

Package ‘TrenchR’

October 12, 2022

Title Tools for Microclimate and Biophysical Ecology

Description Tools for translating environmental change into organismal response. Microclimate models to vertically scale weather station data to organismal heights. The biophysical modeling tools include both general models for heat flows and specific models to predict body temperatures for a variety of ectothermic taxa. Additional functions model and temporally partition air and soil temperatures and solar radiation. Utility functions estimate the organismal and environmental parameters needed for biophysical ecology. 'TrenchR' focuses on relatively simple and modular functions so users can create transparent and flexible biophysical models. Many functions are derived from Gates (1980) <[doi:10.1007/978-1-4612-6024-0](https://doi.org/10.1007/978-1-4612-6024-0)> and Campbell and Norman (1988) <[isbn:9780387949376](https://doi.org/10.1007/978-1-4612-6024-0)>.

Version 0.1.1

Maintainer Lauren Buckley <lbuckley@uw.edu>

License MIT + file LICENSE

Date 2022-09-20

URL <https://trenchproject.github.io/TrenchR/>,
<https://github.com/trenchproject/TrenchR>

BugReports <https://github.com/trenchproject/TrenchR/issues>

VignetteBuilder knitr

Depends R (>= 3.3.1)

Imports deSolve, msm, Rdpack (>= 0.7), stats, zoo

Suggests covr, knitr, rmarkdown, testthat

RdMacros Rdpack

Encoding UTF-8

RoxygenNote 7.2.0

NeedsCompilation no

Author Lauren Buckley [aut, cre] (<<https://orcid.org/0000-0003-1315-3818>>),
Bryan Briones Ortiz [aut],
Isaac Caruso [aut],
Aji John [aut] (<<https://orcid.org/0000-0002-4401-1401>>),
Ofir Levy [aut] (<<https://orcid.org/0000-0003-0920-1207>>),

Abigail Meyer [aut],
 Eric Riddell [aut] (<<https://orcid.org/0000-0002-4229-4911>>),
 Yutaro Sakairi [aut],
 Juniper Simonis [aut] (<<https://orcid.org/0000-0001-9798-0460>>),
 Brian Helmuth [ctb] (<<https://orcid.org/0000-0003-0180-3414>>)

Repository CRAN

Date/Publication 2022-09-20 22:10:08 UTC

R topics documented:

actual_vapor_pressure	4
airpressure_from_elev	5
air_temp_profile	6
air_temp_profile_neutral	7
air_temp_profile_segment	8
angle conversions	9
azimuth_angle	10
boundary_layer_resistance	11
constants	12
daylength	13
day_of_year	14
dec_angle	14
degree_days	15
direct_solar_radiation	16
diurnal_radiation_variation	18
diurnal_temp_variation_sine	19
diurnal_temp_variation_sineexp	20
diurnal_temp_variation_sinesqrt	21
DRYAIR	22
external_resistance_to_water_vapor_transfer	24
free_or_forced_convection	25
Grashof_number	26
Grashof_number_Gates	27
heat_transfer_coefficient	28
heat_transfer_coefficient_approximation	29
heat_transfer_coefficient_simple	30
mass_from_length	32
monthly_solar_radiation	33
Nusselt_from_Grashof	35
Nusselt_from_Reynolds	36
Nusselt_number	37
partition_solar_radiation	38
Prandtl_number	39
proportion_diffuse_solar_radiation	40
proportion_silhouette_area	41
proportion_silhouette_area_shapes	42
Qconduction_animal	43

Qconduction_substrate	45
Qconvection	46
Qemitted_thermal_radiation	47
Qevaporation	49
Qmetabolism_from_mass	50
Qmetabolism_from_mass_temp	51
Qnet_Gates	52
Qradiation_absorbed	53
Qthermal_radiation_absorbed	55
Reynolds_number	56
saturation_vapor_pressure	57
saturation_water_vapor_pressure	58
soil_conductivity	59
soil_specific_heat	60
soil_temperature	61
soil_temperature_equation	63
soil_temperature_function	65
soil_temperature_integrand	66
solar_noon	67
solar_radiation	68
surface_area_from_length	69
surface_area_from_mass	70
surface_area_from_volume	72
surface_roughness	73
Tbed_mussel	74
Tb_butterfly	76
Tb_CampbellNorman	78
Tb_Gates	80
Tb_Gates2	82
Tb_grasshopper	83
Tb_limpet	86
Tb_limpetBH	87
Tb_lizard	89
Tb_lizard_Fei	92
Tb_mussel	94
Tb_salamander_humid	95
Tb_snail	97
temperature_conversions	99
TPC	100
TPC_beta	101
TrenchR	102
Tsoil	102
VAPPRS	103
volume_from_length	104
WETAIR	105
wind_speed_profile_neutral	107
wind_speed_profile_segment	108
zenith_angle	109

actual_vapor_pressure *Actual Vapor Pressure from Dewpoint Temperature*

Description

The function calculates actual vapor pressure from dewpoint temperature based on Stull (2000); Riddell et al. (2018).

Usage

```
actual_vapor_pressure(T_dewpoint)
```

Arguments

T_dewpoint numeric dewpoint temperature (C).

Value

numeric actual vapor pressure (kPa).

Author(s)

Eric Riddell

References

Riddell EA, Odom JP, Damm JD, Sears MW (2018). “Plasticity reveals hidden resistance to extinction under climate change in the global hotspot of salamander diversity.” *Science Advances*, **4**(4). doi: [10.1126/sciadv.aar5471](https://doi.org/10.1126/sciadv.aar5471).

Stull RB (2000). *Meteorology for Scientists and Engineers*. Brooks Cole. ISBN 978-0534372149.

See Also

Other biophysical models: [Grashof_number_Gates\(\)](#), [Grashof_number\(\)](#), [Nusselt_from_Grashof\(\)](#), [Nusselt_from_Reynolds\(\)](#), [Nusselt_number\(\)](#), [Prandtl_number\(\)](#), [Qconduction_animal\(\)](#), [Qconduction_substrate\(\)](#), [Qconvection\(\)](#), [Qemitted_thermal_radiation\(\)](#), [Qevaporation\(\)](#), [Qmetabolism_from_mass_temp\(\)](#), [Qmetabolism_from_mass\(\)](#), [Qnet_Gates\(\)](#), [Qradiation_absorbed\(\)](#), [Qthermal_radiation_absorbed\(\)](#), [Reynolds_number\(\)](#), [Tb_CampbellNorman\(\)](#), [Tb_Gates2\(\)](#), [Tb_Gates\(\)](#), [Tb_butterfly\(\)](#), [Tb_grasshopper\(\)](#), [Tb_limpetBH\(\)](#), [Tb_limpet\(\)](#), [Tb_lizard_Fei\(\)](#), [Tb_lizard\(\)](#), [Tb_mussel\(\)](#), [Tb_salamander_humid\(\)](#), [Tb_snail\(\)](#), [Tbed_mussel\(\)](#), [Tsoil\(\)](#), [boundary_layer_resistance\(\)](#), [external_resistance_to_water_vapor_transfer\(\)](#), [free_or_forced_convection\(\)](#), [heat_transfer_coefficient_approximation\(\)](#), [heat_transfer_coefficient_simple\(\)](#), [heat_transfer_coefficient_saturation_vapor_pressure\(\)](#), [saturation_vapor_pressure\(\)](#), [saturation_water_vapor_pressure\(\)](#)

Examples

```
actual_vapor_pressure(T_dewpoint = 20)
```

airpressure_from_elev *Air Pressure from Elevation*

Description

The function estimates air pressure (kPa) as a function of elevation (Engineering ToolBox 2003).

Usage

```
airpressure_from_elev(elev)
```

Arguments

elev numeric elevation (meters).

Value

numeric air pressure (kPa).

References

Engineering ToolBox (2003). *Atmospheric Pressure vs. Elevation above Sea Level*. https://www.engineeringtoolbox.com/air-altitude-pressure-d_462.html.

See Also

Other utility functions: [azimuth_angle\(\)](#), [day_of_year\(\)](#), [daylength\(\)](#), [dec_angle\(\)](#), [solar_noon\(\)](#), [temperature conversions](#), [zenith_angle\(\)](#)

Examples

```
airpressure_from_elev(elev = 1500)
```

air_temp_profile *Air Temperature Profile using MICRO Routine*

Description

The function estimates air temperature (C) at a specified height (m). Estimates a single, unsegmented temperature profile using the MICRO routine from NicheMapR (Kearney and Porter 2017).

Usage

```
air_temp_profile(T_r, u_r, z_r, z0, z, T_s)
```

Arguments

T_r	numeric air temperature (C) at reference height.
u_r	numeric windspeed ($m.s^{-1}$) at reference height.
z_r	numeric initial reference height (m).
z0	numeric surface roughness (m).
z	numeric height to scale (m).
T_s	numeric surface temperatures (C).

Value

numeric air temperature (C).

References

Kearney MR, Porter WP (2017). “NicheMapR - an R package for biophysical modelling: the microclimate model.” *Ecography*, **40**, 664-674. doi: [10.1111/ecog.02360](https://doi.org/10.1111/ecog.02360).

See Also

Other microclimate functions: [air_temp_profile_neutral\(\)](#), [air_temp_profile_segment\(\)](#), [degree_days\(\)](#), [direct_solar_radiation\(\)](#), [diurnal_radiation_variation\(\)](#), [diurnal_temp_variation_sineexp\(\)](#), [diurnal_temp_variation_sinesqrt\(\)](#), [diurnal_temp_variation_sine\(\)](#), [monthly_solar_radiation\(\)](#), [partition_solar_radiation\(\)](#), [proportion_diffuse_solar_radiation\(\)](#), [solar_radiation\(\)](#), [surface_roughness\(\)](#), [wind_speed_profile_neutral\(\)](#), [wind_speed_profile_segment\(\)](#)

Examples

```
air_temp_profile(T_r = 20,  
                u_r = 0.1,  
                z_r = 0.1,  
                z0 = 0.2,  
                z = 0.15,  
                T_s = 25)
```

`air_temp_profile_neutral`*Air Temperature at a Specified Height Under Neutral Conditions*

Description

The function calculates air temperature (C) at a specified height (m) within a boundary layer near the surface. The velocity profile is the neutral profile described by Sellers (1965). Function is included as equations (2) and (3) of Porter et al. (1973).

Usage

```
air_temp_profile_neutral(T_r, z_r, z_0, z, T_s)
```

Arguments

<code>T_r</code>	numeric air temperature (C) at reference height.
<code>z_r</code>	numeric initial reference height (m).
<code>z_0</code>	numeric surface roughness (m).
<code>z</code>	numeric height to scale to (m).
<code>T_s</code>	numeric surface temperatures (C).

Value

numeric air temperature (C).

References

Porter WP, Mitchell JW, Bekman A, DeWitt CB (1973). "Behavioral implications of mechanistic ecology: thermal and behavioral modeling of desert ectotherms and their microenvironments." *Oecologia*, **13**, 1-54.

Sellers WD (1965). *Physical climatology*. University of Chicago Press, Chicago, IL, USA.

See Also

Other microclimate functions: [air_temp_profile_segment\(\)](#), [air_temp_profile\(\)](#), [degree_days\(\)](#), [direct_solar_radiation\(\)](#), [diurnal_radiation_variation\(\)](#), [diurnal_temp_variation_sineexp\(\)](#), [diurnal_temp_variation_sinesqrt\(\)](#), [diurnal_temp_variation_sine\(\)](#), [monthly_solar_radiation\(\)](#), [partition_solar_radiation\(\)](#), [proportion_diffuse_solar_radiation\(\)](#), [solar_radiation\(\)](#), [surface_roughness\(\)](#), [wind_speed_profile_neutral\(\)](#), [wind_speed_profile_segment\(\)](#)

Examples

```
air_temp_profile_neutral(T_r = 20,  
                        zr = 0.1,  
                        z0 = 0.2,  
                        z = 0.15,  
                        T_s = 25)
```

air_temp_profile_segment

Air Temperature at a Specified Height

Description

The function calculates air temperature (C) at a specified height (m). Estimates a three segment velocity and temperature profile based on user-specified, experimentally determined values for 3 roughness heights and reference heights. Multiple heights are appropriate in heterogenous areas with, for example, a meadow, bushes, and rocks. Implements the MICROSEGMT routine from NicheMapR as described in Kearney and Porter (2017).

Usage

```
air_temp_profile_segment(T_r, u_r, zr, z0, z, T_s)
```

Arguments

T_r	numeric a vector of air temperatures (C) at the 3 reference heights.
u_r	numeric a vector of wind speeds (ms^{-1}) at the 3 reference heights.
zr	numeric a vector of 3 reference heights (meters).
z0	numeric a vector of 3 experimentally determined roughness heights (meters).
z	numeric height for air temperature estimation (meters).
T_s	numeric surface temperatures (C).

Value

numeric air temperature (C).

References

Kearney MR, Porter WP (2017). “NicheMapR - an R package for biophysical modelling: the microclimate model.” *Ecography*, **40**, 664-674. doi: [10.1111/ecog.02360](https://doi.org/10.1111/ecog.02360).

See Also

Other microclimate functions: `air_temp_profile_neutral()`, `air_temp_profile()`, `degree_days()`, `direct_solar_radiation()`, `diurnal_radiation_variation()`, `diurnal_temp_variation_sineexp()`, `diurnal_temp_variation_sinesqrt()`, `diurnal_temp_variation_sine()`, `monthly_solar_radiation()`, `partition_solar_radiation()`, `proportion_diffuse_solar_radiation()`, `solar_radiation()`, `surface_roughness()`, `wind_speed_profile_neutral()`, `wind_speed_profile_segment()`

Examples

```
air_temp_profile_segment(T_r = c(25, 22, 20),
                        u_r = c(0.01, 0.025, 0.05),
                        zr = c(0.05, 0.25, 0.5),
                        z0 = c(0.01, 0.15, 0.2),
                        z   = 0.3,
                        T_s = 27)
```

angle conversions *Convert Angles Between Radians and Degrees*

Description

The function converts angles in radians to degrees or degrees to radians.

Usage

```
radians_to_degrees(rad)
```

```
degrees_to_radians(deg)
```

Arguments

rad numeric angle (radians).

deg numeric angle (degrees).

Value

numeric angle (degrees or radians).

Examples

```
radians_to_degrees(0.831)
degrees_to_radians(47.608)
```

azimuth_angle	<i>Azimuth Angle</i>
---------------	----------------------

Description

The function calculates the azimuth angle, the angle (degrees) from which the sunlight is coming measured from true north or south measured in the horizontal plane. The azimuth angle is measured with respect to due south, increasing in the counter clockwise direction so 90 degrees is east (Campbell and Norman 1998).

Usage

```
azimuth_angle(doy, lat, lon, hour, offset = NA)
```

Arguments

doy	numeric day of year (1-366). This can be obtained from standard date via day_of_year .
lat	numeric latitude (decimal degrees).
lon	numeric longitude (decimal degrees).
hour	numeric hour of the day.
offset	numeric number of hours to add to UTC (Coordinated Universal Time) to get local time (to improve accuracy but not always necessary). Optional. Defaults to NA.

Value

numeric azimuth angle (degrees).

References

Campbell GS, Norman JM (1998). *Introduction to environmental biophysics*, 2nd ed. edition. Springer, New York. ISBN 0387949372.

See Also

Other utility functions: [airpressure_from_elev\(\)](#), [day_of_year\(\)](#), [daylength\(\)](#), [dec_angle\(\)](#), [solar_noon\(\)](#), [temperature conversions](#), [zenith_angle\(\)](#)

Examples

```
azimuth_angle(doy = 112,  
              lat = 47.61,  
              lon = -122.33,  
              hour = 12,  
              offset = -8)
```

boundary_layer_resistance
Boundary Layer Resistance

Description

The function estimates boundary layer resistance under free convection based on the function in Riddell et al. (2018).

Usage

```
boundary_layer_resistance(T_a, e_s, e_a, elev, D, u = NA)
```

Arguments

T_a	numeric air temperature (K).
e_s	numeric saturation vapor pressure (kPa).
e_a	numeric actual vapor pressure (kPa).
elev	numeric elevation (m).
D	numeric characteristic dimension (e.g., body diameter) (m).
u	numeric wind speed (ms^{-1}), if not provided assume free convection; if provided, use forced convection if appropriate.

Value

numeric boundary layer resistance (scm^{-1}).

Author(s)

Eric Riddell

References

Riddell EA, Odom JP, Damm JD, Sears MW (2018). “Plasticity reveals hidden resistance to extinction under climate change in the global hotspot of salamander diversity.” *Science Advances*, **4**(4). doi: [10.1126/sciadv.aar5471](https://doi.org/10.1126/sciadv.aar5471).

See Also

Other biophysical models: [Grashof_number_Gates\(\)](#), [Grashof_number\(\)](#), [Nusselt_from_Grashof\(\)](#), [Nusselt_from_Reynolds\(\)](#), [Nusselt_number\(\)](#), [Prandtl_number\(\)](#), [Qconduction_animal\(\)](#), [Qconduction_substrate\(\)](#), [Qconvection\(\)](#), [Qemitted_thermal_radiation\(\)](#), [Qevaporation\(\)](#), [Qmetabolism_from_mass_temp\(\)](#), [Qmetabolism_from_mass\(\)](#), [Qnet_Gates\(\)](#), [Qradiation_absorbed\(\)](#), [Qthermal_radiation_absorbed\(\)](#), [Reynolds_number\(\)](#), [Tb_CampbellNorman\(\)](#), [Tb_Gates2\(\)](#), [Tb_Gates\(\)](#), [Tb_butterfly\(\)](#), [Tb_grasshopper\(\)](#), [Tb_limpetBH\(\)](#), [Tb_limpet\(\)](#), [Tb_lizard_Fei\(\)](#), [Tb_lizard\(\)](#), [Tb_mussel\(\)](#), [Tb_salamander_humid\(\)](#), [Tb_snail\(\)](#), [Tbed_mussel\(\)](#), [Tsoil\(\)](#),

`actual_vapor_pressure()`, `external_resistance_to_water_vapor_transfer()`, `free_or_forced_convection()`,
`heat_transfer_coefficient_approximation()`, `heat_transfer_coefficient_simple()`, `heat_transfer_coefficient`,
`saturation_vapor_pressure()`, `saturation_water_vapor_pressure()`

Examples

```
boundary_layer_resistance(T_a = 293,
                          e_s = 2.5,
                          e_a = 2.0,
                          elev = 500,
                          D    = 0.007,
                          u    = 2)
```

constants

General Use Constants

Description

Basic functions for numerical constants for conversions.

Usage

```
specific_heat_h2o(units = "J_kg-1_K-1")
```

```
latent_heat_vaporization_h2o(units = "J_kg-1")
```

```
stefan_boltzmann_constant(units = "W_m-2_K-4")
```

```
von_karman_constant(units = "")
```

Arguments

units	character indicating units
	<ul style="list-style-type: none"> specific_heat_h2o: <ul style="list-style-type: none"> "J_kg-1_K-1": $Jkg^{-1}K^{-1}$ latent_heat_vaporization_h2o: <ul style="list-style-type: none"> "J_kg-1": Jkg^{-1} stefan_boltzmann_constant: <ul style="list-style-type: none"> "W_m-2_K-4": $Wm^{-2}K^{-4}$ "mW_cm-2_K-4": $mWcm^{-2}K^{-4}$ con_karman_constant: <ul style="list-style-type: none"> "": dimensionless

Value

numeric values in units.

Examples

```
specific_heat_h2o()  
latent_heat_vaporization_h2o()  
stefan_boltzmann_constant()
```

daylength	<i>Day Length</i>
-----------	-------------------

Description

The function calculates daylength in hours as a function of latitude and day of year. Uses the CMB model (Campbell and Norman 1998).

Usage

```
daylength(lat, doy)
```

Arguments

lat numeric latitude (decimal degrees).
doy numeric day of year (1-366). This can be obtained from standard date via [day_of_year](#).

Value

numeric day length (hours).

References

Campbell GS, Norman JM (1998). *Introduction to environmental biophysics*, 2nd ed. edition. Springer, New York. ISBN 0387949372.

