Animals and their environment

We now apply the physics we have learned to animals and humans.

Example questions

How can dogs survive both cold and hot temperatures?

Why do humans need clothes?

Why are certain types of animals found in particular climates?

How will climate changes affect the animals which inhabit a particular climate?

Task: name a favorite or least favorite animal, the climate in which it lives, and a characteristic of that animal that allows it to live in that environment.

Review handout & definitions.
1 Animal Processes

ecology the study of the distribution and abundance of living organisms and how the distribution and abundance are determined by the interactions between organisms and their environment.

endotherm an organism that generates heat internally to determine the body temperature, also known as warm-blooded.

homeotherm an organism whose body temperature remains relatively constant, normally within 2 °C.

ectotherm an organism whose body temperature is determined by environmental conditions as it cannot generate constant internal heat.

poikilotherm an organism whose body temperature varies.

metabolism chemical changes in living cells which produce energy, some of this energy is used to heat the organism.

heterotroph an organism that must obtain its energy from other organisms as it is unable to photosynthesize.

hibernation long-term drop in temperature, usually preceded by gradual physiological changes in relation to seasonal changes and photoperiod, used by endotherms to conserve energy in extreme environments.

homeostasis maintenance of constant body conditions, such as temperature, levels of cellular fluids, dissolved salts, etc.

hyperthermia at high environmental temperatures, when an endotherm must increase metabolic rate to maintain a constant body temperature, but fails to do so and its temperature continues to rise until death. Body temperatures above 40 °C are life-threatening.

hypothermia at low environmental temperatures, when an endotherm must increase metabolic rate to maintain a constant body temperature, but fails to do so and its temperature continues to fall until death. Body temperatures below 35 °C are life-threatening.

thermoregulation regulation of body conditions (temperature, salt concentrations, water) through behavioral or physiological responses to a changing environment.

thermal neutral zone environmental temperature range under which an endotherm can maintain constant body conditions at the lowest metabolic rate and rate of energy consumption.
torpor nonseasonal, temporary drop in temperature and metabolic rate to save energy during stress (cold temperatures, lack of food or water, etc.).

vasoconstriction constriction (narrowing) of blood vessels when the ambient temperature is cold, resulting in the diversion of heated blood to the animal core and preventing loss of heat.

vasodilation dilation (widening) of blood vessels when the ambient temperature is hot, resulting in the diversion of heated blood to the surface of an animal and increased loss of heat.

2 Body Temperatures

<table>
<thead>
<tr>
<th>organism</th>
<th>°F body temp</th>
<th>°C body temp</th>
<th>regulation type</th>
</tr>
</thead>
<tbody>
<tr>
<td>human</td>
<td>98.6</td>
<td>37</td>
<td>endotherm, homeotherm</td>
</tr>
<tr>
<td>dog</td>
<td>102 ± 1</td>
<td>39 ± 1</td>
<td>endotherm, homeotherm</td>
</tr>
<tr>
<td>cat</td>
<td>101.5 ± 1</td>
<td>38.5 ± 1</td>
<td>endotherm, homeotherm</td>
</tr>
<tr>
<td>pigeon</td>
<td>106.6</td>
<td>41</td>
<td>endotherm, homeotherm</td>
</tr>
<tr>
<td>lizard</td>
<td>87.8–95</td>
<td>31–35</td>
<td>ectotherm, poikilotherm</td>
</tr>
<tr>
<td>salmon</td>
<td>41–62.6</td>
<td>5–17</td>
<td>ectotherm, poikilotherm</td>
</tr>
<tr>
<td>trout</td>
<td>53.6–64.4</td>
<td>12–18</td>
<td>ectotherm, poikilotherm</td>
</tr>
<tr>
<td>rattlesnake</td>
<td>59–98.6</td>
<td>15–37</td>
<td>ectotherm, poikilotherm</td>
</tr>
<tr>
<td>grasshopper</td>
<td>101.5–108</td>
<td>38.6–42.2</td>
<td>ectotherm, poikilotherm</td>
</tr>
</tbody>
</table>

---

**Fig. 12.1** Relation between basal metabolic rate of homeotherms (upper continuous line), maximum metabolic rate for sustained work by homeotherms (upper pecked line) and basal rate for poikilotherms at 20°C (lower continuous line) (from Hemmingsen, 1960).
Animal Energy Budget

Q: Can an animal maintain an acceptable body temperature? Examine the animal's energy budget to find out.

\[ R_{abs} - L_{oe} + M - \Delta E - H - G - q = 0 \quad (1) \]

- **Rabs** = absorbed radiation
- **Loe** = emitted radiation
- **M** = rate of metabolic heat production, per surface area
- **\( \Delta E \)** = latent heat loss through evaporation of water from animal surface or through respiration (vapor)
- **H** = sensible heat exchange (convection)
- **G** = heat exchange with substrate (conduction)
- **q** = rate of heat storage per surface area = \( c_p \Delta T \)
- \( c_p \) = heat capacity of animal body
- \( \Delta T \) = temp change

Note that for a homeotherm, \( \Delta T = 0 \) and \( q = 0 \)

Recall that if \( T_s \) = surface temperature of the animal,

\[ L_{oe} = f(T_s) \]
\[ G = f(T_s) \]
\[ H = f(T_s) \]

Animals can adjust body functions/processes to some extent in order to adjust \( T_s \) in order to balance (1), but in some cases this \( T_s \) may be too high or too low for long-term survival.

