Ecography

E6866
Gifford, M. E. and Kozak, K. H. 2011. Islands in the sky or squeezed at the top? Ecological causes of elevation range limits in montane salamanders. – Ecography 34: xxx–xxx.

Supplementary material

Supplementary material Appendix 1 – Gifford & Kozak

We modeled operative body temperatures of salamanders by solving a standard, steady state energy balance equation including terms representing solar, infra-red, convective, and conductive heat exchange,

$$Q_{solar} + Q_{IRin} = Q_{IRout} + Q_{conv} + Q_{cond}.$$

In our model of nocturnal salamander energetics, we do not consider heat generated via metabolism or lost via evaporation. In general, these salamanders live in cool wet habitats such that the contributions of metabolism and evaporation to the overall energy budget are expected to be minor (Spotila et al. 1992).

This mechanistic modeling approach proceeds by estimating the operative environmental temperature for a salamander, T_e, which is the air temperature reduced or increased by a temperature increment determined by absorbed radiation, wind speed, and animal morphology. This temperature represents the steady-state temperature of an animal with certain physical properties in a given environment. We follow the approach to modeling T_e as outlined in (Campbell and Norman 2000), and implemented in Buckley (2008), with adjustments to the radiant energy budget relevant for nocturnal forest-dwelling salamanders (see below). In order to model T_e, we must simulate the daily behavior of relevant parts of an ecosystem for a given location including, the location of the sun in the sky, daily variation in air and soil temperatures and the components of energy flux between an organism and its environment. All equations of our model are derived by Campbell and Norman (2000), unless indicated otherwise.

Day Length and Sun Angles

Salamander activity is constrained to nighttime hours. The expressions below are used to calculate day length and time of solar noon. Solar declination, the angle between the sun's rays and the equator:

$$\delta = \arcsin[0.39795\cos(0.21631 + 2\arctan\{0.967\tan[0.0086(-186 + J)]\})], \quad \text{(A1)}$$

where J is the calendar day (J = 1 at January 1). Thus, daylength, h_{day} (h), can be calculated using the CBM model of Forsythe et al. (1995) as:

$$h_{day} = 24 - \frac{24}{\pi}\arccos\left[\frac{\sin(6\pi/180) + \sin\phi\sin\delta}{\cos\phi\cos\delta}\right], \quad \text{(A2)}$$

where ϕ is latitude (rad).

The time of solar noon (h) is calculated using

$$t_0 = 12 - LC - ET, \quad \text{(A3)}$$

where LC is the longitude correction and ET is the equation of time. LC is a correction of +1/15 hour for each degree a location is east of a standard meridian, which occur at 0, 15, 30, …, 345°. Thus, ET is a correction for the difference between solar time and clock time, which depends on a calendar day. ET can be calculated from

$$ET = \frac{-104.7\sin f + 596.2\sin 2f + 4.3\sin 3f - 12.7\sin 4f - 429.3\cos f - 2.0\cos 2f + 19.3\cos 3f}{3600}, \quad \text{(A4)}$$

$$f = \frac{\pi}{180}279.575 + 0.9856J. \quad \text{(A5)}$$

The zenith angle, ψ (rad), is the angle of the sun from vertical,

$$\cos\psi = \sin\delta\sin\phi + \cos\delta\cos\phi\cos\frac{\pi}{12(h - t_0)}, \quad \text{(A6)}$$

where h is hour.

Air and Soil Temperatures

Our model estimates hourly variation in air temperature, T_a, using the average maximum and minimum daily temperatures for each month. Hourly temperature variation is modeled using a diurnal temperature function derived by Campbell and Norman (2000):

$$\Gamma = 0.44 - 0.46\sin(0.9 + \omega h) + 0.11\sin(0.9 + 2\omega h), \quad \text{(A7)}$$

where $\omega = \pi/12$. Hourly air temperature is calculated from,

$$T_a = T_x - T_n(1 - \Gamma), \quad \text{(A8)}$$

where T_x and T_n are the maximum and minimum daily temperatures (°C), respectively.

We similarly model hourly soil surface temperature, T_s (K), based on mean soil temperature and diurnal temperature range for an average day each month:

$$T_s - T_{Sa} + A_d \sin[\omega(h - 8)], \quad \text{(A9)}$$

where, T_{Sa} is the average daily soil temperature (K) and A_d is the amplitude of the fluctuation in diurnal soil temperature. In the sine function the variable for time is phase adjusted by eight hours.