See Also

Other utility functions: [airpressure_from_elev\(\)](#), [azimuth_angle\(\)](#), [day_of_year\(\)](#), [dec_angle\(\)](#), [solar_noon\(\)](#), [temperature conversions](#), [zenith_angle\(\)](#)

Examples

```
daylength(lat = 47.61,  
          doy = 112)
```

day_of_year	<i>Julian Day from Date</i>
-------------	-----------------------------

Description

The function converts a date (day, month, year) to Julian Day (day of year).

Usage

```
day_of_year(day, format = "%Y-%m-%d")
```

Arguments

day	character numerical date in standard format (e.g. "2017-01-02", "01-02", "01/02/2017" etc).
format	character date format following as.POSIXlt conventions. Default value = "%Y-%m-%d".

Value

numeric Julian day number, 1-366 (e.g. 1 for January 1st).

See Also

Other utility functions: [airpressure_from_elev\(\)](#), [azimuth_angle\(\)](#), [daylength\(\)](#), [dec_angle\(\)](#), [solar_noon\(\)](#), [temperature conversions](#), [zenith_angle\(\)](#)

Examples

```
day_of_year(day = "2017-04-22",
            format = "%Y-%m-%d")
day_of_year(day = "2017-04-22")
day_of_year(day = "04/22/2017",
            format = "%m/%d/%Y")
```

dec_angle	<i>Solar Declination in Radians</i>
-----------	-------------------------------------

Description

The function calculates solar declination, which is the angular distance of the sun north or south of the earth's equator, based on the day of year (Campbell and Norman 1998).

Usage

```
dec_angle(doy)
```

Arguments

doy numeric day of year (1-366). This can be obtained from standard date via [day_of_year](#).

Value

numeric declination angle (radians).

References

Campbell GS, Norman JM (1998). *Introduction to environmental biophysics*, 2nd ed. edition. Springer, New York. ISBN 0387949372.

See Also

Other utility functions: [airpressure_from_elev\(\)](#), [azimuth_angle\(\)](#), [day_of_year\(\)](#), [daylength\(\)](#), [solar_noon\(\)](#), [temperature conversions](#), [zenith_angle\(\)](#)

Examples

```
dec_angle(doy = 112)
dec_angle(doy = 360)
```

degree_days	<i>Degree Days</i>
-------------	--------------------

Description

The function calculates degree days using the following approximations: single or double sine wave, single or double triangulation (University of California Integrated Pest Management Program 2016). Double approximation methods assume symmetry, such that a day's thermal minimum is equal to that of the previous day. Double sine wave approximation of degree days from Allen (1976).

Usage

```
degree_days(T_min, T_max, LDT = NA, UDT = NA, method = "single.sine")
```

Arguments

T_min numeric Minimum temperature of the day (C).
T_max numeric Maximum temperature of the day (C).
LDT numeric lower developmental threshold (C).
UDT numeric upper developmental threshold (C).
method character type of method being used. Current choices: "single.sine", "double.sine", "single.triangulation", and "double.triangulation".

Value

numeric degree days (C).

References

Allen JC (1976). "A Modified Sine Wave Method for Calculating Degree Days." *Environmental Entomology*, **5**(3), 388-396. doi: [10.1093/ee/5.3.388](https://doi.org/10.1093/ee/5.3.388).

University of California Integrated Pest Management Program (2016). *Degree Days: Methods*. <http://ipm.ucanr.edu/WEATHER/ddfigindex.html>.

See Also

Other microclimate functions: [air_temp_profile_neutral\(\)](#), [air_temp_profile_segment\(\)](#), [air_temp_profile\(\)](#), [direct_solar_radiation\(\)](#), [diurnal_radiation_variation\(\)](#), [diurnal_temp_variation_sine\(\)](#), [diurnal_temp_variation_sinesqrt\(\)](#), [diurnal_temp_variation_sine\(\)](#), [monthly_solar_radiation\(\)](#), [partition_solar_radiation\(\)](#), [proportion_diffuse_solar_radiation\(\)](#), [solar_radiation\(\)](#), [surface_roughness\(\)](#), [wind_speed_profile_neutral\(\)](#), [wind_speed_profile_segment\(\)](#)

Examples

```
degree_days(T_min = 7,
            T_max = 14,
            LDT = 12,
            UDT = 33,
            method = "single.sine")
degree_days(T_min = 7,
            T_max = 14,
            LDT = 12,
            UDT = 33,
            method = "single.triangulation")
```

direct_solar_radiation

Direct Solar Radiation

Description

The function estimates direct solar radiation (W/m^2) based on latitude, day of year, elevation, and time. The function uses two methods (McCullough and Porter 1971; Campbell and Norman 1998) compiled in Tracy et al. (1983).

Usage

```
direct_solar_radiation(lat, doy, elev, t, t0, method = "Campbell 1977")
```


Arguments

lat	numeric latitude (degrees).
doy	numeric day of year (1-366).
elev	numeric elevation (m).
t	numeric local time (decimal hours).
t0	numeric time of local noon (decimal hours), can be estimated using solar_noon .
method	character method for estimating direct solar radiation, options: "Campbell 1977" (default), "Gates 1962".

Value

numeric direct solar radiation (W/m^2).

References

Campbell GS, Norman JM (1998). *Introduction to environmental biophysics*, 2nd ed. edition. Springer, New York. ISBN 0387949372.

McCullough EC, Porter WP (1971). "Computing Clear Day Solar Radiation Spectra for the Terrestrial Ecological Environment." *Ecology*, **52**(6), 1008-1015. doi: [10.2307/1933806](https://doi.org/10.2307/1933806).

Tracy CR, Hammond KA, Lechleitner RA, II WJS, Thompson DB, Whicker AD, Williamson SC (1983). "Estimating clear-day solar radiation: an evaluation of three models." *Journal of Thermal Biology*, **8**(3), 247-251. doi: [10.1016/03064565\(83\)900037](https://doi.org/10.1016/03064565(83)900037), [https://doi.org/10.1016/0306-4565\(83\)90003-7](https://doi.org/10.1016/0306-4565(83)90003-7).

See Also

Other microclimate functions: [air_temp_profile_neutral\(\)](#), [air_temp_profile_segment\(\)](#), [air_temp_profile\(\)](#), [degree_days\(\)](#), [diurnal_radiation_variation\(\)](#), [diurnal_temp_variation_sineexp\(\)](#), [diurnal_temp_variation_sinesqrt\(\)](#), [diurnal_temp_variation_sine\(\)](#), [monthly_solar_radiation\(\)](#), [partition_solar_radiation\(\)](#), [proportion_diffuse_solar_radiation\(\)](#), [solar_radiation\(\)](#), [surface_roughness\(\)](#), [wind_speed_profile_neutral\(\)](#), [wind_speed_profile_segment\(\)](#)

Examples

```
direct_solar_radiation(lat = 47.61,
                      doy = 112,
                      elev = 1500,
                      t = 9,
                      t0 = 12,
                      method = "Campbell 1977")
```

 diurnal_radiation_variation

Hourly Solar Radiation

Description

The function estimates hourly solar radiation ($Wm^{-2}hr^{-1}$) as a function of daily global solar radiation ($Wm^{-2}d^{-1}$). Based on Tham et al. (2010) and Tham et al. (2011).

Usage

```
diurnal_radiation_variation(doy, solrad, hour, lon, lat)
```

Arguments

doy	numeric the day of year.
solrad	numeric solar radiation ($Wm^{-2}d^{-1}$).
hour	numeric hour (0-24).
lon	numeric longitude (degrees).
lat	numeric latitude (degrees).

Value

numeric hourly solar radiation (Wm^{-2}).

References

Tham Y, Muneer T, Davison B (2010). "Estimation of hourly averaged solar irradiation: evaluation of models." *Building Services Engineering Research Technology*, **31**(1). doi: [10.1177/0143624409350547](https://doi.org/10.1177/0143624409350547).

Tham Y, Muneer T, Davison B (2011). "Prediction of hourly solar radiation on horizontal and inclined surfaces for Muscat/Oman." *The Journal of Engineering Research*, **8**(2), 19-31. doi: [10.24200/tjer.vol8iss2pp1931](https://doi.org/10.24200/tjer.vol8iss2pp1931).

See Also

Other microclimate functions: [air_temp_profile_neutral\(\)](#), [air_temp_profile_segment\(\)](#), [air_temp_profile\(\)](#), [degree_days\(\)](#), [direct_solar_radiation\(\)](#), [diurnal_temp_variation_sineexp\(\)](#), [diurnal_temp_variation_sinesqrt\(\)](#), [diurnal_temp_variation_sine\(\)](#), [monthly_solar_radiation\(\)](#), [partition_solar_radiation\(\)](#), [proportion_diffuse_solar_radiation\(\)](#), [solar_radiation\(\)](#), [surface_roughness\(\)](#), [wind_speed_profile_neutral\(\)](#), [wind_speed_profile_segment\(\)](#)

Examples

```
diurnal_radiation_variation(doy = 112,  
                           solrad = 8000,  
                           hour = 12,  
                           lon = -122.33,  
                           lat = 47.61)
```

diurnal_temp_variation_sine

Hourly Temperature Variation assuming a Sine Interpolation

Description

The function estimates temperature for a specified hour using the sine interpolation in Campbell and Norman (1998).

Usage

```
diurnal_temp_variation_sine(T_max, T_min, t)
```

Arguments

T_max, T_min numeric maximum and minimum daily temperatures (C).
t numeric time for temperature estimate (hour).

Value

numeric temperature (C) at a specified hour.

References

Campbell GS, Norman JM (1998). *Introduction to environmental biophysics*, 2nd ed. edition. Springer, New York. ISBN 0387949372.

See Also

Other microclimate functions: [air_temp_profile_neutral\(\)](#), [air_temp_profile_segment\(\)](#), [air_temp_profile\(\)](#), [degree_days\(\)](#), [direct_solar_radiation\(\)](#), [diurnal_radiation_variation\(\)](#), [diurnal_temp_variation_sineexp\(\)](#), [diurnal_temp_variation_sinesqrt\(\)](#), [monthly_solar_radiation\(\)](#), [partition_solar_radiation\(\)](#), [proportion_diffuse_solar_radiation\(\)](#), [solar_radiation\(\)](#), [surface_roughness\(\)](#), [wind_speed_profile_neutral\(\)](#), [wind_speed_profile_segment\(\)](#)

Examples

```
diurnal_temp_variation_sine(T_max = 30,  
                           T_min = 10,  
                           t = 11)
```

diurnal_temp_variation_sineexp

Hourly Temperature Variation assuming Sine and Exponential Components

Description

The function estimates temperature across hours using a diurnal temperature variation function incorporating sine and exponential components (Parton and Logan 1981).

Usage

```
diurnal_temp_variation_sineexp(
  T_max,
  T_min,
  t,
  t_r,
  t_s,
  alpha = 2.59,
  beta = 1.55,
  gamma = 2.2
)
```

Arguments

T_max, T_min	numeric maximum and minimum daily temperatures (C).
t	numeric time for temperature estimate (hour).
t_r, t_s	numeric times of sunrise and sunset (hour).
alpha	numeric time difference between t_x (time of maximum temperature) and noon (hour).
beta	numeric time difference between t_x and sunrise (hour).
gamma	numeric decay parameter for rate of t change from sunset to t_n (time of minimum temp).

Details

Default alpha, beta, and gamma values are the average of 5 North Carolina sites (Wann et al. 1985).

Other alpha, beta, and gamma parameterizations include values for Denver, Colorado from Parton and Logan (1981):

- 150 cm air temperature: alpha = 1.86, beta = 2.20, gamma = -0.17
- 10 cm air temperature: alpha = 1.52, beta = 2.00, gamma = -0.18
- soil surface temperature: alpha = 0.50, beta = 1.81, gamma = 0.49
- 10cm soil temperature: alpha = 0.45, beta = 2.28, gamma = 1.83

Value

numeric temperature (C) at a specified hour.

References

Parton WJ, Logan JA (1981). "A model for diurnal variation in soil and air temperature." *Agricultural Meteorology*, **23**, 205-216. doi: [10.1016/00021571\(81\)901059](https://doi.org/10.1016/00021571(81)901059), <https://www.sciencedirect.com/science/article/abs/pii/0002157181901059>.

Wann M, Yen D, Gold HJ (1985). "Evaluation and calibration of three models for daily cycle of air temperature." *Agricultural and Forest Meteorology*, **34**, 121-128. <https://agris.fao.org/agris-search/search.do?recordID=NL19850065824>.

See Also

Other microclimate functions: [air_temp_profile_neutral\(\)](#), [air_temp_profile_segment\(\)](#), [air_temp_profile\(\)](#), [degree_days\(\)](#), [direct_solar_radiation\(\)](#), [diurnal_radiation_variation\(\)](#), [diurnal_temp_variation_sinesqrt\(\)](#), [diurnal_temp_variation_sine\(\)](#), [monthly_solar_radiation\(\)](#), [partition_solar_radiation\(\)](#), [proportion_diffuse_solar_radiation\(\)](#), [solar_radiation\(\)](#), [surface_roughness\(\)](#), [wind_speed_profile_neutral\(\)](#), [wind_speed_profile_segment\(\)](#)

Examples

```
diurnal_temp_variation_sineexp(T_max = 30,  
                               T_min = 10,  
                               t      = 11,  
                               t_r   = 6,  
                               t_s   = 18,  
                               alpha = 2.59,  
                               beta  = 1.55,  
                               gamma = 2.2)
```

diurnal_temp_variation_sinesqrt

Hourly Temperature Variation using Sine and Square Root Functions

Description

The function estimates temperature for a specified hour using sine and square root functions (Cesaraccio et al. 2001).

Usage

```
diurnal_temp_variation_sinesqrt(t, t_r, t_s, T_max, T_min, T_minp)
```

Arguments

t	numeric hour or hours for temperature estimate.
t_r, t_s	numeric sunrise and sunset hours (0-23).
T_max, T_min	numeric maximum and minimum temperatures of current day (C).
T_minp	numeric minimum temperature of following day (C).

Value

numeric temperature (C) at a specified hour.

References

Cesaraccio C, Spano D, Duce P, Snyder RL (2001). “An improved model for determining degree-day values from daily temperature data.” *International Journal of Biometeorology*, **45**, 161-169. doi: [10.1007/s004840100104](https://doi.org/10.1007/s004840100104), https://www.researchgate.net/publication/11589157_An_improved_model_for_determining_degree-day_values_from_daily_temperature_data.

See Also

Other microclimate functions: [air_temp_profile_neutral\(\)](#), [air_temp_profile_segment\(\)](#), [air_temp_profile\(\)](#), [degree_days\(\)](#), [direct_solar_radiation\(\)](#), [diurnal_radiation_variation\(\)](#), [diurnal_temp_variation_sineexp\(\)](#), [diurnal_temp_variation_sine\(\)](#), [monthly_solar_radiation\(\)](#), [partition_solar_radiation\(\)](#), [proportion_diffuse_solar_radiation\(\)](#), [solar_radiation\(\)](#), [surface_roughness\(\)](#), [wind_speed_profile_neutral\(\)](#), [wind_speed_profile_segment\(\)](#)

Examples

```
diurnal_temp_variation_sinesqrt(t      = 8,
                               t_r    = 6,
                               t_s    = 18,
                               T_max  = 30,
                               T_min  = 10,
                               T_minp = 12)
```

Description

The function calculates several properties of dry air and related characteristics shown as output variables below. The program is based on equations from List (1971) and code implementation from NicheMapR (Kearney and Porter 2017; Kearney and Porter 2020).

The user must supply values for the input variables db, bp, and alt. If alt is known (-1000 < alt < 20000) but not BP, then set bp = 0.

Usage

```
DRYAIR(db, bp = 0, alt = 0)
```

Arguments

db	numeric dry bulb temperature (C).
bp	numeric barometric pressure (Pa).
alt	numeric altitude (m).

Value

Named list with elements

- patmos: numeric standard atmospheric pressure (Pa)
- density: numeric density (kgm^{-3})
- visdyn: numeric dynamic viscosity ($kgm^{-1}s^{-1}$)
- viskin: numeric kinematic viscosity (m^2s^{-1})
- difvpr: numeric diffusivity of water vapor in air (m^2s^{-1})
- thcond: numeric thermal conductivity ($WK^{-1}m^{-1}$)
- htovpr: numeric latent heat of vaporization of water (Jkg^{-1})
- tcoeff: numeric temperature coefficient of volume expansion (K^{-1})
- ggroup: numeric group of variables in Grashof number ($m^{-3}K^{-1}$)
- bbemit: numeric black body emittance (Wm^{-2})
- emtmax: numeric wave length of maximum emittance (m)

References

Kearney MR, Porter WP (2017). “NicheMapR - an R package for biophysical modelling: the microclimate model.” *Ecography*, **40**, 664-674. doi: [10.1111/ecog.02360](https://doi.org/10.1111/ecog.02360).

Kearney MR, Porter WP (2020). “NicheMapR - an R package for biophysical modelling: the ecotherm and Dynamic Energy Budget models.” *Ecography*, **43**(1), 85-96. doi: [10.1111/ecog.04680](https://doi.org/10.1111/ecog.04680).

List RJ (1971). “Smithsonian Meteorological Tables.” *Smithsonian Miscellaneous Collections*, **114**(1), 1-527. <https://repository.si.edu/handle/10088/23746>.

Examples

```
DRYAIR(db = 30,
       bp = 100*1000,
       alt = 0)
```

external_resistance_to_water_vapor_transfer

External Resistance to Water Vapor Transfer

Description

The function estimate external resistance to water vapor transfer using the Lewis rule relating heat and mass transport (Spotila et al. 1992)

Usage

```
external_resistance_to_water_vapor_transfer(H, rhocp = 12000)
```

Arguments

H	numeric heat transfer (convection) coefficient ($Wm^{-2}C^{-1}$).
rhocp	numeric aggregate parameter ($Jm^{-3}C^{-1}$) that is the product of the density of air (kgm^{-3}) and the specific heat of air at constant pressure ($Jkg^{-1}C^{-1}$). Default of 12000 ($Jm^{-3}C^{-1}$) commonly assumed.

Value

numeric external resistance to water vapor transfer (sm^{-1}).

References

Spotila JR, Feder ME, Burggren WW (1992). "Biophysics of Heat and Mass Transfer." *Environmental Physiology of the Amphibians*. <https://press.uchicago.edu/ucp/books/book/chicago/E/bo3636401.html>.

See Also

Other biophysical models: [Grashof_number_Gates\(\)](#), [Grashof_number\(\)](#), [Nusselt_from_Grashof\(\)](#), [Nusselt_from_Reynolds\(\)](#), [Nusselt_number\(\)](#), [Prandtl_number\(\)](#), [Qconduction_animal\(\)](#), [Qconduction_substrate\(\)](#), [Qconvection\(\)](#), [Qemitted_thermal_radiation\(\)](#), [Qevaporation\(\)](#), [Qmetabolism_from_mass_temp\(\)](#), [Qmetabolism_from_mass\(\)](#), [Qnet_Gates\(\)](#), [Qradiation_absorbed\(\)](#), [Qthermal_radiation_absorbed\(\)](#), [Reynolds_number\(\)](#), [Tb_CampbellNorman\(\)](#), [Tb_Gates2\(\)](#), [Tb_Gates\(\)](#), [Tb_butterfly\(\)](#), [Tb_grasshopper\(\)](#), [Tb_limpetBH\(\)](#), [Tb_limpet\(\)](#), [Tb_lizard_Fei\(\)](#), [Tb_lizard\(\)](#), [Tb_mussel\(\)](#), [Tb_salamander_humid\(\)](#), [Tb_snail\(\)](#), [Tbed_mussel\(\)](#), [Tsoil\(\)](#), [actual_vapor_pressure\(\)](#), [boundary_layer_resistance\(\)](#), [free_or_forced_convection\(\)](#), [heat_transfer_coefficient_approximation\(\)](#), [heat_transfer_coefficient_simple\(\)](#), [heat_transfer_coefficient_saturation_vapor_pressure\(\)](#), [saturation_vapor_pressure\(\)](#), [saturation_water_vapor_pressure\(\)](#)

Examples

```
external_resistance_to_water_vapor_transfer(H = 20)
```

 free_or_forced_convection

Determine if Convection is Free or Forced

Description

The function compares the Grashof and Reynolds numbers to determine whether convection is free or forced (Gates 1980).

Usage

```
free_or_forced_convection(Gr, Re)
```

Arguments

Gr numeric Grashof Number (dimensionless).
 Re numeric Reynolds Number (dimensionless).

