mrt - \{[|S|^{0.75}/(s_h \cdot \sigma)+273^4]^{0.25} - 273\} \quad (\text{if } S' < 0\ \mathrm{W \cdot m^{-2}})$$
$$STI = Mrt + \{[|S|^{0.75}/(s_h \cdot \sigma)+273^4]^{0.25} - 273\} \quad (\text{if } S' >= 0\ \mathrm{W \cdot m^{-2}})$$

The following ranges of *STI* represent various thermal load in man:

< -38.0	– extremely cold,
-38.0 - -20.1	– very cold,
-20.0 - -0.5	– cold,
-0.4 - 22.5	– cool,
22.6 - 31.9	– comfortable,
32.0 - 45.9	– warm,
46.0 - 54.9	– hot,
55.0 - 69.9	– very hot,
≥ 70.0°C	– sweltering.

Physiological Strain (*PhS*, dimensionless) expresses intensities of predominant adaptation processes to cold or to warm environment. They depend on basic level of evaporative and convective heat fluxes as follows:

$PhS = C/E$

At *PhS* of 0.75 to 1.5 only a slight response of thermoregulatory system is observed. Cold physiological strain occurs at *PhS* > 1.5 and is manifested by: decrease in skin temperature, reduction of peripheral blood flow, increase in blood pressure, increase in thermal insulation of skin tissue and/or shivering (Blanc, de 1975,). Hot physiological strain occurs at *PhS* < 0.75 and it leads to: increase in peripheral blood flow, decrease in blood pressure, increase in heart rate, intensive sweating and dehydration, great temporal changes in skin temperature (Blazejczyk, 1999, Malchaire, 1991).

The following scale of physiological strain can be applied:

PhS	Physiological strain:
< 0.0	- extreme hot strain
0.00 - 0.24	- great hot strain
0.25 - 0.74	- moderate hot strain
0.75 - 1.50	- thermoneutral (slight strain)
1.51 - 4.00	- moderate cold strain
4.01 - 8.00	- great cold strain
> 8.00	- extreme cold strain

Physiological Subjective Temperature (*PST*) represents subjective feeling of thermal environment by man. **Thermal sensations** in humans are an **effect of signals** from cold and/or warm receptors in the skin and in the nervous system. Thermal impacts of environment are expressed by mean radiant temperature surrounded skin surface (*iMrt*). Actual ambient conditions influence the intensity of heat exchange between human body and the atmosphere and the basic level of net heat storage (S). The signals from temperature receptors activate physiological reactions of an organism to keep homeothermy. In the cold, skin receptors register actual skin temperature that is influenced by ambient conditions. However, in the warm, intensive sweat evaporation leads to cooling of the skin surface (0.066°C for each 1 W·m^2 of evaporation) and thermal receptors register new, low skin temperature (Ts_R). Intensive adaptation processes are supported and regulated by thermal receptors in the nervous system and the resultant level of net heat storage (S_R) is formed.

Physiological Subjective Temperature illustrates the level of thermal stimuli that are form around the skin surface after 15-20 minutes of intensive adaptation processes. *PST* is calculated as follows:

- at $S_R < 0$ W·m^{-2}

$PST = iMrt - \{[|S_R|^{0.75}/(s_h \cdot \sigma) + 273^4]^{0.25} - 273\}$

- at $S_R >= 0$ W·m^{-2}

$PST = iMrt + \{[|S_R|^{0.75}/(s_h \cdot \sigma) + 273^4]^{0.25} - 273\}$

The particular ranges of *PST* indicate various thermal sensations in man as follows:

PST (° C)	Subjective thermal sensations:
< -36.0°C	- frosty
-36.0 - -16.1	- very cold
-16.0 - 4.0	- cold
4.1 - 14.0	- cool
14.1 -24.0	- comfortable
24.1 - 34.0	- warm
34.1 - 44.0	- hot
44.1 - 54.0	- very hot
> 54.0	- sweltering

Heat load in man (*HL*, dimensionless) illustrates the load of central thermoregulation system due to adaptation processes involved in an organism. *HL* is calculated as a combination of the three principal heat fluxes: net heat storage (*S*), absorbed solar radiation (*R*) and evaporative heat loss (*E*) as follows:

- at $S < 0$ W·m^{-2} and $E >= -50$ W·m^{-2}

$HL = [\{S+1000)/1000]^{[5/(1+R)]}$

- at $S >= 0$ W·m^{-2} and $E >= -50$ W·m^{-2}

$HL = [(S+1000)/1000]^{[2-1/(1+R)]}$

- at $S < 0$ W·m^{-2} and $E < -50$ W·m^{-2}

$HL = (E/-50) \cdot [\{S+1000)/1000]^{[5/(1+R)]}$

- at $S >= 0$ W·m^{-2} and $E < -50$ W·m^{-2}

$HL = (E/-50) \cdot [(S+1000)/1000]^{[2-1/(1+R)]}$

(All numerical coefficients are expressed in W·m^{-2}.)