Energy Flux Between an Animal and its Environment

The thermal influence of radiation is dependent on the Stefan-Boltzmann law, which describes the radiant energy over all wavelengths emitted by a blackbody radiator per unit surface area. The result is the emitted flux density, B (Wm^{-2}),

$$B = \sigma(T_a + 273.15)^4, \quad \text{(A10)}$$

where σ is the Stefan-Boltzmann constant (5.67×10^{-8} W m^{-2} K^{-4}). The emissivity, $\varepsilon(\lambda)$, is the fraction of radiation emitted by a blackbody surface at a given wavelength. The emissivity of gray bodies have no wavelength dependency. The emitted energy of a gray body, Φ (W m^{-2}) is,

$$\Phi = \varepsilon B. \quad \text{(A11)}$$

Most natural surfaces have emissivities similar to gray bodies and range from 0.95 to 1.0. We use an emissivity value of 0.96 (Spotila et al. 1992). Clear atmosphere emissivity is considerably lower and can be approximated using the following formula from Swinbank (1963):

$$\varepsilon_{ac} = 9.2 \times 10^{-6} (T_a + 273.15)^2. \quad \text{(A12)}$$

Convective heat transport between an animal's body and the environment depends on wind velocity, u (m s^{-1}) and the characteristic dimension, d (m). Assuming that wind direction is parallel to the axis of a cylindrical approximation of a salamander, d is the animal's length (snout-vent length [m]). Environmental turbulence is accounted for by incorporating a factor of 1.4 (Mitchell 1976). Thus, the boundary conductance of air can be expressed as

$$g_{Ha} = 1.4 \times 0.135 \sqrt{\frac{u}{d}}. \quad \text{(A13)}$$

The operative wind speed (i.e., the wind speed experienced by an organism) is different than the wind speed measured by monitoring instruments and may be attenuated by vegetative cover (i.e., a forest canopy). Wind speed measurements are often taken 10 m above the ground. We model the operative wind speed considering attenuation by a forest canopy by estimating the wind speed at the bottom of the canopy and then translating this estimate to the level of a salamander (~ 5 mm). We assume the top of canopy is 10 m high and the bottom is at ~8 m. The wind speed at the bottom of the canopy can be estimated by

$$u_z = u_H \exp\left[-LAI\left(1 - \frac{z}{H}\right)^{\beta}\right], \quad \text{(A14)}$$

where u_H is the wind speed measured at a reference height, H; LAI is the leaf area index; and z is the height of the bottom of the canopy (Meyers et al. 1998). The exponent, β, is estimated using

$$\beta = 1 - \left(\frac{\Phi - 1}{4} \right), \quad \text{(A15)}$$

where Φ takes a value of 2 for leafed deciduous trees.

The estimated wind speed at the bottom of the canopy, u_z, is then used to compute the wind speed experienced by a salamander under the canopy, u:

$$u = \frac{u^*}{0.4} \ln \frac{z - d}{z_m}, \quad \text{(A16)}$$

where u^* is the friction velocity, d is the zero plane displacement, and z_m is the momentum roughness parameter. This equation is only valid if $z \geq d + z_m$. The zero plane displacement is taken as $d = 0.65h$ and the roughness parameter is $z_m = 0.1h$. h is the height of reference (i.e., the salamander). The friction velocity is calculated from:

$$u^* = 0.4 \left(\frac{u_z}{\ln \left(\frac{z - d}{z_m} \right)} \right). \quad \text{(A17)}$$

Radiative conductance (mol m^{-2} s^{-1}), the thermal exchange between the animal and its environment proportional to differences in temperature is expressed as

$$g_r = \frac{4\varepsilon\sigma(T_a + 273.15)^3}{c_p}, \quad \text{(A18)}$$

where c_p is the specific heat of air (29.3 J mol^{-1} K^{-1}).

We now calculate the radiant energy budget of an organism. Because the salamanders modeled here are nocturnal, they avoid the direct solar radiation component of the radiant energy budget (Spotila et al. 1992). Thus, our model of salamander operative temperature only considers the thermal (long-wave) component.

The thermal (long-wave) component of an organism's radiant energy budget is estimated using the Stefan-Boltzmann law. This quantity is composed of the long-wave flux densities from the atmosphere, L_a, and the ground, L_g. These flux densities are computed as

$$L_a = \varepsilon_{ac}\sigma(T_a + 273.15)^4, \quad \text{(A19)}$$

$$L_g = \varepsilon_s\sigma(T_s + 273.15)^4; \quad \text{(A20)}$$

where ε_{ac} and ε_s are the clear sky and surface emissivities, respectively.