Value

character "free", "forced", or "intermediate".

References

Gates DM (1980). *Biophysical Ecology*. Springer-Verlag, New York, NY, USA.

See Also

Other biophysical models: [Grashof_number_Gates\(\)](#), [Grashof_number\(\)](#), [Nusselt_from_Grashof\(\)](#), [Nusselt_from_Reynolds\(\)](#), [Nusselt_number\(\)](#), [Prandtl_number\(\)](#), [Qconduction_animal\(\)](#), [Qconduction_substrate\(\)](#), [Qconvection\(\)](#), [Qemitted_thermal_radiation\(\)](#), [Qevaporation\(\)](#), [Qmetabolism_from_mass_temp\(\)](#), [Qmetabolism_from_mass\(\)](#), [Qnet_Gates\(\)](#), [Qradiation_absorbed\(\)](#), [Qthermal_radiation_absorbed\(\)](#), [Reynolds_number\(\)](#), [Tb_CampbellNorman\(\)](#), [Tb_Gates2\(\)](#), [Tb_Gates\(\)](#), [Tb_butterfly\(\)](#), [Tb_grasshopper\(\)](#), [Tb_limpetBH\(\)](#), [Tb_limpet\(\)](#), [Tb_lizard_Fei\(\)](#), [Tb_lizard\(\)](#), [Tb_mussel\(\)](#), [Tb_salamander_humid\(\)](#), [Tb_snail\(\)](#), [Tbed_mussel\(\)](#), [Tsoil\(\)](#), [actual_vapor_pressure\(\)](#), [boundary_layer_resistance\(\)](#), [external_resistance_to_water_vapor_transfer\(\)](#), [heat_transfer_coefficient_approximation\(\)](#), [heat_transfer_coefficient_simple\(\)](#), [heat_transfer_coefficient_saturated_vapor_pressure\(\)](#), [saturation_vapor_pressure\(\)](#), [saturation_water_vapor_pressure\(\)](#)

Examples

```
free_or_forced_convection(Gr = 100,  
                          Re = 5)
```

Grashof_number	<i>Grashof Number</i>
----------------	-----------------------

Description

The function estimates the Grashof Number, which describes the ability of a parcel of fluid warmer or colder than the surrounding fluid to rise against or fall with the attractive force of gravity. The Grashof Number is estimated as the ratio of a buoyant force times an inertial force to the square of a viscous force (Campbell and Norman 1998).

Usage

```
Grashof_number(T_a, T_g, D, nu)
```

Arguments

T_a	numeric Air temperature (C).
T_g	numeric ground (surface) temperature (C).
D	numeric characteristic dimension (e.g., body diameter) (meters).
nu	numeric the kinematic viscosity, ratio of dynamic viscosity to density of the fluid (m^2s^{-1}); can calculate from DRYAIR or WETAIR .

Value

numeric Grashof number.

References

Campbell GS, Norman JM (1998). *Introduction to environmental biophysics*, 2nd ed. edition. Springer, New York. ISBN 0387949372.

See Also

Other biophysical models: [Grashof_number_Gates\(\)](#), [Nusselt_from_Grashof\(\)](#), [Nusselt_from_Reynolds\(\)](#), [Nusselt_number\(\)](#), [Prandtl_number\(\)](#), [Qconduction_animal\(\)](#), [Qconduction_substrate\(\)](#), [Qconvection\(\)](#), [Qemitted_thermal_radiation\(\)](#), [Qevaporation\(\)](#), [Qmetabolism_from_mass_temp\(\)](#), [Qmetabolism_from_mass\(\)](#), [Qnet_Gates\(\)](#), [Qradiation_absorbed\(\)](#), [Qthermal_radiation_absorbed\(\)](#), [Reynolds_number\(\)](#), [Tb_CampbellNorman\(\)](#), [Tb_Gates2\(\)](#), [Tb_Gates\(\)](#), [Tb_butterfly\(\)](#), [Tb_grasshopper\(\)](#), [Tb_limpetBH\(\)](#), [Tb_limpet\(\)](#), [Tb_lizard_Fei\(\)](#), [Tb_lizard\(\)](#), [Tb_mussel\(\)](#), [Tb_salamander_humid\(\)](#), [Tb_snail\(\)](#), [Tbed_mussel\(\)](#), [Tsoil\(\)](#), [actual_vapor_pressure\(\)](#), [boundary_layer_resistance\(\)](#), [external_resistance_to_water_vapor_transfer\(\)](#), [free_or_forced_convection\(\)](#), [heat_transfer_coefficient](#), [heat_transfer_coefficient_simple\(\)](#), [heat_transfer_coefficient\(\)](#), [saturation_vapor_pressure\(\)](#), [saturation_water_vapor_pressure\(\)](#)

Examples

```
Grashof_number(T_a = 30,
               T_g = 35,
               D = 0.001,
               nu = 1.2)
```

Grashof_number_Gates *Grashof Number as in Gates (1980)*

Description

The function estimates the Grashof Number, which describes the ability of a parcel of fluid warmer or colder than the surrounding fluid to rise against or fall with the attractive force of gravity (Gates 1980). The Grashof Number is estimated as the ratio of a buoyant force times an inertial force to the square of a viscous force.

Usage

```
Grashof_number_Gates(T_a, T_g, beta, D, nu)
```

Arguments

T_a	numeric Air temperature (C).
T_g	numeric Ground (surface) temperature (C).
beta	numeric coefficient of volumetric thermal expansion, $\beta = 3.67 \times 10^{-3}C^{-1}$ in air and $41.9 \times 10^{-4}C^{-1}$ in water.
D	numeric is characteristic dimension (e.g., body diameter) (m)
nu	numeric is the kinematic viscosity, the ratio of dynamic viscosity to density of the fluid ($m^2 s^{-1}$); can calculate from DRYAIR or WETAIR .

Value

numeric Grashof number.

References

Gates DM (1980). *Biophysical Ecology*. Springer-Verlag, New York, NY, USA.

See Also

Other biophysical models: [Grashof_number\(\)](#), [Nusselt_from_Grashof\(\)](#), [Nusselt_from_Reynolds\(\)](#), [Nusselt_number\(\)](#), [Prandtl_number\(\)](#), [Qconduction_animal\(\)](#), [Qconduction_substrate\(\)](#), [Qconvection\(\)](#), [Qemitted_thermal_radiation\(\)](#), [Qevaporation\(\)](#), [Qmetabolism_from_mass_temp\(\)](#), [Qmetabolism_from_mass\(\)](#), [Qnet_Gates\(\)](#), [Qradiation_absorbed\(\)](#), [Qthermal_radiation_absorbed\(\)](#), [Reynolds_number\(\)](#), [Tb_CampbellNorman\(\)](#), [Tb_Gates2\(\)](#), [Tb_Gates\(\)](#), [Tb_butterfly\(\)](#), [Tb_grasshopper\(\)](#),

Tb_limpetBH(), Tb_limpet(), Tb_lizard_Fei(), Tb_lizard(), Tb_mussel(), Tb_salamander_humid(), Tb_snail(), Tbed_mussel(), Tsoil(), actual_vapor_pressure(), boundary_layer_resistance(), external_resistance_to_water_vapor_transfer(), free_or_forced_convection(), heat_transfer_coefficient, heat_transfer_coefficient_simple(), heat_transfer_coefficient(), saturation_vapor_pressure(), saturation_water_vapor_pressure()

Examples

```
Grashof_number_Gates(T_a = 30,
                    T_g = 35,
                    beta = 0.00367,
                    D = 0.001,
                    nu = 1.2)
```

heat_transfer_coefficient

Estimate the Heat Transfer Coefficient Empirically

Description

The function estimates the heat transfer coefficient for various taxa based on empirical measurements (Mitchell 1976).

Usage

```
heat_transfer_coefficient(V, D, K, nu, taxon = "cylinder")
```

Arguments

V	numeric air velocity ($m s^{-1}$).
D	numeric characteristic dimension (e.g., diameter or snout-vent length) (meters).
K	numeric thermal conductivity of air ($W K^{-1} m^{-1}$), can calculate using DRYAIR or WETAIR .
nu	numeric kinematic viscosity of air ($m^2 s^{-1}$), can calculate using DRYAIR or WETAIR .
taxon	character which class of organism, current choices: "sphere", "cylinder", "frog", "lizard_surface", "lizard_elevated", "flyinginsect", "spider". "cylinder" assumes $40 < Re < 4000$. "lizard_surface" and "lizard_elevated" assume the lizard is prostrate on and elevated above the surface, respectively. The values are the average for lizards parallel and perpendicular to the air flow.

Value

numeric heat transfer coefficient, H_L ($W K^{-1} m^{-2}$).

References

Mitchell JW (1976). "Heat transfer from spheres and other animal forms." *Biophysical Journal*, **16**(6), 561-569. ISSN 0006-3495, doi: [10.1016/S00063495\(76\)857116](https://doi.org/10.1016/S00063495(76)857116), <https://www.sciencedirect.com/science/article/pii/S0006349576857116>.

See Also

Other biophysical models: [Grashof_number_Gates\(\)](#), [Grashof_number\(\)](#), [Nusselt_from_Grashof\(\)](#), [Nusselt_from_Reynolds\(\)](#), [Nusselt_number\(\)](#), [Prandtl_number\(\)](#), [Qconduction_animal\(\)](#), [Qconduction_substrate\(\)](#), [Qconvection\(\)](#), [Qemitted_thermal_radiation\(\)](#), [Qevaporation\(\)](#), [Qmetabolism_from_mass_temp\(\)](#), [Qmetabolism_from_mass\(\)](#), [Qnet_Gates\(\)](#), [Qradiation_absorbed\(\)](#), [Qthermal_radiation_absorbed\(\)](#), [Reynolds_number\(\)](#), [Tb_CampbellNorman\(\)](#), [Tb_Gates2\(\)](#), [Tb_Gates\(\)](#), [Tb_butterfly\(\)](#), [Tb_grasshopper\(\)](#), [Tb_limpetBH\(\)](#), [Tb_limpet\(\)](#), [Tb_lizard_Fei\(\)](#), [Tb_lizard\(\)](#), [Tb_mussel\(\)](#), [Tb_salamander_humid\(\)](#), [Tb_snail\(\)](#), [Tbed_mussel\(\)](#), [Tsoil\(\)](#), [actual_vapor_pressure\(\)](#), [boundary_layer_resistance\(\)](#), [external_resistance_to_water_vapor_transfer\(\)](#), [free_or_forced_convection\(\)](#), [heat_transfer_coefficient_approximation\(\)](#), [heat_transfer_coefficient_simulation\(\)](#), [saturation_vapor_pressure\(\)](#), [saturation_water_vapor_pressure\(\)](#)

Examples

```
heat_transfer_coefficient(V = 0.5,
                          D = 0.05,
                          K = 25.7 * 10-3,
                          nu = 15.3 * 10-6,
                          taxon = "cylinder")
```

heat_transfer_coefficient_approximation

Estimate the Heat Transfer Coefficient Using a Spherical Approximation

Description

The function estimates the heat transfer coefficient for various taxa. Approximates forced convective heat transfer for animal shapes using the convective relationship for a sphere (Mitchell 1976).

Usage

```
heat_transfer_coefficient_approximation(V, D, K, nu, taxon = "sphere")
```

Arguments

V numeric air velocity (ms^{-1}).
 D numeric characteristic dimension (e.g., diameter or snout-vent length) (meters).
 K numeric thermal conductivity of air ($Wm^{-2}K^{-1}$), can calculate using [DRYAIR](#) or [WETAIR](#).

nu	numeric kinematic Viscosity of air (m^2s^{-1}), can calculate using DRYAIR or WETAIR .
taxon	character of which class of organism, current choices: "sphere", "frog", "lizard", "flyinginsect", "spider".

Value

numeric heat transfer coefficient, H_L ($Wm^{-2}K^{-1}$).

References

Mitchell JW (1976). "Heat transfer from spheres and other animal forms." *Biophysical Journal*, **16**(6), 561-569. ISSN 0006-3495, doi: [10.1016/S00063495\(76\)857116](https://doi.org/10.1016/S00063495(76)857116), <https://www.sciencedirect.com/science/article/pii/S0006349576857116>.

See Also

Other biophysical models: [Grashof_number_Gates\(\)](#), [Grashof_number\(\)](#), [Nusselt_from_Grashof\(\)](#), [Nusselt_from_Reynolds\(\)](#), [Nusselt_number\(\)](#), [Prandtl_number\(\)](#), [Qconduction_animal\(\)](#), [Qconduction_substrate\(\)](#), [Qconvection\(\)](#), [Qemitted_thermal_radiation\(\)](#), [Qevaporation\(\)](#), [Qmetabolism_from_mass_temp\(\)](#), [Qmetabolism_from_mass\(\)](#), [Qnet_Gates\(\)](#), [Qradiation_absorbed\(\)](#), [Qthermal_radiation_absorbed\(\)](#), [Reynolds_number\(\)](#), [Tb_CampbellNorman\(\)](#), [Tb_Gates2\(\)](#), [Tb_Gates\(\)](#), [Tb_butterfly\(\)](#), [Tb_grasshopper\(\)](#), [Tb_limpetBH\(\)](#), [Tb_limpet\(\)](#), [Tb_lizard_Fei\(\)](#), [Tb_lizard\(\)](#), [Tb_mussel\(\)](#), [Tb_salamander_humid\(\)](#), [Tb_snail\(\)](#), [Tbed_mussel\(\)](#), [Tsoil\(\)](#), [actual_vapor_pressure\(\)](#), [boundary_layer_resistance\(\)](#), [external_resistance_to_water_vapor_transfer\(\)](#), [free_or_forced_convection\(\)](#), [heat_transfer_coefficient_simple\(\)](#), [heat_transfer_coefficient\(\)](#), [saturation_vapor_pressure\(\)](#), [saturation_water_vapor_pressure\(\)](#)

Examples

```
heat_transfer_coefficient_approximation(V = 3,
                                       D = 0.05,
                                       K = 25.7 * 10^(-3),
                                       nu = 15.3 * 10^(-6),
                                       taxon = "sphere")
```

heat_transfer_coefficient_simple

Estimate the Heat Transfer Coefficient using Simple Relationships

Description

The function estimates the heat transfer coefficient (Mitchell 1976) using either the relationship in Spotila et al. (1992) or that in Gates (1980).

Usage

```
heat_transfer_coefficient_simple(V, D, type)
```

Arguments

V	numeric air velocity ($m s^{-1}$).
D	numeric characteristic dimension (e.g., diameter or snout-vent length) (m).
type	character choice between "Spotila" and "Gates" for equation to use.

Value

numeric heat transfer coefficient, H_L ($W m^{-2} K^{-1}$).

References

Gates DM (1980). *Biophysical Ecology*. Springer-Verlag, New York, NY, USA.

Mitchell JW (1976). "Heat transfer from spheres and other animal forms." *Biophysical Journal*, **16**(6), 561-569. ISSN 0006-3495, doi: [10.1016/S00063495\(76\)857116](https://doi.org/10.1016/S00063495(76)857116), <https://www.sciencedirect.com/science/article/pii/S0006349576857116>.

Spotila JR, Feder ME, Burggren WW (1992). "Biophysics of Heat and Mass Transfer." *Environmental Physiology of the Amphibians*. <https://press.uchicago.edu/ucp/books/book/chicago/E/bo3636401.html>.

See Also

Other biophysical models: [Grashof_number_Gates\(\)](#), [Grashof_number\(\)](#), [Nusselt_from_Grashof\(\)](#), [Nusselt_from_Reynolds\(\)](#), [Nusselt_number\(\)](#), [Prandtl_number\(\)](#), [Qconduction_animal\(\)](#), [Qconduction_substrate\(\)](#), [Qconvection\(\)](#), [Qemitted_thermal_radiation\(\)](#), [Qevaporation\(\)](#), [Qmetabolism_from_mass_temp\(\)](#), [Qmetabolism_from_mass\(\)](#), [Qnet_Gates\(\)](#), [Qradiation_absorbed\(\)](#), [Qthermal_radiation_absorbed\(\)](#), [Reynolds_number\(\)](#), [Tb_CampbellNorman\(\)](#), [Tb_Gates2\(\)](#), [Tb_Gates\(\)](#), [Tb_butterfly\(\)](#), [Tb_grasshopper\(\)](#), [Tb_limpetBH\(\)](#), [Tb_limpet\(\)](#), [Tb_lizard_Fei\(\)](#), [Tb_lizard\(\)](#), [Tb_mussel\(\)](#), [Tb_salamander_humid\(\)](#), [Tb_snail\(\)](#), [Tbed_mussel\(\)](#), [Tsoil\(\)](#), [actual_vapor_pressure\(\)](#), [boundary_layer_resistance\(\)](#), [external_resistance_to_water_vapor_transfer\(\)](#), [free_or_forced_convection\(\)](#), [heat_transfer_coefficient_approximation\(\)](#), [heat_transfer_coefficient\(\)](#), [saturation_vapor_pressure\(\)](#), [saturation_water_vapor_pressure\(\)](#)

Examples

```
heat_transfer_coefficient_simple(V = 0.5,
                                D = 0.05,
                                type = "Gates")
```

mass_from_length	<i>Organism Mass from Length</i>
------------------	----------------------------------

Description

The function estimates mass (g) from length (m) for a variety of taxa.

Usage

```
mass_from_length(l, taxon)
```

Arguments

l	numeric vector of length (m). Can be 1 or more values. Snout-vent length is used for amphibians and reptiles, except turtles where length is carapace length.
taxon	character taxon of organism, current choices: "insect", "lizard", "salamander", "frog", "snake", "turtle".

Details

All models follow ($m = a * l^b$) with mass in grams and length in meters.

- Lizards: Meiri (2010):

$$a = 16368.17$$

$$b = 3.022$$

- Salamanders: Pough (1980):

$$a = 13654.4$$

$$b = 2.94$$

- Frogs: Pough (1980):

$$a = 181197.1$$

$$b = 3.24$$

- Snakes: Pough (1980):

$$a = 723.6756$$

$$b = 3.02$$

- Turtles: Pough (1980):

$$a = 93554.48$$

$$b = 2.69$$

- Insects: Sample et al. (1993):

$$a = 806.0827$$

$$b = 2.494$$

Value

numeric mass (g).

References

Meiri S (2010). “Length - weight allometries in lizards.” *Journal of Zoology*, **281**(3), 218-226. doi: [10.1111/j.14697998.2010.00696.x](https://doi.org/10.1111/j.14697998.2010.00696.x).

Pough FH (1980). “The Advantages of Ectothermy for Tetrapods.” *The American Naturalist*, **115**(1), 92–112. ISSN 00030147, 15375323.

Sample BE, Cooper RJ, Greer RD, Whitmore RC (1993). “Estimation of Insect Biomass by Length and Width.” *The American Midland Naturalist*, **129**(2), 234–240. ISSN 00030031, 19384238, doi: [10.2307/2426503](https://doi.org/10.2307/2426503).

See Also

Other allometric functions: [proportion_silhouette_area_shapes\(\)](#), [proportion_silhouette_area\(\)](#), [surface_area_from_length\(\)](#), [surface_area_from_mass\(\)](#), [surface_area_from_volume\(\)](#), [volume_from_length\(\)](#)

Examples

```
mass_from_length(l = 0.04,
                 taxon = "insect")
mass_from_length(l = 0.04,
                 taxon = "lizard")
mass_from_length(l = 0.04,
                 taxon = "salamander")
mass_from_length(l = 0.04,
                 taxon = "frog")
mass_from_length(l = 0.04,
                 taxon = "snake")
mass_from_length(l = 0.04,
                 taxon = "turtle")
```

monthly_solar_radiation

Average Monthly Solar Radiation

Description

The function estimates average monthly solar radiation ($Wm^{-2}d^{-1}$) using basic topographic and climatic information as input. Cloudiness is stochastically modeled, so output will vary between functional calls. Based on Nikolov and Zeller (1992).

Usage

```
monthly_solar_radiation(lat, lon, doy, elev, T_a, Hr, P)
```

Arguments

lat	numeric latitude (degrees).
lon	numeric longitude (degrees).
doy	numeric day of year (1-366).
elev	numeric elevation (meters).
T_a	numeric mean monthly air temperature (C).
Hr	numeric mean month relative humidity (percentage).
P	numeric total monthly precipitation (mm).

Value

numeric average monthly solar radiation (Wm^{-2}).

