Simulation of Animals' Heat Balance

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Abstract— **A model is presented which allows one to calculate heat production and heat losses of the animal body, depending on its activity and weather and climate conditions (air temperature, wind speed, precipitation, and solar radiation). This version of the model is a special one, as it includes the active system of thermal regulation, which allows keeping the temperature homeostasis of the animal body using all available means. The external factors influence the thermoregulation system indirectly, by changing the animal's body total heat. The model identification results and the recommendations concerning the use of the results are presented.**

Keywords— modeling; heat production; heat losses; weather and climate factors; the animal's activity; thermoregulation

I. Introduction

Weather and climate are the most important environmental factors in the lives of animals. Air temperature, wind, atmospheric precipitation, solar radiation influence directly the amount of thermal currents between animals and the environment, which can lead to hypothermia or overheating of animals' bodies. In the process of ontogenesis animals developed the mechanisms of adaptation and regulation of thermal currents in order to sustain the body heat balance under certain values of weather and climate factors. However, the protective properties of animals are not absolute ones. We know some cases of mass animals' (and especially, calves') death due to weather anomalies. Glaze can be the cause of extinction of certain groups and isolated animal populations.

Our works are devoted to the theoretical study of the correlations between weather and climate factors and animal organisms on the basis of the model approach. We had to develop mathematical models because the possibilities of direct measurements of the constituents of animals' energy balance are quite limited and inadequate for conducting research in the real range of weather and climate conditions change. Unlike full-scale experiments, computer experiments can be made using any values of input data and require far less time and money. The presented heat balance model was developed in St. Petersburg Institute for Informatics and Automation within the framework of the bioclimatic research, which is being done there. It is different from the earlier versions [1] because it includes the active system of regulating thermal currents, not the compensatory one. The external factors influence the thermoregulation system indirectly, by changing the animal's body total heat. As a result, this model is more adequate to a real object.

In particular, it concerns the balance of heat production and heat losses within the scope of the thermoneutral zone. As an experimental tool the model can be used for assessing the influence of climatic factors on energy losses, heat balance and animals' activity. The simulation results can be used for building energy losses fields of the population area and determining bioclimatically neutral zones in which energy balance is sustained using physiological mechanisms of thermoregulation.

II. Biological aspects Prepare Your Paper Before Styling

According to K.P. Ivanov [2] "A body cannot use heat for biological work, and, as a result, it is not a "thermal machine". Therefore, excessive heat should be removed, and it is the task of the thermoregulation system.

The animal's body heat production sources include basal metabolism energy, digestion energy –the so called specific dynamic action of food (SDA), as well as heat production, connected with productive exchange and muscular activity. According to modern conceptions the basal metabolism level is a feature of morpho-physiological organization of animals and cannot be considered as an environmental adaptation factor. Its change is possible only when the interior body temperature changes. Unlike this, the muscles can increase metabolism level manifold [2]. As the muscular work efficiency is small and does not exceed 30%, most of the energy is transformed into heat.

According to the homoitherms' body temperature variability we distinguish between the "core" – the part of the body with relatively constant temperature (variability – deciles of the degree) and "the shell" (variability between several degrees to several tens degrees). The stability of the body temperature when the animal's activity is different is provided by thermal insulation and thermal regulation systems. Thermal insulators include fur, hypodermic fat and "shell" tissues. In order to get rid of excessive heat animals employ sweat secretion and respiration systems, as well as "thermal gaps" – parts of animals' bodies with low thermal insulation. Reindeer have practically no sudoriferous glands on the skin. Heat transfer due to passive diffusion of water and its evaporation does not depend on external temperature and equals about 12.5 kcal/m^2 hr [3].

The thermoregulation system includes the subsystems of physiological, chemical and behavioral regulation.

Physiological mechanisms of thermoregulation include piloerection (change of fur thickness), redistribution of blood currents in "the shell", adaptive changes of the respiration

This work was supported by the Russian Geographic Society (grant 07/19/2011).

system. The subsystems have the following efficiency: due to piloerection fur thermal resistance can exceed the norm by 40-50%. The blood currents redistribution leads to the change of the skin surface temperature and tissue thermal isolation value. The trunk tissue thermal isolation can change two-fold and lower parts of limbs – nearly ten-fold. The reindeer respiratory system adaptation to the low air temperature consists in reducing lung ventilation and the temperature of the exhaled air. As a result, heat losses from breathing are reduced by 40% when the air temperature drops from 0 to -40^{o}C. The animal respiratory system's reaction to overheating consists in increasing the frequency of respiratory cycles, increasing the exhaled air temperature, vapor formation growth. Heat transfer can in this case increase nearly three times compared to heat transfer when the temperature is 0 ^{o}C [4]. Reindeer shedding is another physiological tool of increasing heat transfer in summer and autumn. It begins in early July, but reindeer lose all their winter fur only by mid-August. By November winter fur is formed.

