Biometeorology 2

Roberto Gomes da Silva
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Principles of Animal Biometeorology

Springer

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BIOMETEOROLOGY

Volume 2

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Springer

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ISBN 978-94-007-5732-5 ISBN 978-94-007-5733-2 (eBook)
DOI 10.1007/978-94-007-5733-2
Springer Dordrecht Heidelberg New York London

Library of Congress Control Number: 2012951127

Printed on acid-free paper

Springer is part of Springer Science+Business Media (www.springer.com)

Foreword

Biometeorology is a relatively new scientific area, with three principal subdivisions (human, plant, and animal) being recognized since the International Society of Biometeorology (ISB) was established in 1956. However, the basis for recognition as an area worthy of investigation can be traced back for much longer periods of time. For animal biometeorology in particular, the lineage includes studies of animal calorimetry and bioenergetics as long ago as the eighteenth century (Lavoisier), with more intensive investigations in the early twentieth century by subsequent researchers, resulting in classic references by Samuel Brody (*Bioenergetics and Growth*, 1945) and Max Kleiber (*The Fire of Life*, 1961, revised 1975).

Later in the mid-twentieth century, the focus of animal biometeorology expanded from the basic studies of bioenergetics to the application of the results for improved animal performance, health, and well-being in production systems. Animal scientists, engineers, and veterinarians collaborated in this effort, with numerous research reports and several books published. Notable among the books are those by Esmay (*Principles of Animal Environment*, 1969), Moberg (*Animal Stress*, 1985), Sainsbury and Sainsbury (*Livestock Health and Housing*, 1979), Clark (*Environmental Aspects of Housing for Animal Production*, 1981), Yousef (*Stress Physiology in Livestock,* three volumes, 1985), and DeShazer (*Livestock Energetics and Thermal Environmental Management*, 2009). Additionally, starting in 1974, there have been a series of International Livestock Environment Symposia (organized and proceedings published by the American Society of Agricultural and Biological Engineers) which have provided a forum for discussion and integration of research information for improving animal management in challenging environments. The Congresses of the International Society of Biometeorology, held every 3 years, have furthered that effort.

The authors of the present book, *Principles of Animal Biometeorology*, have extensive research experiences in the field. The material included provides another step in integration of current knowledge about biometeorological principles in assessing the impact of environments on animals of various types. Emphasis is on the physical aspects of heat transfer and heat exchanges in thermal environments (temperature, humidity, wind, and radiation), but with a view toward thermoregulatory responses of the animals. The book should serve as a useful resource for those interested in animal biometeorology and application of such information for understanding and improving animal environments.

G. LeRoy Hahn (Agricultural Engineer and Biometeorologist, retired from the U.S. Meat Animal Research Service, Agricultural Research Service, U.S. Department of Agriculture, Clay Center, Nebraska)

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List of Symbols

Greek Alphabet

α		Absorptance of surface for radiation
α_s		Absorptance of surface for solar radiation
β	degrees	Solar elevation
δ	degrees	Solar declination
ε		Emissivity of surface
ε_{ac}		Apparent emissivity of clear sky
$\mathbf{\Phi}$	W m^{-2}	Energy flux density
Φ_{cap}	L s^{-1}	Air flux through a capsule
γ	C^{-1}	Psychrometric constant
$\mathbf{\Gamma}$	W m^{-2}	Storage of thermal energy
η	degrees	Hour angle of sun
λ	J g^{-1}	Latent heat of vaporisation of water
λ	μm	Wavelength of electromagnetic radiation
μ	g m^{-1} s^{-1}	Dynamic viscosity of air
v	m^2 s^{-1}	Kinematic viscosity of air
θ	degrees	Solar zenith angle
ρ	g m^{-3}	Density of air
ρ		Reflectance of surface
ρ_g		Reflectance of ground surface
σ	W m^{-2} K^{-4}	Stefan-Boltzmann constant $= 5.67 \times 10^{-8}$ W m^{-2} K^{-4}
τ		Transmittance of the air or a surface
$\mathbf{\Psi}$	g m^{-3}	Absolute humidity of air
ω	degrees	Solar azimuth angle
	degrees h^{-1}	Angular speed of Earth