References

Nikolov NT, Zeller K (1992). "A solar radiation algorithm for ecosystem dynamic models." *Ecological Modelling*, **61**(3-4), 149-168. doi: [10.24200/tjer.vol8iss2pp1931](https://doi.org/10.24200/tjer.vol8iss2pp1931), https://www.researchgate.net/publication/253240330_Prediction_of_Hourly_Solar_Radiation_on_Horizontal_and_Inclined_Surfaces_for_MuscatOman.

See Also

Other microclimate functions: [air_temp_profile_neutral\(\)](#), [air_temp_profile_segment\(\)](#), [air_temp_profile\(\)](#), [degree_days\(\)](#), [direct_solar_radiation\(\)](#), [diurnal_radiation_variation\(\)](#), [diurnal_temp_variation_sineexp\(\)](#), [diurnal_temp_variation_sinesqrt\(\)](#), [diurnal_temp_variation_sine\(\)](#), [partition_solar_radiation\(\)](#), [proportion_diffuse_solar_radiation\(\)](#), [solar_radiation\(\)](#), [surface_roughness\(\)](#), [wind_speed_profile_neutral\(\)](#), [wind_speed_profile_segment\(\)](#)

Examples

```
monthly_solar_radiation(lat = 47.61,  
                        lon = -122.33,  
                        doy = 112,  
                        elev = 1500,  
                        T_a = 15,  
                        Hr = 50,  
                        P = 50)
```

Nusselt_from_Grashof *Nusselt Number from the Grashof Number*

Description

The function estimates the Nusselt number from the Grashof Number (Gates 1980).

Usage

```
Nusselt_from_Grashof(Gr)
```

Arguments

Gr numeric Grashof Number (dimensionless).

Value

numeric Nusselt number (dimensionless).

References

Gates DM (1980). *Biophysical Ecology*. Springer-Verlag, New York, NY, USA.

See Also

Other biophysical models: [Grashof_number_Gates\(\)](#), [Grashof_number\(\)](#), [Nusselt_from_Reynolds\(\)](#), [Nusselt_number\(\)](#), [Prandtl_number\(\)](#), [Qconduction_animal\(\)](#), [Qconduction_substrate\(\)](#), [Qconvection\(\)](#), [Qemitted_thermal_radiation\(\)](#), [Qevaporation\(\)](#), [Qmetabolism_from_mass_temp\(\)](#), [Qmetabolism_from_mass\(\)](#), [Qnet_Gates\(\)](#), [Qradiation_absorbed\(\)](#), [Qthermal_radiation_absorbed\(\)](#), [Reynolds_number\(\)](#), [Tb_CampbellNorman\(\)](#), [Tb_Gates2\(\)](#), [Tb_Gates\(\)](#), [Tb_butterfly\(\)](#), [Tb_grasshopper\(\)](#), [Tb_limpetBH\(\)](#), [Tb_limpet\(\)](#), [Tb_lizard_Fei\(\)](#), [Tb_lizard\(\)](#), [Tb_mussel\(\)](#), [Tb_salamander_humid\(\)](#), [Tb_snail\(\)](#), [Tbed_mussel\(\)](#), [Tsoil\(\)](#), [actual_vapor_pressure\(\)](#), [boundary_layer_resistance\(\)](#), [external_resistance_to_water_vapor_transfer\(\)](#), [free_or_forced_convection\(\)](#), [heat_transfer_coefficient](#), [heat_transfer_coefficient_simple\(\)](#), [heat_transfer_coefficient\(\)](#), [saturation_vapor_pressure\(\)](#), [saturation_water_vapor_pressure\(\)](#)

Examples

```
Nusselt_from_Grashof(Gr = 5)
```

Nusselt_from_Reynolds *Nusselt Number from the Reynolds Number*

Description

The function estimates the Nusselt number from the Reynolds number for various taxa using Mitchell (1976) (Table 1: Convective Heat Transfer Relations for Animal Shapes).

Usage

```
Nusselt_from_Reynolds(Re, taxon = "cylinder")
```

Arguments

Re	numeric Reynolds Number (dimensionless).
taxon	character which class of organism. Current choices: "sphere", "cylinder", "frog", "lizard_traverse_to_air_flow", "lizard_parallel_to_air_flow", "lizard_surface", "lizard_elevated", "flyinginsect", "spider".

Value

numeric Nusselt number (dimensionless).

References

Mitchell JW (1976). "Heat transfer from spheres and other animal forms." *Biophysical Journal*, **16**(6), 561-569. ISSN 0006-3495, doi: [10.1016/S00063495\(76\)857116](https://doi.org/10.1016/S00063495(76)857116), <https://www.sciencedirect.com/science/article/pii/S0006349576857116>.

See Also

Other biophysical models: `Grashof_number_Gates()`, `Grashof_number()`, `Nusselt_from_Grashof()`, `Nusselt_number()`, `Prandtl_number()`, `Qconduction_animal()`, `Qconduction_substrate()`, `Qconvection()`, `Qemitted_thermal_radiation()`, `Qevaporation()`, `Qmetabolism_from_mass_temp()`, `Qmetabolism_from_mass()`, `Qnet_Gates()`, `Qradiation_absorbed()`, `Qthermal_radiation_absorbed()`, `Reynolds_number()`, `Tb_CampbellNorman()`, `Tb_Gates2()`, `Tb_Gates()`, `Tb_butterfly()`, `Tb_grasshopper()`, `Tb_limpetBH()`, `Tb_limpet()`, `Tb_lizard_Fei()`, `Tb_lizard()`, `Tb_mussel()`, `Tb_salamander_humid()`, `Tb_snail()`, `Tbed_mussel()`, `Tsoil()`, `actual_vapor_pressure()`, `boundary_layer_resistance()`, `external_resistance_to_water_vapor_transfer()`, `free_or_forced_convection()`, `heat_transfer_coefficient`, `heat_transfer_coefficient_simple()`, `heat_transfer_coefficient()`, `saturation_vapor_pressure()`, `saturation_water_vapor_pressure()`

Examples

```
Nusselt_from_Reynolds(Re = 5,
                      taxon = "cylinder")
```

Nusselt_number	<i>Nusselt Number</i>
----------------	-----------------------

Description

The function estimates the Nusselt Number, which describes dimensionless conductance (Gates 1980).

Usage

```
Nusselt_number(H_L, D, K)
```

Arguments

H_L	numeric convective heat transfer coefficient ($Wm^{-2}K^{-1}$).
D	numeric characteristic dimension (e.g., body diameter) (m).
K	numeric thermal conductivity ($WK^{-1}m^{-1}$).

Value

numeric Nusselt number.

References

Gates DM (1980). *Biophysical Ecology*. Springer-Verlag, New York, NY, USA.

See Also

Other biophysical models: [Grashof_number_Gates\(\)](#), [Grashof_number\(\)](#), [Nusselt_from_Grashof\(\)](#), [Nusselt_from_Reynolds\(\)](#), [Prandtl_number\(\)](#), [Qconduction_animal\(\)](#), [Qconduction_substrate\(\)](#), [Qconvection\(\)](#), [Qemitted_thermal_radiation\(\)](#), [Qevaporation\(\)](#), [Qmetabolism_from_mass_temp\(\)](#), [Qmetabolism_from_mass\(\)](#), [Qnet_Gates\(\)](#), [Qradiation_absorbed\(\)](#), [Qthermal_radiation_absorbed\(\)](#), [Reynolds_number\(\)](#), [Tb_CampbellNorman\(\)](#), [Tb_Gates2\(\)](#), [Tb_Gates\(\)](#), [Tb_butterfly\(\)](#), [Tb_grasshopper\(\)](#), [Tb_limpetBH\(\)](#), [Tb_limpet\(\)](#), [Tb_lizard_Fei\(\)](#), [Tb_lizard\(\)](#), [Tb_mussel\(\)](#), [Tb_salamander_humid\(\)](#), [Tb_snail\(\)](#), [Tbed_mussel\(\)](#), [Tsoil\(\)](#), [actual_vapor_pressure\(\)](#), [boundary_layer_resistance\(\)](#), [external_resistance_to_water_vapor_transfer\(\)](#), [free_or_forced_convection\(\)](#), [heat_transfer_coefficient.](#) [heat_transfer_coefficient_simple\(\)](#), [heat_transfer_coefficient\(\)](#), [saturation_vapor_pressure\(\)](#), [saturation_water_vapor_pressure\(\)](#)

Examples

```
Nusselt_number(H_L = 20,
               D = 0.01,
               K = 0.5)
```

 partition_solar_radiation

Diffuse Fraction for Partitioning Solar Radiation

Description

The function partitions solar radiation (Wm^{-2}) into direct and diffuse components by estimating the diffuse fraction (`k_d`). The function uses the models presented in Wong and Chow (2001).

Usage

```
partition_solar_radiation(method, kt, lat = NA, sol.elev = NA)
```

Arguments

<code>method</code>	character method to use for estimating the diffuse fraction, currently available: "Liu_Jordan", "Orgill_Hollands", "Erbs", "Olyphant", "Spencer", "Reindl-1", "Reindl-2", "Lam_Li".
<code>kt</code>	numeric the clearness index (dimensionless), which is the ratio of the global solar radiation measured at the surface to the total solar radiation at the top of the atmosphere. (0-1)
<code>lat</code>	numeric latitude (degrees). Needed only if method is "Spencer".
<code>sol.elev</code>	numeric the solar elevation angles (degrees). Needed only if method is "Reindl-2".

Value

numeric diffuse fraction.

References

Wong LT, Chow WK (2001). "Solar radiation model." *Applied Energy*, **69**(3), 191-224. ISSN 0306-2619, doi: [10.1016/S03062619\(01\)000125](https://doi.org/10.1016/S03062619(01)000125), <https://www.sciencedirect.com/science/article/pii/S0306261901000125>.

See Also

Other microclimate functions: [air_temp_profile_neutral\(\)](#), [air_temp_profile_segment\(\)](#), [air_temp_profile\(\)](#), [degree_days\(\)](#), [direct_solar_radiation\(\)](#), [diurnal_radiation_variation\(\)](#), [diurnal_temp_variation_sineexp\(\)](#), [diurnal_temp_variation_sinesqrt\(\)](#), [diurnal_temp_variation_sine\(\)](#), [monthly_solar_radiation\(\)](#), [proportion_diffuse_solar_radiation\(\)](#), [solar_radiation\(\)](#), [surface_roughness\(\)](#), [wind_speed_profile_neutral\(\)](#), [wind_speed_profile_segment\(\)](#)

Examples

```
partition_solar_radiation(method = "Erbs",
                          kt     = 0.5,
                          lat    = 40,
                          sol.elev = 60)
```

Prandtl_number	<i>Prandtl Number</i>
----------------	-----------------------

Description

The function estimates the Prandtl Number, which describes the ratio of kinematic viscosity to thermal diffusivity (Gates 1980).

Usage

```
Prandtl_number(c_p, mu, K)
```

Arguments

c_p	numeric specific heat at constant pressure ($Jmol^{-1}K^{-1}$).
mu	numeric dynamic viscosity ($mol s^{-1}m^{-1}$).
K	numeric thermal conductivity ($WK^{-1}m^{-1}$).

Value

numeric Prandtl number.

References

Gates DM (1980). *Biophysical Ecology*. Springer-Verlag, New York, NY, USA.

See Also

Other biophysical models: [Grashof_number_Gates\(\)](#), [Grashof_number\(\)](#), [Nusselt_from_Grashof\(\)](#), [Nusselt_from_Reynolds\(\)](#), [Nusselt_number\(\)](#), [Qconduction_animal\(\)](#), [Qconduction_substrate\(\)](#), [Qconvection\(\)](#), [Qemitted_thermal_radiation\(\)](#), [Qevaporation\(\)](#), [Qmetabolism_from_mass_temp\(\)](#), [Qmetabolism_from_mass\(\)](#), [Qnet_Gates\(\)](#), [Qradiation_absorbed\(\)](#), [Qthermal_radiation_absorbed\(\)](#), [Reynolds_number\(\)](#), [Tb_CampbellNorman\(\)](#), [Tb_Gates2\(\)](#), [Tb_Gates\(\)](#), [Tb_butterfly\(\)](#), [Tb_grasshopper\(\)](#), [Tb_limpetBH\(\)](#), [Tb_limpet\(\)](#), [Tb_lizard_Fei\(\)](#), [Tb_lizard\(\)](#), [Tb_mussel\(\)](#), [Tb_salamander_humid\(\)](#), [Tb_snail\(\)](#), [Tbed_mussel\(\)](#), [Tsoil\(\)](#), [actual_vapor_pressure\(\)](#), [boundary_layer_resistance\(\)](#), [external_resistance_to_water_vapor_transfer\(\)](#), [free_or_forced_convection\(\)](#), [heat_transfer_coefficient.](#), [heat_transfer_coefficient_simple\(\)](#), [heat_transfer_coefficient\(\)](#), [saturation_vapor_pressure\(\)](#), [saturation_water_vapor_pressure\(\)](#)

Examples

```
Prandtl_number(c_p = 29.3,
              mu  = 0.00001,
              K   = 0.5)
```

```
proportion_diffuse_solar_radiation
```

Ratio of Diffuse to Direct Solar Radiation

Description

The function estimates the ratio of diffuse to direct solar radiation based on the approximation of the SOLRAD model (McCullough and Porter 1971) described in Tracy et al. (1983).

Usage

```
proportion_diffuse_solar_radiation(psi, p_a, A)
```

Arguments

psi	numeric Zenith angle of the sun (degrees).
p_a	numeric Atmospheric pressure (kPa).
A	numeric albedo of the substrate (fraction of 1).

Value

numeric diffuse fraction.

References

McCullough EC, Porter WP (1971). "Computing Clear Day Solar Radiation Spectra for the Terrestrial Ecological Environment." *Ecology*, **52**(6), 1008-1015. doi: [10.2307/1933806](https://doi.org/10.2307/1933806).

Tracy CR, Hammond KA, Lechleitner RA, II WJS, Thompson DB, Whicker AD, Williamson SC (1983). "Estimating clear-day solar radiation: an evaluation of three models." *Journal of Thermal Biology*, **8**(3), 247-251. doi: [10.1016/03064565\(83\)900037](https://doi.org/10.1016/03064565(83)900037), [https://doi.org/10.1016/0306-4565\(83\)90003-7](https://doi.org/10.1016/0306-4565(83)90003-7).

See Also

Other microclimate functions: [air_temp_profile_neutral\(\)](#), [air_temp_profile_segment\(\)](#), [air_temp_profile\(\)](#), [degree_days\(\)](#), [direct_solar_radiation\(\)](#), [diurnal_radiation_variation\(\)](#), [diurnal_temp_variation_sineexp\(\)](#), [diurnal_temp_variation_sinesqrt\(\)](#), [diurnal_temp_variation_sine\(\)](#), [monthly_solar_radiation\(\)](#), [partition_solar_radiation\(\)](#), [solar_radiation\(\)](#), [surface_roughness\(\)](#), [wind_speed_profile_neutral\(\)](#), [wind_speed_profile_segment\(\)](#)

Examples

```
proportion_diffuse_solar_radiation(psi = 60,  
                                   p_a = 86.1,  
                                   A   = 0.25)
```

proportion_silhouette_area

Organism Silhouette Area

Description

The function estimates the projected (silhouette) area as a portion of the surface area of the organism as a function of zenith angle. The function is useful for estimating absorbed solar radiation.

Usage

```
proportion_silhouette_area(z, taxon, raz = 0, posture = "prostrate")
```

Arguments

z	numeric zenith angle in degrees between 0 and 360.
taxon	character organism name. Current choices are "lizard", "frog", and "grasshopper".
raz	numeric relative solar azimuth angle (in degrees). Required if taxon = "lizard". This is the horizontal angle of the sun relative to the head and frontal plane of the lizard and options currently include 0 (in front), 90 (to side), and 180 (behind) degrees.
posture	character value describing posture. Required if taxon = "lizard". Options include "prostrate" (default) and "elevated".

Details

Relationships come from

- Lizards: Muth (1977)
- Frogs: Tracy (1976)
- Grasshoppers: Anderson et al. (1979)

Value

numeric silhouette area as a proportion.

References

Anderson RV, Tracy CR, Abramsky Z (1979). "Habitat Selection in Two Species of Short-Horned Grasshoppers. The Role of Thermal and Hydric Stresses." *Oecologia*, **38**(3), 359–374. doi: [10.1007/BF00345194](https://doi.org/10.1007/BF00345194).

Muth A (1977). "Thermoregulatory Postures and Orientation to the Sun: A Mechanistic Evaluation for the Zebra-Tailed Lizard, *Callisaurus draconoides*." *Copeia*, **4**, 710 - 720.

Tracy CR (1976). "A Model of the Dynamic Exchanges of Water and Energy between a Terrestrial Amphibian and Its Environment." *Ecological Monographs*, **46**(3), 293-326. doi: [10.2307/1942256](https://doi.org/10.2307/1942256).

See Also

Other allometric functions: [mass_from_length\(\)](#), [proportion_silhouette_area_shapes\(\)](#), [surface_area_from_length\(\)](#), [surface_area_from_mass\(\)](#), [surface_area_from_volume\(\)](#), [volume_from_length\(\)](#)

Examples

```
proportion_silhouette_area(z      = 60,
                          taxon   = "frog")
proportion_silhouette_area(z      = 60,
                          taxon   = "grasshopper")
proportion_silhouette_area(z      = 60,
                          taxon   = "lizard",
                          posture = "prostrate",
                          raz      = 90)
proportion_silhouette_area(z      = 60,
                          taxon   = "lizard",
                          posture = "elevated",
                          raz      = 180)
```

proportion_silhouette_area_shapes

Organism Silhouette Area using Shape Approximations

Description

The function estimates the projected (silhouette) area as a portion of the surface area of the organism. The function estimates the projected area as a function of the dimensions and the angle between the solar beam and the longitudinal axis of the solid, using Figure 11.6 in Campbell and Norman (1998). The function is useful for estimating absorbed solar radiation.

Usage

```
proportion_silhouette_area_shapes(shape, theta, h, d)
```

Arguments

shape	character Shape to use to approximate an organism. Shapes are assumed to be prolate or have the longest axis parallel with the ground. Current choices are "spheroid", "cylinder flat ends", and "cylinder hemisphere ends".
theta	numeric angle between the solar beam and the longitudinal axis (degrees).
h	numeric height (long axis in m). Cross section length for spheroid.
d	numeric diameter (short axis in m). Cross section length for spheroid.

Value

numeric silhouette area as a proportion.

References

Campbell GS, Norman JM (1998). *Introduction to environmental biophysics*, 2nd ed. edition. Springer, New York. ISBN 0387949372.

See Also

Other allometric functions: [mass_from_length\(\)](#), [proportion_silhouette_area\(\)](#), [surface_area_from_length\(\)](#), [surface_area_from_mass\(\)](#), [surface_area_from_volume\(\)](#), [volume_from_length\(\)](#)

Examples

```

proportion_silhouette_area_shapes(shape = "spheroid",
                                theta = 60,
                                h     = 0.01,
                                d     = 0.001)
proportion_silhouette_area_shapes(shape = "cylinder flat ends",
                                theta = 60,
                                h     = 0.01,
                                d     = 0.001)
proportion_silhouette_area_shapes(shape = "cylinder hemisphere ends",
                                theta = 60,
                                h     = 0.01,
                                d     = 0.001)

```

Qconduction_animal *Conductance Assuming Animal Thermal Conductivity is Rate Limiting*

Description

The function calculates conductance (W) of an ectothermic animal to its substrate. Method assumes the major resistance to conduction is within surface layers of the animal and that the interior of the animal is equal in temperature to its surface (thermally well mixed) (Spotila et al. 1992).

Usage

Qconduction_animal(T_g, T_b, d, K = 0.5, A, proportion)

Arguments

T_g numeric ground surface temperature (Kelvin).
 T_b numeric body temperature (Kelvin).
 d numeric mean thickness of the animal skin (surface) in (meters). The function assumes a well mixed interior.
 K numeric thermal conductivity ($W K^{-1} m^{-1}$). $K = 0.5$ for naked skin and $K = 0.15$ for insect cuticle (Galushko et al. 2005). The conductivity of the ground is generally greater than that of animal tissues, so animal thermal conductivity is generally the rate limiting step.
 A numeric surface area (m^2).
 proportion numeric proportion of body in contact with the surface (0-1).