Armed with these quantities we can estimate the total amount of absorbed energy as

$$R_{abs} = \alpha_L(F_a L_a + F_g L_g), \quad \text{(A21)}$$

where α_L is the absorptivity in the thermal waveband and F_a and F_g are the view factors between the surface of the salamander and the thermal radiation. Because of their high water content, salamanders are nearly perfect absorbers and emitters of thermal radiation. Absorptivity ranges between 0.95 and 1.0 (Gates 1980), suggesting that a salamander will absorb between 95 and 100% of the thermal radiation that strikes its surface. We assume a longwave absorptance of 0.96 for our calculations (Spotila et al. 1992). We also assume that one-half of the thermal radiation is received from both the ground and the sky as these animals lie with the ventral surface of their body flat against the substrate and the dorsal half exposed to the surroundings, thus F_a and F_g are both assumed to be 0.5 (following Buckley 2008). So, for a given site, the operative environmental temperature for a salamander is calculated as

$$T_e = T_a + \frac{R_{abs} - \varepsilon_s\sigma(T_a + 273.15)^4}{c_p(g_r + g_{Ha})}. \quad \text{(A22)}$$

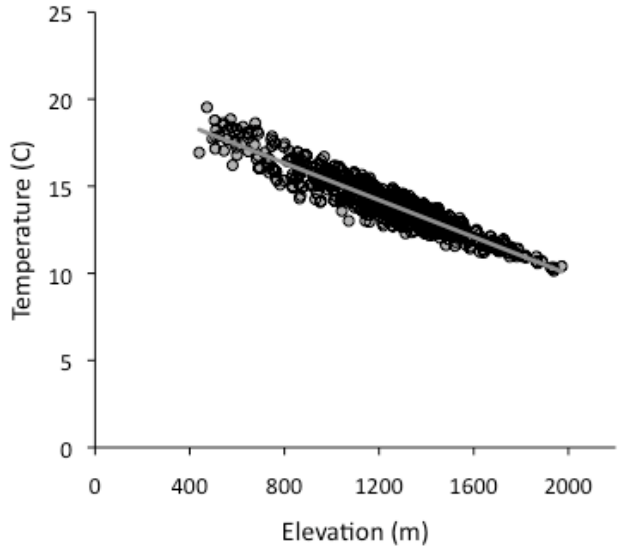
129 Table A1. Sampling localities for field abundance estimation. UTM zone for all localities is
130 UTM17.

Site	Elevation (m)	Easting	Northing
1	1239	290816.90	3944136.62
2	1192	290246.58	3943395.24
3	947	288745.63	3942786.91
4	892	289177.36	3941877.60
5	774	290221.24	3939621.90
6	740	290746.19	3938033.41
7	1475	302089.70	3943018.00
8	1427	302424.40	3944294.00
9	1082	301206.80	3944879.00
10	940	299170.90	3943044.00

131

132

132 Figure A1.



133

134 Figure A1. The relationship between mean temperature and elevation are strongly correlated.

135 Temperature data represent near-ground conditions generated from the microclimate model of

136 Fridley (2009).

137

Literature Cited:

Buckley, L. B. 2008. Linking traits to energetics and population dynamics to predict lizard ranges in changing environments. American Naturalist 171:E1-E19.

Campbell, G., and J. Norman. 2000. *An introduction to environmental biophysics*. Springer, New York.

Forsythe, W. C., E. J. Rykiel, R. S. Stahl, H. I. Wu, and R. M. Schoolfield. 1995. A model comparison for daylength as a function of latitude and day of year. Ecological Modeling 80:87-95.

Fridley, J. D. 2009. Downscaling climate over complex terrain: high fine-scale spatial variation of near-ground temperatures in a montane forested landscape (Great Smoky Mountains, USA). - Journal of Applied Meteorology and Climatology 48: 1033-1049.

Gates, D. M. 1980. *Biophysical ecology*. Springer, New York.

Meyers, T. P., P. Finkelstein, J. Clarke, T. G. Ellestad, and P. F. Sims. 1998. A multilayer model for inferring dry deposition using standard meterological measurements. Journal of Geophysical Research 103,:22645-22661.

Mitchell, J. W. 1976. Heat transfer from spheres and other animal forms. Biophysical Journal 16:561-569.

Spotila, J. R., M. P. O'Connor, and G. S. Bakken. 1992. Biophysics of heat and mass transfer. In *Environmental physiology of the amphibians* (eds. M. E. Feder & W. W. Burggren), pp. 59-80. Chicago: University of Chicago Press.

Swinbank, W. C. 1963. Long-wave radiation from clear skies. Quarterly Journal of the Royal Meteorological Society 89:339-348.