Latin Alphabet

A	m^2	Surface area
$\mathbf{C}$	$W\ m^{-2}$	Convective heat flux density
$\mathbf{C_S}$	$W\ m^{-2}$	Convective heat flux density at body surface
$\mathbf{C_R}$	$W\ m^{-2}$	Convective heat flux density at respiratory surfaces
c_0	$m\ s^{-1}$	Light speed $= 2.99792458 \times 10^8$
c		Cloud-type coefficient
c_p	$J\ g^{-1}\ K^{-1}$	Specific heat of air at constant pressure
c_v	$J\ g^{-1}\ K^{-1}$	Specific heat of air at constant volume
c_{pt}	$J\ g^{-1}\ K^{-1}$	Specific heat of body tissues
c_{pv}	$J\ g^{-1}\ K^{-1}$	Specific heat of water vapour
d	m	Characteristic dimension of surface
d		Ordinal number of the year day (1–365)
D	$m^2\ s^{-1}$	Thermal diffusivity coefficient
D_a	$m^2\ s^{-1}$	Thermal diffusivity coefficient of air
D_v	$m^2\ s^{-1}$	Thermal diffusivity coefficient of water vapour in air
e		Exponential number $= 2.7182818284\ldots$
$\mathbf{E}$	$W\ m^{-2}$	Evaporative heat flux density
$\mathbf{E_R}$	$W\ m^{-2}$	Evaporative heat flux density at respiratory surfaces
$\mathbf{E_S}$	$W\ m^{-2}$	Evaporative heat flux density at body surface
F_c		Shape factor of surface for radiation
F_r	breaths min^{-1}	Respiratory rate
$\mathbf{G}$	$W\ m^{-2}$	Irradiance of surface
G_r		Grashof number
g	$m\ s^{-2}$	Gravitational constant
H	$kJ\ kg^{-1}$	Enthalpy of air
h		Hour
h	J s	Planck's constant $= 6.626076 \times 10^{-34}$
h_c	$W\ m^{-2}\ K^{-1}$	Convection coefficient
I_c	$W^{-1}\ m^2\ °C$	Thermal insulation of hair coat
I_t	$W^{-1}\ m^2\ °C$	Thermal insulation of tissues
$\mathbf{J}$	$W\ m^{-2}$	Radiosity of surface
k	$W\ m^{-1}\ K^{-1}$	Thermal conductivity
k	$J\ K^{-1}$	Boltzmann constant $= 1.380658 \times 10^{-23}$
K	$W\ m^{-2}\ K^{-1}$	Thermal conductance of body
$\mathbf{L}$	$W\ m^{-2}$	Long-wave irradiance of surface
LCT	°C	Lower critical temperature
$\mathbf{L_D}$	$W\ m^{-2}$	Long-wave irradiance, downwards
$\mathbf{L_U}$	$W\ m^{-2}$	Long-wave irradiance, upwards
L_t	degrees	Latitude

L_g	degrees	Longitude
$\mathbf{M}$	$W\ m^{-2}$	Metabolic rate
M	$g\ mol^{-1}$	Molecular mass
M_w	$g\ mol^{-1}$	Molecular mass of water = 18,016 $g\ mol^{-1}$
m		Air mass number
$\dot{m}$	$kg\ s^{-1}$	Mass flux
N_u	nondimensional	Nusselt number
n		Proportion of sky cloudiness
P_r	nondimensional	Prandtl number
P_a	kPa	Atmospheric pressure
$P_s(T)$	kPa	Saturation vapour pressure at temperature T
P_v	kPa	Partial air vapour pressure
$\mathbf{R}$	$W\ m^{-2}$	Thermal flux by radiation
		Emissive power of a surface
		Thermal energy exchange by radiation
R_e	nondimensional	Reynolds number
R	$J\ mol^{-1}\ K^{-1}$	Universal gas constant = 8.3143 $J\ mol^{-1}\ K^{-1}$
R_a	$J\ mol^{-1}\ K^{-1}$	Gas constant of air =287.04 $J\ mol^{-1}\ K^{-1}$
r	m	Geometric radius
r		Correlation coefficient
r	$s\ m^{-1}$	Thermal resistance
r_t	$s\ m^{-1}$	Thermal resistance of tissues
r_H	$s\ m^{-1}$	Thermal resistance for convection
r_K	$s\ m^{-1}$	Thermal resistance for conduction
r_R	$s\ m^{-1}$	Thermal resistance for radiation
r_V	$s\ m^{-1}$	Thermal resistance for evaporation
$\mathbf{S}$	$W\ m^{-2}$	Short-wave irradiance of surface
S_c	nondimensional	Schmidt number
S_h	nondimensional	Sherwood number
t	s	Time
t		Atmospheric turbidity coefficient
T	°C, K	Temperature
T_a	°C, K	Air temperature, dry bulb temperature
T_b	°C, K	Mean body temperature
T_c	°C, K	Body core temperature
T_{dp}	°C, K	Dew point temperature
T_{exp}	°C	Temperature of expired air
T_g	°C, K	Black globe temperature
T_o	°C, K	Operative temperature
T_{oe}	°C, K	Equivalent operative temperature
T_r	°C	Rectal temperature