Value

numeric conductance (W).

References

Galushko D, Ermakov N, Karpovski M, Palevski A, Ishay JS, Bergman DJ (2005). “Electrical, thermoelectric and thermophysical properties of hornet cuticle.” *Semiconductor Science and Technology*, **20**(3), 286–289. doi: [10.1088/02681242/20/3/005](https://doi.org/10.1088/02681242/20/3/005).

Spotila JR, Feder ME, Burggren WW (1992). “Biophysics of Heat and Mass Transfer.” *Environmental Physiology of the Amphibians*. <https://press.uchicago.edu/ucp/books/book/chicago/E/bo3636401.html>.

See Also

Other biophysical models: [Grashof_number_Gates\(\)](#), [Grashof_number\(\)](#), [Nusselt_from_Grashof\(\)](#), [Nusselt_from_Reynolds\(\)](#), [Nusselt_number\(\)](#), [Prandtl_number\(\)](#), [Qconduction_substrate\(\)](#), [Qconvection\(\)](#), [Qemitted_thermal_radiation\(\)](#), [Qevaporation\(\)](#), [Qmetabolism_from_mass_temp\(\)](#), [Qmetabolism_from_mass\(\)](#), [Qnet_Gates\(\)](#), [Qradiation_absorbed\(\)](#), [Qthermal_radiation_absorbed\(\)](#), [Reynolds_number\(\)](#), [Tb_CampbellNorman\(\)](#), [Tb_Gates2\(\)](#), [Tb_Gates\(\)](#), [Tb_butterfly\(\)](#), [Tb_grasshopper\(\)](#), [Tb_limpetBH\(\)](#), [Tb_limpet\(\)](#), [Tb_lizard_Fei\(\)](#), [Tb_lizard\(\)](#), [Tb_mussel\(\)](#), [Tb_salamander_humid\(\)](#), [Tb_snail\(\)](#), [Tbed_mussel\(\)](#), [Tsoil\(\)](#), [actual_vapor_pressure\(\)](#), [boundary_layer_resistance\(\)](#), [external_resistance_to_water_vapor_transfer\(\)](#), [free_or_forced_convection\(\)](#), [heat_transfer_coefficient](#), [heat_transfer_coefficient_simple\(\)](#), [heat_transfer_coefficient\(\)](#), [saturation_vapor_pressure\(\)](#), [saturation_water_vapor_pressure\(\)](#)

Examples

```
Qconduction_animal(T_g      = 293,
                   T_b      = 303,
                   d         = 10^-6,
```

```

K          = 0.5,
A          = 10^-3,
proportion = 0.2)

```

Qconduction_substrate *Conductance Assuming Substrate Thermal Conductivity is Rate Limiting*

Description

The function calculates conductance (W) of an ectothermic animal to its substrate. The method assumes the major resistance to conduction is the substrate and that the interior of the animal is equal in temperature to its surface (thermally well mixed) (Spotila et al. 1992).

Usage

```
Qconduction_substrate(T_g, T_b, D, K_g = 0.5, A, proportion)
```

Arguments

T_g	numeric surface temperature (K).
T_b	numeric body temperature (K).
D	numeric characteristic dimension of the animal (m).
K_g	numeric thermal conductivity of substrate ($WK^{-1}m^{-1}$).
A	numeric surface area (m^2).
proportion	numeric proportion in contact to the surface.

Value

numeric conductance (W).

References

Spotila JR, Feder ME, Burggren WW (1992). "Biophysics of Heat and Mass Transfer." *Environmental Physiology of the Amphibians*. <https://press.uchicago.edu/ucp/books/book/chicago/E/bo3636401.html>.

See Also

Other biophysical models: [Grashof_number_Gates\(\)](#), [Grashof_number\(\)](#), [Nusselt_from_Grashof\(\)](#), [Nusselt_from_Reynolds\(\)](#), [Nusselt_number\(\)](#), [Prandtl_number\(\)](#), [Qconduction_animal\(\)](#), [Qconvection\(\)](#), [Qemitted_thermal_radiation\(\)](#), [Qevaporation\(\)](#), [Qmetabolism_from_mass_temp\(\)](#), [Qmetabolism_from_mass\(\)](#), [Qnet_Gates\(\)](#), [Qradiation_absorbed\(\)](#), [Qthermal_radiation_absorbed\(\)](#), [Reynolds_number\(\)](#), [Tb_CampbellNorman\(\)](#), [Tb_Gates2\(\)](#), [Tb_Gates\(\)](#), [Tb_butterfly\(\)](#), [Tb_grasshopper\(\)](#), [Tb_limpetBH\(\)](#), [Tb_limpet\(\)](#), [Tb_lizard_Fei\(\)](#), [Tb_lizard\(\)](#), [Tb_mussel\(\)](#), [Tb_salamander_humid\(\)](#), [Tb_snail\(\)](#), [Tbed_mussel\(\)](#), [Tsoil\(\)](#), [actual_vapor_pressure\(\)](#), [boundary_layer_resistance\(\)](#),

`external_resistance_to_water_vapor_transfer()`, `free_or_forced_convection()`, `heat_transfer_coefficient`,
`heat_transfer_coefficient_simple()`, `heat_transfer_coefficient()`, `saturation_vapor_pressure()`,
`saturation_water_vapor_pressure()`

Examples

```
Qconduction_substrate(T_g      = 293,
                      T_b      = 303,
                      D         = 0.01,
                      K_g       = 0.3,
                      A         = 10^-2,
                      proportion = 0.2)
```

Qconvection

Organismal Convection

Description

The function calculates convection from an organism to its environment as in Mitchell (1976). It includes an enhancement factor associated with outdoor environments.

Usage

```
Qconvection(T_a, T_b, A, proportion, H_L = 10.45, ef = 1.23)
```

Arguments

T_a	numeric air temperature (K).
T_b	numeric initial body temperature (K).
A	numeric surface area (m^2).
proportion	numeric proportion of surface area exposed to air.
H_L	numeric convective heat transfer coefficient ($W K^{-1} m^{-2}$).
ef	numeric is the enhancement factor, used to adjust H to field conditions. Approximated as mean value of 1.23 by default, but see Mitchell (1976) for further information.

Value

numeric convection (W).

References

Mitchell JW (1976). "Heat transfer from spheres and other animal forms." *Biophysical Journal*, **16**(6), 561-569. ISSN 0006-3495, doi: [10.1016/S00063495\(76\)857116](https://doi.org/10.1016/S00063495(76)857116), <https://www.sciencedirect.com/science/article/pii/S0006349576857116>.

See Also

Other biophysical models: [Grashof_number_Gates\(\)](#), [Grashof_number\(\)](#), [Nusselt_from_Grashof\(\)](#), [Nusselt_from_Reynolds\(\)](#), [Nusselt_number\(\)](#), [Prandtl_number\(\)](#), [Qconduction_animal\(\)](#), [Qconduction_substrate\(\)](#), [Qemitted_thermal_radiation\(\)](#), [Qevaporation\(\)](#), [Qmetabolism_from_mass_temp\(\)](#), [Qmetabolism_from_mass\(\)](#), [Qnet_Gates\(\)](#), [Qradiation_absorbed\(\)](#), [Qthermal_radiation_absorbed\(\)](#), [Reynolds_number\(\)](#), [Tb_CampbellNorman\(\)](#), [Tb_Gates2\(\)](#), [Tb_Gates\(\)](#), [Tb_butterfly\(\)](#), [Tb_grasshopper\(\)](#), [Tb_limpetBH\(\)](#), [Tb_limpet\(\)](#), [Tb_lizard_Fei\(\)](#), [Tb_lizard\(\)](#), [Tb_mussel\(\)](#), [Tb_salamander_humid\(\)](#), [Tb_snail\(\)](#), [Tbed_mussel\(\)](#), [Tsoil\(\)](#), [actual_vapor_pressure\(\)](#), [boundary_layer_resistance\(\)](#), [external_resistance_to_water_vapor_transfer\(\)](#), [free_or_forced_convection\(\)](#), [heat_transfer_coefficient.](#), [heat_transfer_coefficient_simple\(\)](#), [heat_transfer_coefficient\(\)](#), [saturation_vapor_pressure\(\)](#), [saturation_water_vapor_pressure\(\)](#)

Examples

```
Qconvection(T_a      = 293,
            T_b      = 303,
            H_L      = 10.45,
            A        = 0.0025,
            proportion = 0.85)
```

Qemitted_thermal_radiation

Emitted Thermal Radiation

Description

The function estimates thermal radiation (W) emitted by the surface of an animal (Gates 1980; Spotila et al. 1992).

Usage

```
Qemitted_thermal_radiation(
  epsilon = 0.96,
  A,
  psa_dir,
  psa_ref,
  T_b,
  T_g,
  T_a,
  enclosed = FALSE
)
```

Arguments

epsilon	numeric longwave infrared emissivity of skin (proportion), 0.95 to 1 for most animals (Gates 1980).
A	numeric surface area (m^2).
psa_dir	numeric proportion surface area exposed to sky (or enclosure) (0-1)
psa_ref	numeric proportion surface area exposed to ground (0-1).
T_b	numeric body surface temperature (K).
T_g	numeric ground surface temperature (K).
T_a	numeric ambient air temperature (K), only required if the animal is in an enclosed environment.
enclosed	logical whether the animal is an enclosed environment or not.

Value

numeric emitted thermal radiation, Qemit (W).

References

Gates DM (1980). *Biophysical Ecology*. Springer-Verlag, New York, NY, USA.

Spotila JR, Feder ME, Burggren WW (1992). "Biophysics of Heat and Mass Transfer." *Environmental Physiology of the Amphibians*. <https://press.uchicago.edu/ucp/books/book/chicago/E/bo3636401.html>.

See Also

Other biophysical models: `Grashof_number_Gates()`, `Grashof_number()`, `Nusselt_from_Grashof()`, `Nusselt_from_Reynolds()`, `Nusselt_number()`, `Prandtl_number()`, `Qconduction_animal()`, `Qconduction_substrate()`, `Qconvection()`, `Qevaporation()`, `Qmetabolism_from_mass_temp()`, `Qmetabolism_from_mass()`, `Qnet_Gates()`, `Qradiation_absorbed()`, `Qthermal_radiation_absorbed()`, `Reynolds_number()`, `Tb_CampbellNorman()`, `Tb_Gates2()`, `Tb_Gates()`, `Tb_butterfly()`, `Tb_grasshopper()`, `Tb_limpetBH()`, `Tb_limpet()`, `Tb_lizard_Fei()`, `Tb_lizard()`, `Tb_mussel()`, `Tb_salamander_humid()`, `Tb_snail()`, `Tbed_mussel()`, `Tsoil()`, `actual_vapor_pressure()`, `boundary_layer_resistance()`, `external_resistance_to_water_vapor_transfer()`, `free_or_forced_convection()`, `heat_transfer_coefficient`, `heat_transfer_coefficient_simple()`, `heat_transfer_coefficient()`, `saturation_vapor_pressure()`, `saturation_water_vapor_pressure()`

Examples

```
Qemitted_thermal_radiation(epsilon = 0.96,
                             A       = 1,
                             psa_dir = 0.4,
                             psa_ref = 0.6,
                             T_b     = 303,
                             T_g     = 293,
                             T_a     = 298,
                             enclosed = FALSE)
```

 Qevaporation

Heat Loss Associated with Evaporative Water Loss

Description

The function estimates heat loss associated with evaporative water loss for an amphibian (Spotila et al. 1992) or lizard. The lizard estimation is based on empirical measurements in Porter et al. (1973).

Usage

Qevaporation(A, T_b, taxon, rho_s = NA, rho_a = NA, h = NA, H = NA, r_i = NA)

Arguments

A	numeric surface area (m^2).
T_b	numeric body temperature (K).
taxon	character organism type. Current choices: "lizard", "amphibian_wetskin" (fully wet skin), "amphibian" (not fully wet skin).
rho_s	numeric saturation water vapor density at skin surface (kgm^{-3}) (needed if amphibian).
rho_a	numeric saturation water vapor density in ambient air (kgm^{-3}) (needed if amphibian).
h	numeric relative humidity (0-1) (needed if amphibian).
H	numeric convective heat transfer coefficient ($Wm^{-2}K^{-1}$) (needed if amphibian).
r_i	numeric internal (cutaneous) resistance to vapor transport (sm^{-1}) (needed if amphibian).

Value

numeric evaporative heat loss (W).

References

Porter WP, Mitchell JW, Bekman A, DeWitt CB (1973). "Behavioral implications of mechanistic ecology: thermal and behavioral modeling of desert ectotherms and their microenvironments." *Oecologia*, **13**, 1-54.

Spotila JR, Feder ME, Burggren WW (1992). "Biophysics of Heat and Mass Transfer." *Environmental Physiology of the Amphibians*. <https://press.uchicago.edu/ucp/books/book/chicago/E/bo3636401.html>.

See Also

Other biophysical models: [Grashof_number_Gates\(\)](#), [Grashof_number\(\)](#), [Nusselt_from_Grashof\(\)](#), [Nusselt_from_Reynolds\(\)](#), [Nusselt_number\(\)](#), [Prandtl_number\(\)](#), [Qconduction_animal\(\)](#), [Qconduction_substrate\(\)](#), [Qconvection\(\)](#), [Qemitted_thermal_radiation\(\)](#), [Qmetabolism_from_mass_temp\(\)](#), [Qmetabolism_from_mass\(\)](#), [Qnet_Gates\(\)](#), [Qradiation_absorbed\(\)](#), [Qthermal_radiation_absorbed\(\)](#), [Reynolds_number\(\)](#), [Tb_CampbellNorman\(\)](#), [Tb_Gates2\(\)](#), [Tb_Gates\(\)](#), [Tb_butterfly\(\)](#), [Tb_grasshopper\(\)](#), [Tb_limpetBH\(\)](#), [Tb_limpet\(\)](#), [Tb_lizard_Fei\(\)](#), [Tb_lizard\(\)](#), [Tb_mussel\(\)](#), [Tb_salamander_humid\(\)](#), [Tb_snail\(\)](#), [Tbed_mussel\(\)](#), [Tsoil\(\)](#), [actual_vapor_pressure\(\)](#), [boundary_layer_resistance\(\)](#), [external_resistance_to_water_vapor_transfer\(\)](#), [free_or_forced_convection\(\)](#), [heat_transfer_coefficient.](#) [heat_transfer_coefficient_simple\(\)](#), [heat_transfer_coefficient\(\)](#), [saturation_vapor_pressure\(\)](#), [saturation_water_vapor_pressure\(\)](#)

Examples

```
Qevaporation(A      = 0.1,
             T_b    = 293,
             taxon   = "amphibian",
             rho_s   = 0.003,
             rho_a   = 0.002,
             h       = 0.5,
             H       = 20,
             r_i     = 50)
Qevaporation(A      = 0.1,
             T_b    = 293,
             taxon   = "lizard")
```

Qmetabolism_from_mass *Metabolism as a Function of Mass*

Description

The function estimates the field metabolic rate (W) of various taxa as a function of mass (g). The function does not account for temperature and is based on empirical relationships from Nagy (2005).

Usage

```
Qmetabolism_from_mass(m, taxon = "reptile")
```

Arguments

m numeric mass (grams).
taxon character taxon for calculation. Options: "reptile", "bird", "mammal".

Value

numeric metabolism (W).

References

Nagy KA (2005). "Field metabolic rate and body size." *Journal of Experimental Biology*, **208**, 1621-1625. doi: [10.1242/jeb.01553](https://doi.org/10.1242/jeb.01553), <https://journals.biologists.com/jeb/article/208/9/1621/9364/Field-metabolic-rate-and-body-size>.

See Also

Other biophysical models: [Grashof_number_Gates\(\)](#), [Grashof_number\(\)](#), [Nusselt_from_Grashof\(\)](#), [Nusselt_from_Reynolds\(\)](#), [Nusselt_number\(\)](#), [Prandtl_number\(\)](#), [Qconduction_animal\(\)](#), [Qconduction_substrate\(\)](#), [Qconvection\(\)](#), [Qemitted_thermal_radiation\(\)](#), [Qevaporation\(\)](#), [Qmetabolism_from_mass_temp\(\)](#), [Qnet_Gates\(\)](#), [Qradiation_absorbed\(\)](#), [Qthermal_radiation_absorbed\(\)](#), [Reynolds_number\(\)](#), [Tb_CampbellNorman\(\)](#), [Tb_Gates2\(\)](#), [Tb_Gates\(\)](#), [Tb_butterfly\(\)](#), [Tb_grasshopper\(\)](#), [Tb_limpetBH\(\)](#), [Tb_limpet\(\)](#), [Tb_lizard_Fei\(\)](#), [Tb_lizard\(\)](#), [Tb_mussel\(\)](#), [Tb_salamander_humid\(\)](#), [Tb_snail\(\)](#), [Tbed_mussel\(\)](#), [Tsoil\(\)](#), [actual_vapor_pressure\(\)](#), [boundary_layer_resistance\(\)](#), [external_resistance_to_water_vapor_transfer\(\)](#), [free_or_forced_convection\(\)](#), [heat_transfer_coefficient](#), [heat_transfer_coefficient_simple\(\)](#), [heat_transfer_coefficient\(\)](#), [saturation_vapor_pressure\(\)](#), [saturation_water_vapor_pressure\(\)](#)

Examples

```
Qmetabolism_from_mass(m      = 12,
                      taxon = "reptile")
```

Qmetabolism_from_mass_temp

Metabolism as a Function of Mass and Body Temperature

Description

The function estimates basal (or resting) metabolic rate (W) as a function of mass (g) and temperature (K). The function is based on empirical data and the metabolic theory of ecology (assumes a 3/4 scaling exponent) (Gillooly et al. 2001).

Usage

```
Qmetabolism_from_mass_temp(m, T_b, taxon)
```

Arguments

m	numeric mass (grams).
T_b	numeric body temperature (K).
taxon	character organism type. Options: "bird", "mammal", "reptile", "amphibian", "invertebrate".

Value

numeric basal metabolism (W).

References

Gillooly JF, Brown JH, West GB, Savage VM, Charnov EL (2001). "Effects of size and temperature on metabolic rate." *Science*, **293**, 2248-2251. doi: [10.1126/science.1061967](https://doi.org/10.1126/science.1061967).

See Also

Other biophysical models: `Grashof_number_Gates()`, `Grashof_number()`, `Nusselt_from_Grashof()`, `Nusselt_from_Reynolds()`, `Nusselt_number()`, `Prandtl_number()`, `Qconduction_animal()`, `Qconduction_substrate()`, `Qconvection()`, `Qemitted_thermal_radiation()`, `Qevaporation()`, `Qmetabolism_from_mass()`, `Qnet_Gates()`, `Qradiation_absorbed()`, `Qthermal_radiation_absorbed()`, `Reynolds_number()`, `Tb_CampbellNorman()`, `Tb_Gates2()`, `Tb_Gates()`, `Tb_butterfly()`, `Tb_grasshopper()`, `Tb_limpetBH()`, `Tb_limpet()`, `Tb_lizard_Fei()`, `Tb_lizard()`, `Tb_mussel()`, `Tb_salamander_humid()`, `Tb_snail()`, `Tbed_mussel()`, `Tsoil()`, `actual_vapor_pressure()`, `boundary_layer_resistance()`, `external_resistance_to_water_vapor_transfer()`, `free_or_forced_convection()`, `heat_transfer_coefficient`, `heat_transfer_coefficient_simple()`, `heat_transfer_coefficient()`, `saturation_vapor_pressure()`, `saturation_water_vapor_pressure()`

Examples

```
Qmetabolism_from_mass_temp(m      = 100,
                           T_b    = 303,
                           taxon  = "reptile")
```

Qnet_Gates

Net Energy Exchange Between an Animal and the Environment

Description

The function estimates the net energy exchange (W) between an animal and the environment. The function follows Gates (1980) and others.

Usage

```
Qnet_Gates(Qabs, Qemit, Qconv, Qcond, Qmet, Qevap)
```

Arguments

Qabs	numeric solar radiation absorbed (W).
Qemit	numeric thermal radiation emitted (W).
Qconv	numeric energy exchange due to convection; Energy exchange from an animal to its surrounding environment (air or water) (W).
Qcond	numeric energy exchange due to conduction; Energy exchange from animal to a surface if they are in contact (W).
Qmet	numeric energy emitted due to metabolism (W).
Qevap	numeric energy emitted due to evaporative water loss (W).