Animals' cold-resistance is pre-conditioned by the lowest critical temperature of the environment, i.e. the temperature range, within which the animals do not have to use chemical thermal regulation for sustaining temperature homeostasis. Beyond this range physiological tools do not provide the body temperature stabilization. Hypothermia threat is eliminated by using different kinds of chemical thermal regulation which provide the compensation of heat losses due to the growth of the animal's body heat production. As a rule, they include cold muscular shiver (heat production of rest increase 2-2.5 times) and thermoregulatory muscular tonus (heat production of rest increase by 50%). Besides, when animals are adapted to cold, the processes of oxidation and phosphorylation in mitochondria are uncoupled, which leads to the decrease of muscular contractions efficiency and heat production growth. When chemical types of thermal regulation start working the animal's body stops saving energy and starts its intensive dispersal exclusively for the sake of cold protection. Therefore chemical types can only serve as a short-term compensator of heat losses before the animals move to more thermally comfortable zones or conditions [2].

Livelihoods of reindeer includes the following types of behavior: locomotion, digging snow (in winter), free grazing or eating fodder from holes, rest in a standing position or lying down. Time budget of animals for different seasons can be found in [3,5]. Behavior types alternate and repeat in a cycle. The reindeer performs 5-6 cycles a day in winter. Each of behavior types is characterized by its own ratio of heat production and consumption. It allows the animals to compensate heat balance disruption within a cycle with behavior types both with excessive heat production and with heat production insufficient for compensating heat losses [6]. In general, the behavioral activities as a means of thermoregulation aimed in winter at reducing heat loss. In order to reduce energy consumption the animals spend more time lying (10-12 in winter, 9:00 in summer), in windy weather, animals are moved to the mountain valleys, forests and other places protected from the wind. They move against wind. In summer, when the weather is hot, thermoregulatory behavior types aimed at getting rid of heat excess – search for open, ventilated territories, coastal regions. In extreme cases reindeer practically stop eating in order to reduce the body heat production by reducing energy consumption for SDA.

III. The Description of the Heat Balance Model

It should be pointed out that the thermal processes in the animal's body follow the laws of thermodynamics and they can be described by mathematical physics equations. However, the complexity of these processes, the big number of factors, influencing them, the difficulties of obtaining required experimental results lead to the necessity of substantial simplification of real processes or transition to computer simulation.

The present model belongs to the class of compartment models. It consists of two layers. The first layer is presented by the "core" compartment, the second layer – by the "shell" compartments. These are the compartments of the head, neck, trunk, upper and lower parts of the limbs. Such structure is caused by the peculiarities of the animal body thermal characteristics and the availability of the information required for the adjustment of the model. For each compartment of the shell certain thermal tissue characteristics are set (minimum and maximum thermal resistance), as well as the fur cover characteristics (thickness, thermal resistance or conductivity, piloerection coefficient). The area of the shell compartments surface taken from [6].

The core is the heat production source in the model; the shell provides the thermal isolation of the core and the regulation of heat currents. The following thermoregulation mechanisms are realized in the model:

- fur cover piloerection,
- the change of shell tissues thermal conductivity,
- the change of heat losses in the respiration process.

The heat production (kcal / hr) at rest lying Q0hL and standing Q0hS defined by:

$$Q0hL = Q0h + CDD,$$

$$Q0hS = Q0hL + Qpoza,$$

where: Q0h is power of basal metabolism, SDA is specific dynamic action of food, Qpoza is heat production to maintain posture:

$$Q0h = 90 * (m \wedge 0.75) / 24,$$

$$SDA = 0.3 * Q0h,$$

$$Qpoza = Q0hL * 0.12 .$$

Total heat production of mechanical work Q0AX defined by:

$$Q0AX = Q0hS + kpdT * X,$$

where: X is mechanical power, kpdT is conversion factor of mechanical power into heat. To calculate the value of X in various forms of animal activity were used V.G.Gorshkov known relations [7].

Thermal conductivity of the coat ($kcal/m^2hr$) is given by:

TC = (eps + ita) / h + D * u * zzu / (log (h / z)) ^ 2,

where: eps, ita - the coefficients of convective heat and the long-wave heat transfer, h, z - the thickness of the guard and pile fur, D - turbulent diffusion coefficient, u - wind velocity, zzu - inter-system coefficient.