T_{rm}	°C, K	Mean radiant temperature
T_{rm}^*	°C, K	Effective mean radiant temperature
T_s	°C, K	Surface temperature
T_w	°C, K	Wet bulb temperature
U	m s^{-1}	Wind speed
UCT	°C	Upper critical temperature
U_R	%	Air relative humidity
V	m^3	Volume
V_T	m^3 breath^{-1}	Tidal volume
W	kg	Body weight
z	m	Altitude

Tables

Table A1 Système International (SI) units

Quantity	Name	Symbol	Definition c.g.s.
Concentration of substance	Mole	mol	
Electric current	Ampère	A	
Electric potential difference	Volt	V	
Linear dimension	Metre	m	
Energy	Joule	J	kg m^2 s^{-2}
Force	Newton	N	kg m s^{-2}
Frequency	Hertz	Hz	Oscillations s^{-1}
Mass	Kilogram	kg	
	Gram	g	
Power	Watt	W	J s^{-1}
Pressure	Pascal	Pa	kg m^{-1} s^{-2}
Temperature	Kelvin	K	
	Celsius	°C	
Time	Second	s	
Velocity			m s^{-1}
Volume	Litre	L	10^{-3} m^3

Table A2 Multiples and submultiples of SI units

Multiplier	Prefix	Symbol
10^{12} = 1,000,000,000,000	Tera	T
10^{9} = 1,000,000,000	Giga	G
10^{6} = 1,000,000	Mega	M
10^{3} = 1,000	Kilo	k
10^{2} = 100	Hecto	h
10^{1} = 10	Deca	da
10^{-1} = 0.1	Deci	d
10^{-2} = 0.01	Centi	c
10^{-3} = 0.001	Milli	m
10^{-6} = 0.000001	Micro	μ
10^{-9} = 0.000000001	Nano	n
10^{-12} = 0.000000000001	Pico	p

Table A3 Equivalence of some units

Quantity	Unit	Equivalence
Linear dimension	Inch (″, in)	0.0254 m
	Foot = 12 in. (ft)	0.3048 m
	Yard (yd)	0.9144 m
	Mile (mi)	1,609.34 m
	Mile, nautical (mi)	1,852 m
Area	Square inches (sq.in)	0.000645 m^2
	Square foot (sq.ft)	0.092903 m^2
	Acre	4,047 m^2
	Hectare	10,000 m^2
Mass	Pound (lb)	0.453592 kg
Volume	Litre (L)	1,000 cm^3
	Gallon, British (ga)	4.546 L
	Gallon, American (ga)	3.785 L
Temperature	Celsius (°C)	K − 273.15
	Kelvin (K)	°C + 273.15
	Fahrenheit (F)	(9/5)°C + 32
	Rankin (R)	F + 460
Pressure	Kilopascal (kPa)	1.000 Pa
	Millibar (mb, mbar)	0.1 kPa
	Millimetres of mercury (mmHg)	0.1333224 kPa
Thermal energy	British thermal unit (BTU)	1,055.1 J
	Calorie (cal)	4.186938 J
	Watt (W)	3.412806 BTU h^{-1}
	Watt (W)	0.238838 cal s^{-1}
	cal $(cm^2 \, min)^{-1}$	697.823071 W m^{-2}
	BTU $(h \, ft^2)^{-1}$	3.154723 W m^{-2}
	W m^{-2}	0.316985 BTU $(h \, ft^2)^{-1}$
	Mcal day^{-1}	48.459931 W