Value

numeric net energy exchange (W).

References

Gates DM (1980). *Biophysical Ecology*. Springer-Verlag, New York, NY, USA.

See Also

Other biophysical models: [Grashof_number_Gates\(\)](#), [Grashof_number\(\)](#), [Nusselt_from_Grashof\(\)](#), [Nusselt_from_Reynolds\(\)](#), [Nusselt_number\(\)](#), [Prandtl_number\(\)](#), [Qconduction_animal\(\)](#), [Qconduction_substrate\(\)](#), [Qconvection\(\)](#), [Qemitted_thermal_radiation\(\)](#), [Qevaporation\(\)](#), [Qmetabolism_from_mass_temp\(\)](#), [Qmetabolism_from_mass\(\)](#), [Qradiation_absorbed\(\)](#), [Qthermal_radiation_absorbed\(\)](#), [Reynolds_number\(\)](#), [Tb_CampbellNorman\(\)](#), [Tb_Gates2\(\)](#), [Tb_Gates\(\)](#), [Tb_butterfly\(\)](#), [Tb_grasshopper\(\)](#), [Tb_limpetBH\(\)](#), [Tb_limpet\(\)](#), [Tb_lizard_Fei\(\)](#), [Tb_lizard\(\)](#), [Tb_mussel\(\)](#), [Tb_salamander_humid\(\)](#), [Tb_snail\(\)](#), [Tbed_mussel\(\)](#), [Tsoil\(\)](#), [actual_vapor_pressure\(\)](#), [boundary_layer_resistance\(\)](#), [external_resistance_to_water_vapor_transfer\(\)](#), [free_or_forced_convection\(\)](#), [heat_transfer_coefficient_external\(\)](#), [heat_transfer_coefficient_internal\(\)](#), [heat_transfer_coefficient_simple\(\)](#), [heat_transfer_coefficient\(\)](#), [saturation_vapor_pressure\(\)](#), [saturation_water_vapor_pressure\(\)](#)

Examples

```
Qnet_Gates(Qabs = 500,
           Qemit = 10,
           Qconv = 100,
           Qcond = 100,
           Qmet = 10,
           Qevap = 5)
```

Qradiation_absorbed *Absorbed Solar and Thermal Radiation*

Description

The function estimates solar and thermal radiation (W) absorbed by the surface of an animal following (Gates 1980) and (Spotila et al. 1992).

Usage

```
Qradiation_absorbed(
  a = 0.9,
  A,
  psa_dir,
  psa_ref,
  S_dir,
  S_dif,
  S_ref = NA,
```

```

    a_s = NA
)

```

Arguments

a	numeric solar absorptivity of animal surface (proportion), default value is for reptiles (0-1).
A	numeric surface area (m^2).
psa_dir	numeric proportion surface area exposed to solar radiation (0-1).
psa_ref	numeric proportion surface area exposed to reflected solar radiation (0-1).
S_dir	numeric direct solar radiation (Wm^{-2}).
S_dif	numeric diffuse solar radiation (Wm^{-2}).
S_ref	numeric reflected solar radiation (Wm^{-2}), either provided or estimated if surface albedo is provided instead
a_s	numeric is surface albedo (proportion), optional (not used) if reflected radiation is provided. Values available in (Gates 1980) Table 8.2.

Value

numeric solar radiation absorbed (W)

References

Gates DM (1980). *Biophysical Ecology*. Springer-Verlag, New York, NY, USA.

Spotila JR, Feder ME, Burggren WW (1992). "Biophysics of Heat and Mass Transfer." *Environmental Physiology of the Amphibians*. <https://press.uchicago.edu/ucp/books/book/chicago/E/bo3636401.html>.

See Also

Other biophysical models: [Grashof_number_Gates\(\)](#), [Grashof_number\(\)](#), [Nusselt_from_Grashof\(\)](#), [Nusselt_from_Reynolds\(\)](#), [Nusselt_number\(\)](#), [Prandtl_number\(\)](#), [Qconduction_animal\(\)](#), [Qconduction_substrate\(\)](#), [Qconvection\(\)](#), [Qemitted_thermal_radiation\(\)](#), [Qevaporation\(\)](#), [Qmetabolism_from_mass_temp\(\)](#), [Qmetabolism_from_mass\(\)](#), [Qnet_Gates\(\)](#), [Qthermal_radiation_absorbed\(\)](#), [Reynolds_number\(\)](#), [Tb_CampbellNorman\(\)](#), [Tb_Gates2\(\)](#), [Tb_Gates\(\)](#), [Tb_butterfly\(\)](#), [Tb_grasshopper\(\)](#), [Tb_limpetBH\(\)](#), [Tb_limpet\(\)](#), [Tb_lizard_Fei\(\)](#), [Tb_lizard\(\)](#), [Tb_mussel\(\)](#), [Tb_salamander_humid\(\)](#), [Tb_snail\(\)](#), [Tbed_mussel\(\)](#), [Tsoil\(\)](#), [actual_vapor_pressure\(\)](#), [boundary_layer_resistance\(\)](#), [external_resistance_to_water_vapor_transfer\(\)](#), [free_or_forced_convection\(\)](#), [heat_transfer_coefficient](#), [heat_transfer_coefficient_simple\(\)](#), [heat_transfer_coefficient\(\)](#), [saturation_vapor_pressure\(\)](#), [saturation_water_vapor_pressure\(\)](#)

Examples

```

Qradiation_absorbed(a      = 0.9,
                    A      = 1,
                    psa_dir = 0.4,
                    psa_ref = 0.4,

```

```
S_dir = 1000,
S_dif = 200,
a_s = 0.5)
```

Qthermal_radiation_absorbed

Absorbed Thermal Radiation

Description

The function estimates longwave (thermal) radiation (W) absorbed from the sky and the ground (Campbell and Norman 1998; Riddell et al. 2018).

Usage

```
Qthermal_radiation_absorbed(
  T_a,
  T_g,
  epsilon_ground = 0.97,
  a_longwave = 0.965
)
```

Arguments

T_a	numeric air temperature (C).
T_g	numeric ground temperature (C).
epsilon_ground	numeric emissivity (proportion) for more soil types (Campbell and Norman 1998).
a_longwave	numeric absorptance (proportion) of organism to longwave radiation (Bartlett and Gates 1967; Buckley 2008).

Value

numeric thermal radiation absorbed (W).

Author(s)

Eric Riddell

References

Bartlett PN, Gates DM (1967). "The energy budget of a lizard on a tree trunk." *Ecology*, **48**, 316-322.

Buckley LB (2008). "Linking traits to energetics and population dynamics to predict lizard ranges in changing environments." *American Naturalist*, **171**(1), E1 - E19. doi: [10.1086/523949](https://doi.org/10.1086/523949), [https:](https://doi.org/10.1086/523949)

[//pubmed.ncbi.nlm.nih.gov/18171140/](https://pubmed.ncbi.nlm.nih.gov/18171140/).

Campbell GS, Norman JM (1998). *Introduction to environmental biophysics*, 2nd ed. edition. Springer, New York. ISBN 0387949372.

Riddell EA, Odom JP, Damm JD, Sears MW (2018). “Plasticity reveals hidden resistance to extinction under climate change in the global hotspot of salamander diversity.” *Science Advances*, **4**(4). doi: [10.1126/sciadv.aar5471](https://doi.org/10.1126/sciadv.aar5471).

See Also

Other biophysical models: [Grashof_number_Gates\(\)](#), [Grashof_number\(\)](#), [Nusselt_from_Grashof\(\)](#), [Nusselt_from_Reynolds\(\)](#), [Nusselt_number\(\)](#), [Prandtl_number\(\)](#), [Qconduction_animal\(\)](#), [Qconduction_substrate\(\)](#), [Qconvection\(\)](#), [Qemitted_thermal_radiation\(\)](#), [Qevaporation\(\)](#), [Qmetabolism_from_mass_temp\(\)](#), [Qmetabolism_from_mass\(\)](#), [Qnet_Gates\(\)](#), [Qradiation_absorbed\(\)](#), [Reynolds_number\(\)](#), [Tb_CampbellNorman\(\)](#), [Tb_Gates2\(\)](#), [Tb_Gates\(\)](#), [Tb_butterfly\(\)](#), [Tb_grasshopper\(\)](#), [Tb_limpetBH\(\)](#), [Tb_limpet\(\)](#), [Tb_lizard_Fei\(\)](#), [Tb_lizard\(\)](#), [Tb_mussel\(\)](#), [Tb_salamander_humid\(\)](#), [Tb_snail\(\)](#), [Tbed_mussel\(\)](#), [Tsoil\(\)](#), [actual_vapor_pressure\(\)](#), [boundary_layer_resistance\(\)](#), [external_resistance_to_water_vapor_transfer\(\)](#), [free_or_forced_convection\(\)](#), [heat_transfer_coefficient_heat_transfer_coefficient_simple\(\)](#), [heat_transfer_coefficient\(\)](#), [saturation_vapor_pressure\(\)](#), [saturation_water_vapor_pressure\(\)](#)

Examples

```
Qthermal_radiation_absorbed(T_a      = 20,
                             T_g      = 25,
                             epsilon_ground = 0.97,
                             a_longwave = 0.965)
```

Reynolds_number	<i>Reynolds Number</i>
-----------------	------------------------

Description

The function estimates the Reynolds Number, which describes the dynamic properties of the fluid surrounding the animal as the ratio of internal viscous forces (Gates 1980).

Usage

```
Reynolds_number(u, D, nu)
```

Arguments

u	numeric wind speed (ms^{-1}).
D	numeric characteristic dimension (e.g., body diameter) (m)
nu	numeric the kinematic viscosity, ratio of dynamic viscosity to density of the fluid (m^2s^{-1}); can calculate from DRYAIR or WETAIR .

Value

numeric Reynolds number.

References

Gates DM (1980). *Biophysical Ecology*. Springer-Verlag, New York, NY, USA.

See Also

Other biophysical models: [Grashof_number_Gates\(\)](#), [Grashof_number\(\)](#), [Nusselt_from_Grashof\(\)](#), [Nusselt_from_Reynolds\(\)](#), [Nusselt_number\(\)](#), [Prandtl_number\(\)](#), [Qconduction_animal\(\)](#), [Qconduction_substrate\(\)](#), [Qconvection\(\)](#), [Qemitted_thermal_radiation\(\)](#), [Qevaporation\(\)](#), [Qmetabolism_from_mass_temp\(\)](#), [Qmetabolism_from_mass\(\)](#), [Qnet_Gates\(\)](#), [Qradiation_absorbed\(\)](#), [Qthermal_radiation_absorbed\(\)](#), [Tb_CampbellNorman\(\)](#), [Tb_Gates2\(\)](#), [Tb_Gates\(\)](#), [Tb_butterfly\(\)](#), [Tb_grasshopper\(\)](#), [Tb_limpetBH\(\)](#), [Tb_limpet\(\)](#), [Tb_lizard_Fei\(\)](#), [Tb_lizard\(\)](#), [Tb_mussel\(\)](#), [Tb_salamander_humid\(\)](#), [Tb_snail\(\)](#), [Tbed_mussel\(\)](#), [Tsoil\(\)](#), [actual_vapor_pressure\(\)](#), [boundary_layer_resistance\(\)](#), [external_resistance_to_water_vapor_transfer\(\)](#), [free_or_forced_convection_heat_transfer_coefficient_approximation\(\)](#), [heat_transfer_coefficient_simple\(\)](#), [heat_transfer_coefficient_saturated_vapor_pressure\(\)](#), [saturation_vapor_pressure\(\)](#), [saturation_water_vapor_pressure\(\)](#)

Examples

```
Reynolds_number(u = 1,
                D = 0.001,
                nu = 1.2)
```

saturation_vapor_pressure

Saturation Vapor Pressure

Description

The function calculates saturation vapor pressure (kPa) based on the Clausius-Clapeyron equation (Stull 2000; Riddell et al. 2018).

Usage

```
saturation_vapor_pressure(T_a)
```

Arguments

T_a numeric air temperature (K).

Value

numeric saturation vapor pressure, e_s (kPa).

Author(s)

Eric Riddell

References

Riddell EA, Odom JP, Damm JD, Sears MW (2018). “Plasticity reveals hidden resistance to extinction under climate change in the global hotspot of salamander diversity.” *Science Advances*, **4**(4). doi: [10.1126/sciadv.aar5471](https://doi.org/10.1126/sciadv.aar5471).

Stull RB (2000). *Meteorology for Scientists and Engineers*. Brooks Cole. ISBN 978-0534372149.

See Also

Other biophysical models: [Grashof_number_Gates\(\)](#), [Grashof_number\(\)](#), [Nusselt_from_Grashof\(\)](#), [Nusselt_from_Reynolds\(\)](#), [Nusselt_number\(\)](#), [Prandtl_number\(\)](#), [Qconduction_animal\(\)](#), [Qconduction_substrate\(\)](#), [Qconvection\(\)](#), [Qemitted_thermal_radiation\(\)](#), [Qevaporation\(\)](#), [Qmetabolism_from_mass_temp\(\)](#), [Qmetabolism_from_mass\(\)](#), [Qnet_Gates\(\)](#), [Qradiation_absorbed\(\)](#), [Qthermal_radiation_absorbed\(\)](#), [Reynolds_number\(\)](#), [Tb_CampbellNorman\(\)](#), [Tb_Gates2\(\)](#), [Tb_Gates\(\)](#), [Tb_butterfly\(\)](#), [Tb_grasshopper\(\)](#), [Tb_limpetBH\(\)](#), [Tb_limpet\(\)](#), [Tb_lizard_Fei\(\)](#), [Tb_lizard\(\)](#), [Tb_mussel\(\)](#), [Tb_salamander_humid\(\)](#), [Tb_snail\(\)](#), [Tbed_mussel\(\)](#), [Tsoil\(\)](#), [actual_vapor_pressure\(\)](#), [boundary_layer_resistance\(\)](#), [external_resistance_to_water_vapor_transfer\(\)](#), [free_or_forced_convection\(\)](#), [heat_transfer_coefficient_approximation\(\)](#), [heat_transfer_coefficient_simp](#), [heat_transfer_coefficient\(\)](#), [saturation_water_vapor_pressure\(\)](#)

Examples

```
saturation_vapor_pressure(T_a = 293)
```

```
saturation_water_vapor_pressure
```

Saturation Water Vapor Pressure

Description

The function approximates saturation water vapor pressure as a function of ambient temperature for temperatures from 0 to 40 C using Rosenberg (1974) in Spotila et al. (1992). See also NicheMapR [WETAIR](#) and [DRYAIR](#) (Kearney and Porter 2020).

Usage

```
saturation_water_vapor_pressure(T_a)
```

Arguments

`T_a` numeric air temperature (C).

Value

numeric Saturation water vapor pressure, e_s (Pa).

References

Kearney MR, Porter WP (2020). “NicheMapR - an R package for biophysical modelling: the ecotherm and Dynamic Energy Budget models.” *Ecography*, **43**(1), 85-96. doi: [10.1111/ecog.04680](https://doi.org/10.1111/ecog.04680).

Rosenberg NJ (1974). *Microclimate: the biological environment*. Wiley, New York.

Spotila JR, Feder ME, Burggren WW (1992). “Biophysics of Heat and Mass Transfer.” *Environmental Physiology of the Amphibians*. <https://press.uchicago.edu/ucp/books/book/chicago/E/bo3636401.html>.

See Also

Other biophysical models: [Grashof_number_Gates\(\)](#), [Grashof_number\(\)](#), [Nusselt_from_Grashof\(\)](#), [Nusselt_from_Reynolds\(\)](#), [Nusselt_number\(\)](#), [Prandtl_number\(\)](#), [Qconduction_animal\(\)](#), [Qconduction_substrate\(\)](#), [Qconvection\(\)](#), [Qemitted_thermal_radiation\(\)](#), [Qevaporation\(\)](#), [Qmetabolism_from_mass_temp\(\)](#), [Qmetabolism_from_mass\(\)](#), [Qnet_Gates\(\)](#), [Qradiation_absorbed\(\)](#), [Qthermal_radiation_absorbed\(\)](#), [Reynolds_number\(\)](#), [Tb_CampbellNorman\(\)](#), [Tb_Gates2\(\)](#), [Tb_Gates\(\)](#), [Tb_butterfly\(\)](#), [Tb_grasshopper\(\)](#), [Tb_limpetBH\(\)](#), [Tb_limpet\(\)](#), [Tb_lizard_Fei\(\)](#), [Tb_lizard\(\)](#), [Tb_mussel\(\)](#), [Tb_salamander_humid\(\)](#), [Tb_snail\(\)](#), [Tbed_mussel\(\)](#), [Tsoil\(\)](#), [actual_vapor_pressure\(\)](#), [boundary_layer_resistance\(\)](#), [external_resistance_to_water_vapor_transfer\(\)](#), [free_or_forced_convection\(\)](#), [heat_transfer_coefficient_approximation\(\)](#), [heat_transfer_coefficient_simulation\(\)](#), [heat_transfer_coefficient\(\)](#), [saturation_vapor_pressure\(\)](#)

Examples

```
saturation_water_vapor_pressure(T_a = 20)
```

soil_conductivity	<i>Soil Thermal Conductivity</i>
-------------------	----------------------------------

Description

The function estimates soil thermal conductivity ($Wm^{-1}K^{-1}$) using the methods of deVries (1963).

Usage

```
soil_conductivity(x, lambda, g_a)
```

Arguments

x	numeric vector of volume fractions of soil constituents (e.g., clay, quartz, minerals other than quartz, organic matter, water, air). The volume fractions should sum to 1. Note that x and lambda values in the example correspond to these soil constituents.
lambda	numeric vector of the thermal conductivities ($Wm^{-1}K^{-1}$) of the soil constituents.
g_a	numeric shape factor on soil particles. The soil particles are assumed to be ellipsoids with axes g_a, g_b, and g_c, where g_a + g_b + g_c = 1 and g_a = g_b. deVries (1952) suggests g_a = g_b = 0.125.

Value

numeric soil thermal conductivity ($Wm^{-1}K^{-1}$).

Author(s)

Joseph Grigg

References

deVries DA (1952). "Thermal Conductivity of Soil." *Nature*, **178**, 1074. doi: [10.1038/1781074a0](https://doi.org/10.1038/1781074a0).

deVries DA (1963). "Thermal Properties of Soils." In *Physics of Plant Environment*. North Holland Publishing Company. doi: [10.1002/qj.49709038628](https://doi.org/10.1002/qj.49709038628).

See Also

Other soil temperature functions: [soil_specific_heat\(\)](#), [soil_temperature_equation\(\)](#), [soil_temperature_function\(\)](#), [soil_temperature_integrand\(\)](#), [soil_temperature\(\)](#)

Examples

```
soil_conductivity(x = c(0.10, 0.40, 0.11, 0.01, 0.2, 0.18),
                 lambda = c(0.10, 0.40, 0.11, 0.01, 0.2, 0.18),
                 g_a = 0.125)
```

soil_specific_heat *Soil Specific Heat*

Description

The function estimates soil specific heat ($Jkg^{-1}K^{-1}$) using the methods of deVries (1963). The function incorporates the volume fraction of organic material, minerals, and water in soil.

Usage

```
soil_specific_heat(x_o, x_m, x_w, rho_so)
```

Arguments

x_o	numeric volume fraction of organic material (0-1).
x_m	numeric volume fraction of minerals (0-1).
x_w	numeric volume fraction of water (0-1).
rho_so	numeric particle density of soil in (kgm^{-3}) (bulk density).

Value

numeric soil specific heat ($Jkg^{-1}K^{-1}$).

Author(s)

Joseph Grigg

References

deVries DA (1963). "Thermal Properties of Soils." In *Physics of Plant Environment*. North Holland Publishing Company. doi: [10.1002/qj.49709038628](https://doi.org/10.1002/qj.49709038628).