**Goal:** an animal must find an environment in which \( R_{abs} \) and \( T_a \) (environmental temp) allow it to vary \( L_{oe}, M, \Delta E, H, \) and \( G \) to survive.
Assuming $G=0$,

\[ M - \lambda E \to (T_b) \to \text{tissue} \to \text{skin} \to \text{conduction} \to \text{skin} \to \text{ambient} \]

\[ T_b = \text{body cavity temperature} \]
\[ T_k = \text{skin temperature} \]
\[ T_s = \text{surface temperature} \]
\[ T_a = \text{air temperature} \]

We'll put $\lambda E$ in here for now, justification is that panting is the main $\lambda E$ pathway for a resting animal.

rewritten

\[ M - \lambda E \to (T_b) \to \frac{1}{g_{hh} + g_{hc}} \to T_s \to g_{ha} \to T_a \]

\[ g_{hhb} = \text{body conductance} = \frac{1}{g_{hh} + g_{hc}} \]

\[ M - \lambda E = g_{hhb} C_p (T_b - T_o) \quad (2) \]

heat generated in body core
less latent heat flux
heat flow through the body
\[ \text{to the outside } \quad (\text{assuming } \lambda = 0) \]

rewriting (1)

\[ (3) \quad R_a e_{so} T_s^4 + (M - \lambda E) - g_{hh} C_p (T_s - T_a) = 0, \quad \text{if } G = g = 0 \]

strategy: use (2) to get rid of $T_s$ in (3) since $T_s$ is variable and difficult to measure, $T_a$ is determined by the environment, and $T_b$ is well known for many homeotherms.
Metabolism

Metabolic rate is generally measured per unit mass of animal. A minimum or basal rate is required to support basic body functions in all animals, and in endotherms, to control body temperature.

\[ B_m = \text{basal metabolic rate} = C \cdot m^n \quad [B_m] = \text{W} \]

\[ m = \text{animal mass, kg} \quad n = \frac{3}{4} \]

\[ C = \text{constant between 3 and 5 for endotherms, 0.1 and 0.3 for ectotherms} \]

See Figure 12.1 of Motterdo and Unsworth, where \( M \) is used instead of \( B_m \).

For an animal energy budget, we need \( Wm^{-2} \), so we will use a mass and surface area relationship that is suitable for many animals:

\[ A = \text{animal surface area} = 0.1 \text{ m}^2 \quad [A] = \text{m}^2 \quad \rho = \frac{2}{3} \]

\[ M_b = \frac{B_m}{A} = \text{basal metabolic rate per surface area} \]

\[ = 30-50 \text{ Wm}^{-2} \text{ for endotherms} \]

Metabolic rate increases with activity. If the "animal machine" is 30% efficient, then about 2 units of heat are produced for every 1 unit of work done.

Maximum metabolic rate = 10 \( M_b \)

\[ M = M_b \left( 1 + 9 \frac{x}{M} \right), \quad \text{where} \quad \frac{x}{M} = \text{fraction of maximum sustainable activity} \]
Latent Heat Exchange

\[ \Delta E = \Delta E_s + \Delta E_r = \text{Latent heat flux from evaporation} \quad + \quad \text{Latent heat flux due to respiration} \]

Note: \( \Delta E_r \) must be some function of \( M \) since \( M \) requires inhalation of oxygen ("burn" food) and an increase in \( M \) requires an increase in breathing rate (like during exercise).

At most (i.e., inhaling dry air), \( \Delta E_r = 10\% \) of \( M \)

i.e. part of \( M \) simply used to humidify air breathed in

Model

\[ \Delta E_r = M \frac{\lambda (e - e_i)}{\Gamma (C_{oi} - C_{oe})} = M \frac{\lambda (C_{vre} - C_{vi})}{\Gamma (C_{oi} - C_{oe})} \]

where

\( e \) = exhaled vapor pressure

\( C_{vre} = \text{exhaled vapor mole concentration, mol} \cdot \text{mol}^{-1} \)

\( e_i, C_{vi} = \text{inhaled vapor pressure, mole concentration} \)

\( C_{oe}, C_{oi} = \text{exhaled, inhaled oxygen (O}_2\text{) mole concentration} \)

\( \lambda = 441 \text{ kJ} \cdot \text{mol}^{-1} \)

\( p_a = \text{air pressure} \)

\( \Gamma = \text{heat produced per mole O}_2\text{ consumed} = 480 \text{ kJ} \cdot \text{mol}^{-1} \)

\[ \Delta E_s = \Delta g v \frac{e_s - e_a}{p_a} = \lambda g v (C_{vs} - C_{va}) \]

\( C_{vs} = \text{vapor mole concentration @ surface} \)

\( C_{va} = \text{ambient vapor mole concentration} \)

\[ g v = \frac{1}{g_{va} + \frac{1}{g_{ve}} + \frac{1}{g_s}} \]

At rest \( \Delta E_r + \Delta E_s = 0.2M \) for endotherms \quad \Delta E_r + \Delta E_s = M \) for ectotherms
Figure 12.3. Temperature of exhaled air as a function of air temperature for several species (after Schmidt-Nielsen, 1972).