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Chapter 1
The Environment

Abstract In this chapter, the following are presented: environmental factors and definition of tropical climate, definitions and discussion about radiation environment (solar constant, solar radiation variation with latitude and season), equations for determination of sun angles (zenith, elevation, declination and hour angles of sun), aspects of the short-wave radiation at the ground level, atmospheric transmittance, diffuse and reflected radiation, influence of clouds, reflectance of ground surfaces and estimation of total short-wave radiation. The determination of downward and upward long-wave radiation is discussed, along with the respective formulas. The concepts of radiant heat load and the mean radiant temperature are discussed, and the respective methods of determination are presented. The theory of black globe is presented, and its practical use is discussed. The structure of the atmospheric layers, together with the gas components of the atmosphere, is described. The importance of CO_2, ozone and methane is discussed, together with that of aerosol pollutants; the evolution of atmospheric CO_2 is also discussed. The equations to determine the physical properties of the air are presented: atmospheric pressure, specific heat, density, thermal conductivity, viscosity, latent heat of vaporisation, psychrometric constant and diffusivity of vapour; the methods of air humidity specification are presented: saturation and partial vapour pressure, relative humidity, absolute humidity and dew point temperature.

Keywords Atmospheric layers • Atmospheric properties • Carbon dioxide • Long wave • Ozone • Radiant heat load • Short wave • Solar radiation • Tropical climate

1.1 Environmental Factors

1.1.1 Domains of the Environment

Physical environment is constituted by four domains or spheres which are not superimposed one over another but exchange energy among them: *atmosphere,*

R. Gomes da Silva and A.S. Campos Maia, *Principles of Animal Biometeorology*, Biometeorology 2, DOI 10.1007/978-94-007-5733-2_1,

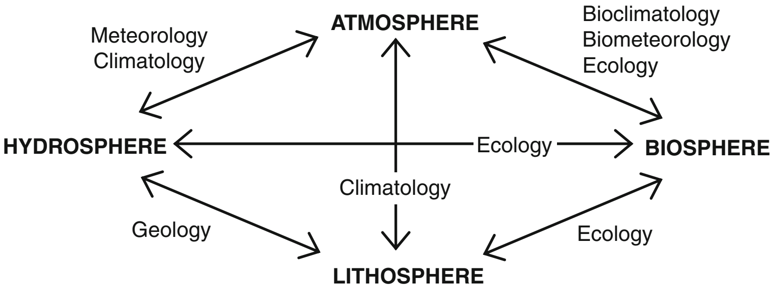

Fig. 1.1 Relationships among the four domains of the physical environment and the sciences which are associated to them

lithosphere, hydrosphere and biosphere. The first three include the air, the land and the waters, respectively, while the last is the universe of all live beings of the Earth. Between those four domains, there are close relationships and mutual interactions (illustrated in Fig. 1.1), which are of uttermost importance for sustaining life on the Earth.

The term environment includes all sources of energy, especially the radiant energy used for the plant photosynthesis that is stored as nutrients (proteins, carbohydrates, lipids). Such a material is the prime source of energy for other terrestrial and aquatic forms of life. All the live organisms in the biosphere are constituted by the water from hydrosphere; by the nitrogen, oxygen and other gases from the atmosphere; and by the minerals from the lithosphere.

Environmental factors as temperature and photoperiod determine growth rates of plants and affect reproduction of both animals and plants; besides, they control food availability and searching for animals. Gravity and light stimulate animals and plants and constitute references for them in terms of space and time, involving important processes as the sense of equilibrium and the biological clocks. Climatic and geological factors, among others, affect the spreading and viability of pathogenic agents and parasites which attack the organisms.

1.1.2 Weather and Climate

Among the environmental factors, variation of the atmospheric conditions is one of the most important effects upon the biosphere. In order to understand that variation, we must refer to two different terms: *weather* and *climate*.

Weather is the instantaneous state of the atmosphere and its study is the object of meteorology. The term “instantaneous” means here different periods of time, but in general, it is a 24-h period. Then, meteorological reports refer to the weather giving, as, for example, maximum and minimum air temperatures for a given location, or mentioning the occurrence of rain or winds in that period.