See Also

Other soil temperature functions: [soil_conductivity\(\)](#), [soil_temperature_equation\(\)](#), [soil_temperature_function\(\)](#), [soil_temperature_integrand\(\)](#), [soil_temperature\(\)](#)

Examples

```
soil_specific_heat(x_o = 0.01,  
                  x_m = 0.6,  
                  x_w = 0.2,  
                  rho_so = 1620)
```

soil_temperature

Calculate Soil Temperature using ODEs

Description

This function is called to calculate soil temperature (C) as in Beckman et al. (1973). This function calls [soil_temperature_function](#), which uses ODEs to calculate a soil profile using equations from deVries (1963)

Usage

```

soil_temperature(
  z_r.intervals = 12,
  z_r,
  z,
  T_a,
  u,
  Tsoil0,
  z0,
  SSA,
  TimeIn,
  H,
  water_content = 0.2,
  air_pressure,
  rho_so = 1620,
  shade = FALSE
)

```

Arguments

<code>z_r.intervals</code>	numeric the number of intervals in the soil profile to calculate, defaults to 12.
<code>z_r</code>	numeric reference height (m).
<code>z</code>	numeric interval of the soil profile to return (1 to <code>z_r.intervals</code>).
<code>T_a</code>	numeric vector of air temperature (degrees C), Note: missing values will be linearly interpolated.
<code>u</code>	numeric vector of wind speeds (ms^{-1}).
<code>Tsoil0</code>	numeric initial soil temperature (degrees C).
<code>z0</code>	numeric surface roughness (m).
<code>SSA</code>	numeric solar absorptivity of soil surface as a fraction.
<code>TimeIn</code>	numeric vector of time periods for the model.
<code>H</code>	numeric vector of solar radiation (Wm^{-2}).
<code>water_content</code>	numeric percent water content (percent).
<code>air_pressure</code>	numeric air pressure (kPa).
<code>rho_so</code>	numeric particle density of soil.
<code>shade</code>	logical whether or not soil temperature should be calculated in the shade.

Value

numeric soil temperature (C).

Author(s)

Joseph Grigg

References

Beckman WA, Mitchell JW, Porter WP (1973). “Thermal Model for Prediction of a Desert Iguana’s Daily and Seasonal Behavior.” *Journal of Heat Transfer*, **95**(2), 257-262. doi: [10.1115/1.3450037](https://doi.org/10.1115/1.3450037).

deVries DA (1963). “Thermal Properties of Soils.” In *Physics of Plant Environment*. North Holland Publishing Company. doi: [10.1002/qj.49709038628](https://doi.org/10.1002/qj.49709038628).

See Also

Other soil temperature functions: [soil_conductivity\(\)](#), [soil_specific_heat\(\)](#), [soil_temperature_equation\(\)](#), [soil_temperature_function\(\)](#), [soil_temperature_integrand\(\)](#)

Examples

```
set.seed(123)
temp_vector      <- runif(48, min = -10, max = 10)
wind_speed_vector <- runif(48, min = 0, max = 0.4)
time_vector      <- rep(1:24, 2)
solrad_vector    <- rep(c(rep(0, 6),
                          seq(10, 700, length.out = 6),
                          seq(700, 10, length.out = 6),
                          rep(0, 6)),
                        2)

soil_temperature(z_r.intervals = 12,
                 z_r           = 1.5,
                 z             = 2,
                 T_a           = temp_vector,
                 u             = wind_speed_vector,
                 Tsoil0       = 20,
                 z0           = 0.02,
                 SSA          = 0.7,
                 TimeIn       = time_vector,
                 H            = solrad_vector,
                 water_content = 0.2,
                 air_pressure = 85,
                 rho_so       = 1620,
                 shade        = FALSE)
```

soil_temperature_equation

Core Function Called to Solve Equation for Soil Temperature

Description

The function called by [soil_temperature_function](#) to solve equation for soil temperature from Beckman et al. (1973).

Usage

```
soil_temperature_equation(L, rho_a, c_a, V_inst, z_r, z0, T_inst, T_s)
```

Arguments

L	numeric Monin-Obukhov length, a measure of the instability of heat flow (see Beckman et al. (1973)).
rho_a	numeric density of air (kgm^{-3}).
c_a	numeric specific heat of air ($Jkg^{-1}K^{-1}$).
V_inst	numeric instantaneous wind speed (ms^{-1}).
z_r	numeric reference height (m).
z0	numeric surface roughness (m).
T_inst	numeric instantaneous air temperature (K).
T_s	numeric initial soil surface temperature (C).

Value

numeric soil temperature (C).

Author(s)

Joseph Grigg

References

Beckman WA, Mitchell JW, Porter WP (1973). "Thermal Model for Prediction of a Desert Iguana's Daily and Seasonal Behavior." *Journal of Heat Transfer*, **95**(2), 257-262. doi: [10.1115/1.3450037](https://doi.org/10.1115/1.3450037).

See Also

Other soil temperature functions: [soil_conductivity\(\)](#), [soil_specific_heat\(\)](#), [soil_temperature_function\(\)](#), [soil_temperature_integrand\(\)](#), [soil_temperature\(\)](#)

Examples

```
soil_temperature_equation(L      = -10,
                          rho_a  = 1.177,
                          c_a    = 1006,
                          V_inst = 0.3,
                          z_r    = 1.5,
                          z0     = 0.02,
                          T_inst = 265,
                          T_s    = 20)
```

soil_temperature_function

Core Function for Calculating Soil Temperature

Description

This function is called to calculate soil temperature as in Beckman et al. (1973). Parameters are passed as a list to facilitating solving the equations. This function is not intended to be called directly. The energy balance equations are from Porter et al. (1973) and Kingsolver (1979)

Usage

```
soil_temperature_function(j, T_so, params)
```

Arguments

j	numeric the number of the iteration of running the model.
T_so	numeric the initial soil temperature profile in C.
params	list containing the following param, which are described or calculated in soil_temperature : SSA, epsilon_so, k_so, c_so, dz, z_r, z0, H, T_a, u, rho_a, rho_so, c_a, TimeIn, dt, shade.

Value

Soil temperature profile as a list.

Author(s)

Joseph Grigg

References

Beckman WA, Mitchell JW, Porter WP (1973). "Thermal Model for Prediction of a Desert Iguana's Daily and Seasonal Behavior." *Journal of Heat Transfer*, **95**(2), 257-262. doi: [10.1115/1.3450037](https://doi.org/10.1115/1.3450037).

Kingsolver JG (1979). "Thermal and hydric aspects of environmental heterogeneity in the pitcher plant mosquito." *Ecological Monographs*, **49**, 357-376.

Porter WP, Mitchell JW, Bekman A, DeWitt CB (1973). "Behavioral implications of mechanistic ecology: thermal and behavioral modeling of desert ectotherms and their microenvironments." *Oecologia*, **13**, 1-54.

See Also

Other soil temperature functions: [soil_conductivity\(\)](#), [soil_specific_heat\(\)](#), [soil_temperature_equation\(\)](#), [soil_temperature_integrand\(\)](#), [soil_temperature\(\)](#)

Examples

```

set.seed(123)
temp_vector      <- runif(96, min = -10, max = 10)
wind_speed_vector <- runif(96, min = 0, max = 0.4)
time_vector      <- rep(1:24, 4)
solrad_vector    <- rep(c(rep(0, 6),
                          seq(10, 700, length.out = 6),
                          seq(700, 10, length.out = 6),
                          rep(0, 6)),
                        4)
params           <- list(SSA      = 0.7,
                        epsilon_so = 0.98,
                        k_so      = 0.293,
                        c_so      = 800,
                        dz        = 0.05,
                        z_r       = 1.5,
                        z0        = 0.02,
                        H          = solrad_vector,
                        T_a        = temp_vector,
                        u          = wind_speed_vector,
                        rho_a      = 1.177,
                        rho_so     = 1620,
                        c_a        = 1006,
                        TimeIn     = time_vector,
                        dt         = 60 * 60,
                        shade      = FALSE)

soil_temperature_function(j      = 1,
                          T_so   = rep(20,13),
                          params = params)

```

soil_temperature_integrand

Solve Equation for Soil Temperature

Description

This function is called by [soil_temperature_equation](#) to solve the equation for soil temperature from Beckman et al. (1973). The function represents the integrand in the equation. It is not intended to be called directly.

Usage

```
soil_temperature_integrand(x, L, z0)
```

Arguments

x	numeric vector of volume fractions of soil constituents (e.g., clay, quartz, minerals other than quartz, organic matter, water, air). The volume fractions should sum to 1. Note that x and lambda values in the example correspond to these soil constituents.
L	numeric Monin-Obukhov length, a measure of the instability of heat flow (Beckman et al. 1973).
z0	numeric surface roughness (m).

Value

numeric integrand for soil temperature function.

Author(s)

Joseph Grigg

References

Beckman WA, Mitchell JW, Porter WP (1973). "Thermal Model for Prediction of a Desert Iguana's Daily and Seasonal Behavior." *Journal of Heat Transfer*, **95**(2), 257-262. doi: [10.1115/1.3450037](https://doi.org/10.1115/1.3450037).

See Also

Other soil temperature functions: [soil_conductivity\(\)](#), [soil_specific_heat\(\)](#), [soil_temperature_equation\(\)](#), [soil_temperature_function\(\)](#), [soil_temperature\(\)](#)

Examples

```
soil_temperature_integrand(x = c(0.10, 0.40, 0.11, 0.01, 0.2, 0.18),
                          L = -10,
                          z0 = 0.2)
```

solar_noon

Time of Solar Noon

Description

The function calculates the time of solar noon in hours as a function of the day of year and longitude (Campbell and Norman 1998).

Usage

```
solar_noon(lon, doy, offset = NA)
```

Arguments

lon	numeric longitude (decimal degrees).
doy	numeric day of year (1-366). This can be obtained from a standard date via day_of_year .
offset	numeric number of hours to add to UTC (Coordinated Universal Time) to get local time (improves accuracy but not always necessary). Defaults to NA.

Value

numeric time of solar noon (hours).

References

Campbell GS, Norman JM (1998). *Introduction to environmental biophysics*, 2nd ed. edition. Springer, New York. ISBN 0387949372.

See Also

Other utility functions: [airpressure_from_elev\(\)](#), [azimuth_angle\(\)](#), [day_of_year\(\)](#), [daylength\(\)](#), [dec_angle\(\)](#), [temperature conversions](#), [zenith_angle\(\)](#)

Examples

```
solar_noon(lon = -122.335,
           doy = 112)
```

solar_radiation	<i>Estimate the Three Components of Solar Radiation (Direct, Diffuse and Reflected)</i>
-----------------	---

Description

The function estimate direct, diffuse, and reflected components of solar radiation (Wm^{-2}) as a function of day of year using the model in Campbell and Norman (1998).

Usage

```
solar_radiation(doy, psi, tau, elev, rho = 0.7)
```

Arguments

doy	numeric the day of year; day_of_year .
psi	numeric zenith angle (radians).
tau	numeric atmospheric transmissivity (proportion), which is ratio of global solar radiation at ground level to extra-terrestrial solar radiation.
elev	numeric elevation (meters).
rho	numeric albedo as a proportion (0-1).

Value

numeric radiation components - direct, diffused and reflected (Wm^{-2}).

References

Campbell GS, Norman JM (1998). *Introduction to environmental biophysics*, 2nd ed. edition. Springer, New York. ISBN 0387949372.

See Also

Other microclimate functions: `air_temp_profile_neutral()`, `air_temp_profile_segment()`, `air_temp_profile()`, `degree_days()`, `direct_solar_radiation()`, `diurnal_radiation_variation()`, `diurnal_temp_variation_sineexp()`, `diurnal_temp_variation_sinesqrt()`, `diurnal_temp_variation_sine()`, `monthly_solar_radiation()`, `partition_solar_radiation()`, `proportion_diffuse_solar_radiation()`, `surface_roughness()`, `wind_speed_profile_neutral()`, `wind_speed_profile_segment()`

Examples

```
solar_radiation(doy = 112,  
                psi = 1,  
                tau = 0.6,  
                elev = 1500,  
                rho = 0.7)
```

surface_area_from_length

Organism Surface Area from Length

Description

This function estimates surface area (m^2) from length (m) by approximating the animal's body as a rotational ellipsoid with half the body length as the semi-major axis.

Usage

```
surface_area_from_length(l)
```

Arguments

l numeric length (m).

Details

Following Samietz et al. (2005) and Lactin and Johnson (1998).

Value

numeric surface area (m^2).

References

Lactin DJ, Johnson DL (1998). "Convective heat loss and change in body temperature of grasshopper and locust nymphs: Relative importance of wind speed, insect size and insect orientation." *Journal of Thermal Biology*, **23**(1), 5-13. ISSN 0306-4565, doi: [10.1016/S03064565\(97\)000375](https://doi.org/10.1016/S03064565(97)000375), <https://www.sciencedirect.com/science/article/pii/S0306456597000375>.

Samietz J, Salser MA, Dingle H (2005). "Altitudinal variation in behavioural thermoregulation: local adaptation vs. plasticity in California grasshoppers." *Journal of Evolutionary Biology*, **18**(4), 1087-1096. doi: [10.1111/j.14209101.2005.00893.x](https://doi.org/10.1111/j.14209101.2005.00893.x).

See Also

Other allometric functions: [mass_from_length\(\)](#), [proportion_silhouette_area_shapes\(\)](#), [proportion_silhouette_area_from_length\(\)](#), [surface_area_from_mass\(\)](#), [surface_area_from_volume\(\)](#), [volume_from_length\(\)](#)

Examples

```
surface_area_from_length(l = 0.04)
```

```
surface_area_from_mass
```

Organism Surface Area from Mass

Description

The function estimates surface area (m^2) from mass (g) for one of a variety of taxa.

Usage

```
surface_area_from_mass(m, taxon)
```

Arguments

m	numeric vector of mass (g).
taxon	character taxonomic classification of organism, current choices: "lizard", "salamander", "frog", "insect".

Details

All models follow ($SA = aM^b$) with mass in grams and surface area in *meters*².

- Lizards (Norris 1965; Porter and James 1979; Roughgarden 1981; O'Connor 1999; Fei et al. 2012):

$$a = 0.000314\pi$$

$$b = 2/3$$

- Salamanders (Whitford and Hutchison 1967; Riddell et al. 2017):

$$a = 0.000842$$

$$b = 0.694$$

- Frogs (McClanahan and Baldwin 1969):

$$a = 0.00099$$

$$b = 0.56$$

- Insects (Lactin and Johnson 1997):

$$a = 0.0013$$

$$b = 0.8$$

Value

numeric surface area (m^2).

References

- Fei T, Skidmore AK, Venus V, Wang T, Schlerf M, Toxopeus B, van Overjijk S, Bian M, Liu Y (2012). “A body temperature model for lizards as estimated from the thermal environment.” *Journal of Thermal Biology*, **37**(1), 56-64. ISSN 0306-4565, doi: [10.1016/j.jtherbio.2011.10.013](https://doi.org/10.1016/j.jtherbio.2011.10.013), <https://www.sciencedirect.com/science/article/pii/S0306456511001513>.
- Lactin DJ, Johnson DL (1997). “Response of body temperature to solar radiation in restrained nymphal migratory grasshoppers (Orthoptera: Acrididae): influences of orientation and body size.” *Physiological Entomology*, **22**(2), 131-139. doi: [10.1111/j.13653032.1997.tb01150.x](https://doi.org/10.1111/j.13653032.1997.tb01150.x).
- McClanahan L, Baldwin R (1969). “Rate of water uptake through the integument of the desert toad, *Bufo punctatus*.” *Comparative Biochemistry and Physiology*, **28**(1), 381-389. ISSN 0010-406X, doi: [10.1016/0010406X\(69\)913516](https://doi.org/10.1016/0010-406X(69)91351-6), [https://doi.org/10.1016/0010-406X\(69\)91351-6](https://doi.org/10.1016/0010-406X(69)91351-6).
- Norris KS (1965). “Color adaptation in desert reptiles and its thermal relationships.” In *Symposium on Lizard Ecology*, 162- 229. U. Missouri Press.
- O’Connor M (1999). “Physiological and ecological implications of a simple model of heating and cooling in reptiles.” *Journal of Thermal Biology*, **24**, 113-136.
- Porter WP, James FC (1979). “Behavioral Implications of Mechanistic Ecology II: The African Rainbow Lizard, *Agama agama*.” *Copeia*, **1979**(4), 594–619. ISSN 00458511, 19385110, doi: [10.2307/1443867](https://doi.org/10.2307/1443867).
- Riddell EA, Apanovitch EK, Odom JP, Sears MW (2017). “Physical calculations of resistance to water loss improve predictions of species range models.” *Ecological Monographs*, **87**(1), 21-33. doi: [10.1002/ecm.1240](https://doi.org/10.1002/ecm.1240).
- Roughgarden J (1981). “Resource partitioning of space and its relationship to body temperature in *Anolis* lizard populations.” *Oecologia*, **50**, 256 – 264. <https://link.springer.com/article/>

[10.1007/BF00348048](https://doi.org/10.1007/BF00348048).

Whitford WG, Hutchison VH (1967). "Body Size and Metabolic Rate in Salamanders." *Physiological Zoology*, **40**(2), 127-133. doi: [10.1086/physzool.40.2.30152447](https://doi.org/10.1086/physzool.40.2.30152447).

See Also

Other allometric functions: [mass_from_length\(\)](#), [proportion_silhouette_area_shapes\(\)](#), [proportion_silhouette_area_from_length\(\)](#), [surface_area_from_length\(\)](#), [surface_area_from_volume\(\)](#), [volume_from_length\(\)](#)

Examples

```
surface_area_from_mass(m = 1:50,
                      taxon = "lizard")
surface_area_from_mass(m = 1:50,
                      taxon = "salamander")
surface_area_from_mass(m = 1:50,
                      taxon = "frog")
surface_area_from_mass(m = seq(0.1, 5, 0.1),
                      taxon = "insect")
```

surface_area_from_volume

Organism Surface Area from Volume

Description

The function estimates surface area (m^2) from volume (m^3) for a variety of taxa following Mitchell (1976).

Usage

```
surface_area_from_volume(V, taxon)
```

Arguments

V numeric vector of volume (m^3). Can be one or more values.
 taxon character taxon of organism, current choices: "lizard", "frog", "sphere".

Details

All models follow ($SA = Ka * V^{2/3}$) with surface area and volume in meters.

- Lizards: Norris (1965):

$Ka = 11.0$

- Frogs: Tracy (1972):

$$Ka = 11.0$$

- Sphere: Mitchell (1976):

$$Ka = 4.83$$

Value

numeric surface area (m^2).

References

Mitchell JW (1976). "Heat transfer from spheres and other animal forms." *Biophysical Journal*, **16**(6), 561-569. ISSN 0006-3495, doi: [10.1016/S00063495\(76\)857116](https://doi.org/10.1016/S00063495(76)857116), <https://www.sciencedirect.com/science/article/pii/S0006349576857116>.

Norris KS (1965). "Color adaptation in desert reptiles and its thermal relationships." In *Symposium on Lizard Ecology*, 162- 229. U. Missouri Press.

Tracy CR (1972). "Newton's Law: Its Application for Expressing Heat Losses from Homeotherms." *BioScience*, **22**(11), 656-659. ISSN 0006-3568, doi: [10.2307/1296267](https://doi.org/10.2307/1296267).

See Also

Other allometric functions: [mass_from_length\(\)](#), [proportion_silhouette_area_shapes\(\)](#), [proportion_silhouette_area_from_length\(\)](#), [surface_area_from_length\(\)](#), [surface_area_from_mass\(\)](#), [volume_from_length\(\)](#)

Examples

```
surface_area_from_volume(V = 0.001,
                        taxon = "lizard")
surface_area_from_volume(V = 0.001,
                        taxon = "frog")
surface_area_from_volume(V = 0.001,
                        taxon = "sphere")
```

surface_roughness

Surface Roughness from Empirical Measurements

Description

The function estimates surface roughness (m) from empirical wind speed (ms^{-1}) data collected at a vector of heights (m) (Kingsolver and Buckley 2015; Campbell and Norman 1998; Porter and James 1979).

Usage

```
surface_roughness(u_r, zr)
```

Arguments

`u_r` numeric wind velocity (ms^{-1}) at a vector of reference heights.
`zr` numeric vector of reference heights (m).

Value

numeric surface roughness (m).

References

Campbell GS, Norman JM (1998). *Introduction to environmental biophysics*, 2nd ed. edition. Springer, New York. ISBN 0387949372.

Kingsolver JG, Buckley LB (2015). “Climate variability slows evolutionary responses of *Colias* butterflies to recent climate change.” *Proceedings of the Royal Society B*, **282**(1802). doi: [10.1098/rspb.2014.2470](https://doi.org/10.1098/rspb.2014.2470).