Level of heat load can be assessed as follows:

HL	Heat load in man:
<= 0.250	- extreme cold stress
0.251-0.820	- great cold stress
0.821-0.975	- moderate cold stress
0.976-1.025	- thermoneutral
1.026-1.180	- moderate hot load
1.181-1.750	- great hot load
>=1.751	- extreme hot load

Water loss (*SW*, g/hour) represents amount of water that is sweated through the skin. *SW* is calculated taking into account 5% level of relative humidity of air (f) as follows:

$$SW = -2{,}6 \cdot Epot$$

$$Epot = he \cdot [epot - \mathrm{es}] \cdot w \cdot Ie - [0.42 \cdot (M - 58) + 5.04]$$

where: $epot = 6.112 \cdot 10^{[(7.5 \cdot t) / (237.7 + t)]}\ 0.05$

Dehydration Risk (*DhR*) is an effect of Water loss (*SW*). The water lost from the body can lead to dehydration. Due to acclimation level of the subject, the risk related to dehydration depends according to ISO/DIS 7933 on *SW* as follows:

Acclimated subject:

No risk	- *SW* < 780 g/hour
Dehydration warning	- *SW* between 780 and 1040 g/hour
Dehydration hazard	- *SW* > 1040 g/hour

Non-acclimated subject:

No risk	- *SW* < 520 g/hour
Dehydration warning	- *SW* between 520 and 650 g/hour
Dehydration hazard	- *SW* > 650 g/hour.

Overcooling Risk. During prolonged stay at extreme ambient conditions physiological processes of thermoregulation can be insufficient to keep homeothermy. According to Hardy (1965) warning level of overcooling is noted at body core temperature (*Tc*) of about 31°C and hypothermia risk occurs when *Tc* falls to about 25°C. That correspond to changes in body heat content of 1800 kJ and 3600 kJ, respectively.

Overcooling Warning (Oc_W) is a time (in min) that lead to great decrease in body heat content and significant decrease in body temperature. Oc_W is calculated as follows:

- for $S_R < 0$ W·m^{-2}:

$$Oc\_W = [(1800000 - 1.6 \cdot 1200 \cdot |S|)/(1.6 \cdot |S_R|)]/60$$

Hypothermia Risk (Oc_H) is a time (in min) that due to great decrease in body heat content fatal hypothermia can occur. Oc_H is calculated as follows:

- for $S_R < 0$ W·m^{-2}:

$$Oc\_H = 2 \cdot [(1800000 - 1.6 \cdot 1200 \cdot |S|)/(1.6 \cdot |S_R|)]/60$$

For both, Oc_W and Oc_H, when $S_R >= 0$ W·m^{-2}, there is no overcooling risk and hence no time limit.

Overheating Risk. During prolonged stay at extreme ambient conditions physiological processes of thermoregulation can be insufficient to keep homeothermy. According to Hardy (1965) at body core temperature (*Tc*) of about 40°C (that correspond to heat accumulation of about 900 kJ) thermoregulation disorders are observed and at *Tc* of 43°C (change in body heat content of +1800 kJ) hyperthermia and heat stroke arise.

Overheating Warning (Oh_W) is a time (in min) that lead to great increase in body heat content and significant increase in body temperature. Oh_W is calculated as follows:

- for $S_R >= 0$ W·m^{-2}:

$$Oh\_W = [(900000 - 1.6 \cdot 1200 \cdot |S|)/(1.6 \cdot |S_R|)]/60$$

Hyperthermia Risk (Oh_H) is a time (in min) that due to great increase in body heat content hyperthermia can occur. (Oh_H) is calculated as follows:

- for $S_R >= 0$ W·m^{-2}:

$$Oh\_H = 2 \cdot [(900000 - 1.6 \cdot 1200\ |S|)/(1.6 \cdot |S_R|)]/60$$

For both, Oc_W and Oc_H, when $S_R < 0$ W·m^{-2}, there is no overheating risk and hence no time limit.

Available tool:

All components of the MENEX_2005 model and output variables can be calculated with the use of BioKlima© 2.4. software package. The Software can be downloaded from: www.igipz.pan.pl/geoekoklimat/blaz/bioklima.htm

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