On the other hand, climate is the average weather conditions prevailing in a given location; it is established in the long range, after 10–30 years of continuous meteorological observations. Climatology is the science of the climate and has similar content to that of meteorology; however, they differ one from another with respect to the methodology. Climatologists use mainly statistical and cartographic techniques, while meteorologists use the laws of physics and mathematical techniques. Another difference is that the main concern of meteorology is the development and dynamics of the atmospheric phenomena, while that of climatology is the consequence of those phenomena.

Biometeorology is just a specialised field of meteorology that refers to the relationships between atmosphere and biosphere, which are aimed also by ecology and bioclimatology.

1.1.3 Definition of Tropical Climate

The word "tropical" refers to that zone of the Earth lying between the tropics of Cancer and Capricorn, which are, respectively, the 23°27′ north and south parallels. It is a belt that includes all the regions where the sun can be in some time at zenith. According to Ayoade (1983), the following definitions of a tropical region are valid:

(a) A region without winter or cold season
(b) A region where the annual average temperature is equal to or less than the average daily variation
(c) A region where the average temperature at sea level never is less than 18°C

It is generally considered that, despite the so-called tropical zone remains between the two 23°27′ parallels, these limits are not adequate because they are very rigid ones. In fact, some regions that are clearly nontropical can be found close to the equatorial line, such as parts of the Andes mountains in South America, the region of Mount Kilimanjaro in Kenya and some regions in Mexico, Central America and New Guinea (Nieuwolt 1978).

The use of temperature limits to demonstrate absence of winter in a tropical region seems also to be a misunderstanding; for example, considering an average temperature of 18°C for the coldest month can leave to the exclusion of the tablelands and highlands in tropical regions, where air temperature often falls beneath such a limit. Until some years ago, climates were described by meteorological standards, and several climatic classifications were used, as that of Köppen. However, such classifications were purely descriptive, leaving often too erroneous conceptions of the climatic variations in terms of biological significance, because of the used methodology – which was unable to explain the processes involved in the climatic variations.

In fact, interactions of the atmosphere with the other physical domains are dynamic and not static, involving continuous changes in the conditions of the ground surface, water distribution and alterations of the biosphere – especially the vegetation.

Therefore, climatic zoning and mapping could sometimes leave to a wrong idea about a given situation, because changing from a climate type to another is gradual. On the other hand, the atmospheric characteristics of a given region can be well understood only when they are considered within the environment as a whole.

Modern climatology concerns with long- or medium-term alterations of the climatic conditions, involving a number of factors – for example, solar radiation, environmental pollution and forest depletion. One of its basic instruments is the remote sensing by means of specialised satellites.

Then, in the present study, we do not consider any climatic classification, using rather a more practical division into *tropical*, *temperate* and *cold* climates. The term tropical is used to indicate a region located within the two tropics. The word "subtropical" has been extensively used to name a region with climatic conditions intermediary between tropical and temperate; it must be avoided, as showed by Nieuwolt (1978).

1.2 Radiation Environment

1.2.1 Short-Wave Solar Radiation

1.2.1.1 Solar Constant

All the energy at the surface of the Earth comes from the sun to be used for the biological and physical processes. Analyses of the solar spectrum show that the sun behaves almost as a perfect radiator, whose surface has an apparent temperature of $T_S = 5{,}755$ K.

Considering the Stefan-Boltzmann law, the radiation flux reaching the Earth outside atmosphere can be given as

$$\mathbf{S}_0 = \sigma T_s^4 r_s^2 r_t^{-2} \ \text{W m}^{-2} \tag{1.1}$$

where $r_s \cong 0.7 \times 10^6$ km is the radius of the sun, $r_t = 149 \times 10^6$ km the mean radius of Earth's orbit and σ is the Stefan-Boltzmann constant. Then,

$$\begin{aligned}\mathbf{S}_0 &= 5.67 \times 10^{-8}(5{,}755)^4\left(0.7 \times 10^6\right)^2\left(149 \times 10^6\right)^{-2} \\ &= 1{,}372.7 \ \text{W m}^{-2}\end{aligned}$$

which is the *solar constant*. However, it is not really a constant, since the flux of solar energy reaching the Earth varies according to the level of sun activity. The above given $\mathbf{S}_0$ figure is close to the average of observations (ranging from 1,369 to