The heat losses from the body surface ($kcal/m^2hr$) are determined by the formula [1]:

TP = ((tr-tb) * TC + (1 - (TC ^ 2/a15) * lmd) * QR * zzs) / ((TC/a15 * lmd +1) * (TC/a15 +1)) + TW,

where: tr, tb - rectal (core) temperature and air temperature, lmd - thermal resistance of the tissues, QR - the total solar radiation, the A15 - the heat transfer factor, zzs - inter-system coefficient, TW - the heat loss due to passive diffusion of water.

The heat loss from breading TD can be approximated by the expression:

TD = 16.1 * m / (tr-tb).

When the heat balance is disrupted regulation processes begin. They lead to the increase or decrease of heat losses and prevent the body from overheating or hypothermia. The regulation takes place simultaneously in all shell compartments. Regulation of heat loss from the body surface is performed by changing the values of h and lmd, heat with the breath - by changing tb (as a fictitious temperature of inhaled air) in such a way as to minimize the magnitude of the mismatch between heat production and heat loss of the body. The regulation takes place simultaneously in all compartments of the shell.

Heat production and heat losses in the model can be calculated for all basic types of animal behavior – rest standing or lying, movement, digging snow, eating fodder from holes and free grazing.

In order to adjust the model's parameters and verify it we used the results of observations and experiments, published in [3, 4, 8-10] and materials on thermoregulation of the Svalbard reindeer from C.Cuyler [11].

Consider some of the results of calculations for a deer weighing 100 kg., the behavior - rest standing, rectal temperature equal to 38.5 °. According to the results of computer experiments, the heat production is equal to 5.46 $kcal/kg^{0.75}hr$, energy metabolism is equal to 1.73 kcal/kg hr. At 3^oC air temperature, average thermal resistance of fur (in clo) is 2.5, the tissues - 0.18. At - 40 ° C, the thermal resistance increases to 5 for the fur and to 0.3 for the tissues. Thermal conductivity of fur on the side of the body is about 1 $kcal/m^2$ hr ^oC (1.2 w/m^2 ^oC) at a thickness of fur 4.1 cm in calm air. The obtained values are close to the results of biological experiments. Thus, heat production the reindeer in the winter from the experimental data [3, 4] is 5.2-5.7 $kcal/kg^{0.75}hr$, the energy metabolism – 1.66-1.8 kcal/kg hr. Thermal conductivity of caribou fur is about 1.2 w/m^2 ^oC at a thickness 5 cm [8]. Thermal conductivity of Svalbard reindeer fur is about 0.65 w/m^2 ^oC at a thickness 6.7 cm in calm air [11].

As an example in Table 1 one can find the data about the animal's skin temperature, obtained during the experiments and calculated on the model.

TABLE I. TEMPERATURE OF THE ANIMAL'S BODY PARTS ^oC, (CALCULATION ON THE MODEL / EXPERIMENTAL DATA ON [4])

Body pats	*Air temperature ^oC*			
	3	-20	-30	-40
Side of animal	36.7/36.6	36.3/36.3	36.2/36.2	36.1/36
Upper legs	36.3/36.2	35.4/35.6	35.1/35	34.9/35
Lower legs	31.3/30.6	21.7/21.7	15.6/13.1	9.1/9.3

Table 2 shows the data about the lower limit of the reindeer thermoneutral zone (rest lying), found on the model for the animals with different weight and different wind speed.

TABLE II. DEPENDENCE BOUNDARY THERMO NEUTRAL ZOON ^oC FROM BODY WEIGHT AND WIND VELOCITY

body weight (kg)	*wind velocity (m/c)*				
	0	5	10	15	20
130	-62	-41	-33	-27	-20
80	-53	-38	-29	-24	-17

IV. CONCLUSION

Using the notion of cold resistance we can introduce the concept of bioclimatic resistance of animals, defined as the resistance to the action of environmental weather and climate factors. The value range of weather and climate factors, in which the temperature stability is provided by the physiological thermoregulation system is called a bioclimatically neutral zone. Animals cannot survive out of the boundaries of this zone. In winter – due to increased energy consumption when chemical thermoregulation are switched on, in summer – due to nourishment cessation. Building up the fields of animals' energy consumption and defining the boundaries of bioclimatically neutral zones is the urgent task of bioclimatic research and simulation [12]. The obtained data can be used for selecting or predicting the most favorable animals' habitats and increasing the efficiency of agriculture and commercial hunting in the conditions of unstable weather and climate conditions.

The model, presented in this work, is adjusted using the data for reindeer. However, with the corresponding modification such an approach can be used for studying the influence of weather and climate factors on other wild and domestic animal species.

ACKNOWLEDGMENT

The author thanks A.V. Kushnir for his assistance in obtaining data about reindeer bioenergy and to K. Cuyler for

her materials on thermoregulation and physiology of the Svalbard archipelago reindeer.

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