Porter WP, James FC (1979). “Behavioral Implications of Mechanistic Ecology II: The African Rainbow Lizard, *Agama agama*.” *Copeia*, **1979**(4), 594–619. ISSN 00458511, 19385110, doi: [10.2307/1443867](https://doi.org/10.2307/1443867).

See Also

Other microclimate functions: [air_temp_profile_neutral\(\)](#), [air_temp_profile_segment\(\)](#), [air_temp_profile\(\)](#), [degree_days\(\)](#), [direct_solar_radiation\(\)](#), [diurnal_radiation_variation\(\)](#), [diurnal_temp_variation_sineexp\(\)](#), [diurnal_temp_variation_sinesqrt\(\)](#), [diurnal_temp_variation_sine\(\)](#), [monthly_solar_radiation\(\)](#), [partition_solar_radiation\(\)](#), [proportion_diffuse_solar_radiation\(\)](#), [solar_radiation\(\)](#), [wind_speed_profile_neutral\(\)](#), [wind_speed_profile_segment\(\)](#)

Examples

```
surface_roughness(u_r = c(0.01, 0.025, 0.05, 0.1, 0.2),
                 zr = c(0.05, 0.25, 0.5, 0.75, 1))
```

Tbed_mussel

Operative Environmental Temperature of a Mussel Bed

Description

The function estimates body temperature of a mussel (C). The function implements a steady-state model, which assumes unchanging environmental conditions. Based on Helmuth (1999).

Usage

```
Tbed_mussel(l, T_a, S, k_d, u, evap = FALSE, cl = NA)
```

Arguments

l	numeric mussel length (anterior/posterior axis) (m).
T_a	numeric air temperature at 4 m above ground (C).
S	numeric direct solar flux density (Wm^{-2}).
k_d	numeric diffuse fraction, proportion of solar radiation that is diffuse.
u	numeric wind speed at 4 m above ground (ms^{-1}).
evap	logical Are mussels gaping to evaporatively cool? If TRUE, assumes constant mass loss rate of 5 percent of initial body mass per hour.
cl	numeric fraction of the sky covered by cloud, optional.

Details

Conduction is considered negligible due to a small area of contact.

Thermal radiative flux is calculated following Helmuth (1998), Helmuth (1999), and Idso and Jackson (1969).

Value

numeric predicted body (operative environmental) temperature (C).

References

Helmuth B (1999). “Thermal biology of rocky intertidal mussels: quantifying body temperatures using climatological data.” *Ecology*, **80**(1), 15-34. <https://esajournals.onlinelibrary.wiley.com/doi/abs/10.1890/0012-9658%281999%29080%5B0015%3ATBORIM%5D2.0.CO%3B2>.

Helmuth BST (1998). “Intertidal Mussel Microclimates: Predicting the Body Temperature of a Sessile Invertebrate.” *Ecological Monographs*, **68**(1), 51–74. ISSN 00129615, doi: [10.2307/2657143](https://doi.org/10.2307/2657143).

Idso SB, Jackson RD (1969). “Thermal radiation from the atmosphere.” *Journal of Geophysical Research (1896-1977)*, **74**(23), 5397-5403. doi: [10.1029/JC074i023p05397](https://doi.org/10.1029/JC074i023p05397).

See Also

Other biophysical models: [Grashof_number_Gates\(\)](#), [Grashof_number\(\)](#), [Nusselt_from_Grashof\(\)](#), [Nusselt_from_Reynolds\(\)](#), [Nusselt_number\(\)](#), [Prandtl_number\(\)](#), [Qconduction_animal\(\)](#), [Qconduction_substrate\(\)](#), [Qconvection\(\)](#), [Qemitted_thermal_radiation\(\)](#), [Qevaporation\(\)](#), [Qmetabolism_from_mass_temp\(\)](#), [Qmetabolism_from_mass\(\)](#), [Qnet_Gates\(\)](#), [Qradiation_absorbed\(\)](#), [Qthermal_radiation_absorbed\(\)](#), [Reynolds_number\(\)](#), [Tb_CampbellNorman\(\)](#), [Tb_Gates2\(\)](#), [Tb_Gates\(\)](#), [Tb_butterfly\(\)](#), [Tb_grasshopper\(\)](#), [Tb_limpetBH\(\)](#), [Tb_limpet\(\)](#), [Tb_lizard_Fei\(\)](#), [Tb_lizard\(\)](#), [Tb_mussel\(\)](#), [Tb_salamander_humid\(\)](#), [Tb_snail\(\)](#), [Tsoil\(\)](#), [actual_vapor_pressure\(\)](#), [boundary_layer_resistance\(\)](#), [external_resistance_to_water_vapor_transfer\(\)](#), [free_or_forced_convection\(\)](#)

[heat_transfer_coefficient_approximation\(\)](#), [heat_transfer_coefficient_simple\(\)](#), [heat_transfer_coefficient_saturated\(\)](#), [saturation_vapor_pressure\(\)](#), [saturation_water_vapor_pressure\(\)](#)

Examples

```
Tbed_mussel(l = 0.1,
            T_a = 25,
            S = 500,
            k_d = 0.2,
            u = 1,
            evap = FALSE)
```

Tb_butterfly

Operative Environmental Temperature of a Butterfly

Description

The function estimates body temperatures (C, operative environmental temperatures) of a butterfly based on Kingsolver (1983) and Buckley and Kingsolver (2012). The function is designed for butterflies that bask with closed wings such as *Colias*.

Usage

```
Tb_butterfly(
  T_a,
  T_g,
  T_sh,
  u,
  H_sdir,
  H_sdif,
  z,
  D,
  delta,
  alpha,
  r_g = 0.3,
  shade = FALSE
)
```

Arguments

T_a	numeric air temperature (C).
T_g	numeric surface temperature (C) in the sunlight.
T_sh	numeric surface temperature (C) in the shade.
u	numeric wind speed ($m s^{-1}$).
H_sdir	numeric direct solar radiation flux ($W m^{-2}$).

H_sdif	numeric diffuse solar radiation flux (Wm^{-2}).
z	numeric solar zenith angle (degrees).
D	numeric thoracic diameter (cm).
delta	numeric thoracic fur thickness (mm).
alpha	numeric wing solar absorptivity (proportion). The range for Colias butterflies is 0.4 to 0.7.
r_g	numeric substrate solar reflectivity (proportion). See Kingsolver (1983).
shade	logical whether body temperature should be calculated in sun (FALSE) or shade (TRUE).

Details

Thermal radiative flux is calculated following Gates (1980) based on Swinbank (1960). Kingsolver (1983) estimates using the Brunt equation with black body sky temperature from Swinbank (1963).

Value

numeric predicted body (operative environmental) temperature (C).

References

Buckley LB, Kingsolver JG (2012). “The demographic impacts of shifts in climate means and extremes on alpine butterflies.” *Functional Ecology*, **26**(4), 969-977. doi: [10.1111/j.13652435.2012.01969.x](https://doi.org/10.1111/j.13652435.2012.01969.x).

Gates DM (1980). *Biophysical Ecology*. Springer-Verlag, New York, NY, USA.

Kingsolver JG (1983). “Thermoregulation and Flight in Colias Butterflies: Elevational Patterns and Mechanistic Limitations.” *Ecology*, **64**(3), 534-545. doi: [10.2307/1939973](https://doi.org/10.2307/1939973).

Swinbank WC (1960). “Wind profile in thermally stratified flow.” *Nature*, **186**, 463-464.

Swinbank WC (1963). “Long-wave radiation from clear skies.” *Quarterly Journal of the Royal Meteorological Society*, **89**, 339-348.

See Also

Other biophysical models: [Grashof_number_Gates\(\)](#), [Grashof_number\(\)](#), [Nusselt_from_Grashof\(\)](#), [Nusselt_from_Reynolds\(\)](#), [Nusselt_number\(\)](#), [Prandtl_number\(\)](#), [Qconduction_animal\(\)](#), [Qconduction_substrate\(\)](#), [Qconvection\(\)](#), [Qemitted_thermal_radiation\(\)](#), [Qevaporation\(\)](#), [Qmetabolism_from_mass_temp\(\)](#), [Qmetabolism_from_mass\(\)](#), [Qnet_Gates\(\)](#), [Qradiation_absorbed\(\)](#), [Qthermal_radiation_absorbed\(\)](#), [Reynolds_number\(\)](#), [Tb_CampbellNorman\(\)](#), [Tb_Gates2\(\)](#), [Tb_Gates\(\)](#), [Tb_grasshopper\(\)](#), [Tb_limpetBH\(\)](#), [Tb_limpet\(\)](#), [Tb_lizard_Fei\(\)](#), [Tb_lizard\(\)](#), [Tb_mussel\(\)](#), [Tb_salamander_humid\(\)](#), [Tb_snail\(\)](#), [Tbed_mussel\(\)](#), [Tsoil\(\)](#), [actual_vapor_pressure\(\)](#), [boundary_layer_resistance\(\)](#), [external_resistance_to_water_vapor_transfer\(\)](#), [free_or_forced_convection\(\)](#), [heat_transfer_coefficient_approximation\(\)](#), [heat_transfer_coefficient_simple\(\)](#), [heat_transfer_coefficient_saturated_vapor_pressure\(\)](#), [saturation_vapor_pressure\(\)](#), [saturation_water_vapor_pressure\(\)](#)

Examples

```
Tb_butterfly(T_a = 25,
             T_g = 25,
             T_sh = 20,
             u = 0.4,
             H_sdir = 300,
             H_sdif = 100,
             z = 30,
             D = 0.36,
             delta = 1.46,
             alpha = 0.6,
             r_g = 0.3)
```

Tb_CampbellNorman	<i>Operative Environmental Temperature of an Ectotherm based on Campbell and Norman (1988)</i>
-------------------	--

Description

The function estimates body temperatures (K, operative environmental temperature) of an ectotherm using an approximation based on Campbell and Norman (1998) and Mitchell (1976).

Usage

```
Tb_CampbellNorman(
  T_a,
  T_g,
  S,
  alpha_S = 0.7,
  alpha_L = 0.96,
  epsilon = 0.96,
  c_p = 29.3,
  D,
  V
)
```

Arguments

T_a	numeric air temperature (K).
T_g	numeric ground temperature (K).
S	numeric flux density of solar radiation (Wm^{-2}), combining direct, diffuse, and reflected radiation accounting for view factors.
alpha_S	numeric organismal solar absorptivity (proportion).
alpha_L	numeric organismal thermal absorptivity (proportion); 0.965 for lizards (Bartlett and Gates 1967).

epsilon	numeric longwave infrared emissivity of skin (proportion), 0.95 to 1 for most animals (Gates 1980).
c_p	numeric specific heat of air ($Jmol^{-1}K^{-1}$).
D	numeric characteristic dimension of the animal (m).
V	numeric wind speed (ms^{-1}).

Details

Boundary conductance uses a factor of 1.4 to account for increased convection (Mitchell 1976). The function assumes forced conduction.

Value

numeric operative environmental temperature, T_e (K).

References

- Bartlett PN, Gates DM (1967). "The energy budget of a lizard on a tree trunk." *Ecology*, **48**, 316-322.
- Campbell GS, Norman JM (1998). *Introduction to environmental biophysics*, 2nd ed. edition. Springer, New York. ISBN 0387949372.
- Gates DM (1980). *Biophysical Ecology*. Springer-Verlag, New York, NY, USA.
- Mitchell JW (1976). "Heat transfer from spheres and other animal forms." *Biophysical Journal*, **16**(6), 561-569. ISSN 0006-3495, doi: [10.1016/S00063495\(76\)857116](https://doi.org/10.1016/S00063495(76)857116), <https://www.sciencedirect.com/science/article/pii/S0006349576857116>.

See Also

Other biophysical models: [Grashof_number_Gates\(\)](#), [Grashof_number\(\)](#), [Nusselt_from_Grashof\(\)](#), [Nusselt_from_Reynolds\(\)](#), [Nusselt_number\(\)](#), [Prandtl_number\(\)](#), [Qconduction_animal\(\)](#), [Qconduction_substrate\(\)](#), [Qconvection\(\)](#), [Qemitted_thermal_radiation\(\)](#), [Qevaporation\(\)](#), [Qmetabolism_from_mass_temp\(\)](#), [Qmetabolism_from_mass\(\)](#), [Qnet_Gates\(\)](#), [Qradiation_absorbed\(\)](#), [Qthermal_radiation_absorbed\(\)](#), [Reynolds_number\(\)](#), [Tb_Gates2\(\)](#), [Tb_Gates\(\)](#), [Tb_butterfly\(\)](#), [Tb_grasshopper\(\)](#), [Tb_limpetBH\(\)](#), [Tb_limpet\(\)](#), [Tb_lizard_Fei\(\)](#), [Tb_lizard\(\)](#), [Tb_mussel\(\)](#), [Tb_salamander_humid\(\)](#), [Tb_snail\(\)](#), [Tbed_mussel\(\)](#), [Tsoil\(\)](#), [actual_vapor_pressure\(\)](#), [boundary_layer_resistance\(\)](#), [external_resistance_to_water_vapor_transfer\(\)](#), [free_or_forced_convection\(\)](#), [heat_transfer_coefficient_approximation\(\)](#), [heat_transfer_coefficient_simple\(\)](#), [heat_transfer_coefficient_saturation_vapor_pressure\(\)](#), [saturation_water_vapor_pressure\(\)](#)

Examples

```
Tb_CampbellNorman (T_a = 303,
                  T_g = 303,
                  S = 823,
                  alpha_S = 0.7,
                  alpha_L = 0.96,
```

```

epsilon = 0.96,
c_p     = 29.3,
D       = 0.17,
V       = 1)

```

Tb_Gates *Operative Environmental Temperature of an Ectotherm Based on Gates (1980)*

Description

The function predicts body temperatures (K, operative environmental temperature) of an ectotherm using the approximation in Gates (1980). The functions omits evaporative and metabolic heat loss (Mitchell 1976; Kingsolver 1983).

Usage

```

Tb_Gates(
  A,
  D,
  psa_dir,
  psa_ref,
  psa_air,
  psa_g,
  T_g,
  T_a,
  Qabs,
  epsilon,
  H_L,
  ef = 1.3,
  K
)

```

Arguments

A	numeric surface area (m^2).
D	numeric characteristic dimension for conduction (meters).
psa_dir	numeric proportion surface area exposed to direct radiation from the sky (or enclosure) (0-1).
psa_ref	numeric proportion surface area exposed to reflected radiation from the ground (0-1).
psa_air	numeric proportion surface area exposed to air (0-1).
psa_g	numeric proportion surface area in contact with substrate (0-1).
T_g	numeric ground surface temperature (K).

T_a	numeric ambient air temperature (K).
Qabs	numeric Solar radiation absorbed (W).
epsilon	numeric longwave infrared emissivity of skin (proportion), 0.95 to 1 for most animals (Gates 1980).
H_L	numeric Convective heat transfer coefficient ($Wm^{-2}K^{-1}$).
ef	numeric enhancement factor used to adjust H_L to field conditions using h_L approximation from Mitchell (1976). Approximated as 1.23 by default, but see Mitchell (1976) for relationship.
K	numeric Thermal conductivity ($WK^{-1}m^{-1}$), $K = 0.5 WK^{-1}m^{-1}$ for naked skin, $K = 0.15 WK^{-1}m^{-1}$ for insect cuticle Galushko et al. (2005); conductivity of the ground is generally greater than that of animal tissues, so animal thermal conductivity is generally the rate limiting step.

Value

numeric operative environmental temperature, T_e (K).

References

- Galushko D, Ermakov N, Karpovski M, Palevski A, Ishay JS, Bergman DJ (2005). “Electrical, thermoelectric and thermophysical properties of hornet cuticle.” *Semiconductor Science and Technology*, **20**(3), 286–289. doi: [10.1088/02681242/20/3/005](https://doi.org/10.1088/02681242/20/3/005).
- Gates DM (1980). *Biophysical Ecology*. Springer-Verlag, New York, NY, USA.
- Kingsolver JG (1983). “Thermoregulation and Flight in Colias Butterflies: Elevational Patterns and Mechanistic Limitations.” *Ecology*, **64**(3), 534-545. doi: [10.2307/1939973](https://doi.org/10.2307/1939973).
- Mitchell JW (1976). “Heat transfer from spheres and other animal forms.” *Biophysical Journal*, **16**(6), 561-569. ISSN 0006-3495, doi: [10.1016/S00063495\(76\)857116](https://doi.org/10.1016/S00063495(76)857116), <https://www.sciencedirect.com/science/article/pii/S0006349576857116>.

See Also

Other biophysical models: [Grashof_number_Gates\(\)](#), [Grashof_number\(\)](#), [Nusselt_from_Grashof\(\)](#), [Nusselt_from_Reynolds\(\)](#), [Nusselt_number\(\)](#), [Prandtl_number\(\)](#), [Qconduction_animal\(\)](#), [Qconduction_substrate\(\)](#), [Qconvection\(\)](#), [Qemitted_thermal_radiation\(\)](#), [Qevaporation\(\)](#), [Qmetabolism_from_mass_temp\(\)](#), [Qmetabolism_from_mass\(\)](#), [Qnet_Gates\(\)](#), [Qradiation_absorbed\(\)](#), [Qthermal_radiation_absorbed\(\)](#), [Reynolds_number\(\)](#), [Tb_CampbellNorman\(\)](#), [Tb_Gates2\(\)](#), [Tb_butterfly\(\)](#), [Tb_grasshopper\(\)](#), [Tb_limpetBH\(\)](#), [Tb_limpet\(\)](#), [Tb_lizard_Fei\(\)](#), [Tb_lizard\(\)](#), [Tb_mussel\(\)](#), [Tb_salamander_humid\(\)](#), [Tb_snail\(\)](#), [Tbed_mussel\(\)](#), [Tsoil\(\)](#), [actual_vapor_pressure\(\)](#), [boundary_layer_resistance\(\)](#), [external_resistance_to_water_vapor_transfer\(\)](#), [free_or_forced_convection\(\)](#), [heat_transfer_coefficient_approximation\(\)](#), [heat_transfer_coefficient_simple\(\)](#), [heat_transfer_coefficient_saturation_vapor_pressure\(\)](#), [saturation_water_vapor_pressure\(\)](#)

Examples

```
Tb_Gates (A      = 1,
          D      = 0.001,
          psa_dir = 0.6,
          psa_ref = 0.4,
          psa_air = 0.6,
          psa_g   = 0.2,
          T_g     = 303,
          T_a     = 310,
          Qabs    = 2,
          epsilon = 0.95,
          H_L     = 10,
          ef      = 1.23,
          K       = 0.5)
```

Tb_Gates2 *Operative Environmental Temperature of an Ectotherm Based on a Variant of Gates (1980)*

Description

The function predicts body temperatures (K, operative environmental temperature) of an ectotherm using the approximation in Gates (1980). The function omits evaporative and metabolic heat loss.

Usage

```
Tb_Gates2(A, D, T_g, T_a, Qabs, V, epsilon)
```

Arguments

A	numeric surface area (m^2).
D	numeric characteristic dimension for conduction (meters).
T_g	numeric ground surface temperature (K).
T_a	numeric ambient air temperature (K).
Qabs	numeric Solar radiation absorbed (W).
V	numeric Wind speed (ms^{-1}).
epsilon	numeric longwave infrared emissivity of skin (proportion), 0.95 to 1 for most animals (Gates 1980).

Value

numeric operative environmental temperature (K).

References

Gates DM (1980). *Biophysical Ecology*. Springer-Verlag, New York, NY, USA.

See Also

Other biophysical models: `Grashof_number_Gates()`, `Grashof_number()`, `Nusselt_from_Grashof()`, `Nusselt_from_Reynolds()`, `Nusselt_number()`, `Prandtl_number()`, `Qconduction_animal()`, `Qconduction_substrate()`, `Qconvection()`, `Qemitted_thermal_radiation()`, `Qevaporation()`, `Qmetabolism_from_mass_temp()`, `Qmetabolism_from_mass()`, `Qnet_Gates()`, `Qradiation_absorbed()`, `Qthermal_radiation_absorbed()`, `Reynolds_number()`, `Tb_CampbellNorman()`, `Tb_Gates()`, `Tb_butterfly()`, `Tb_grasshopper()`, `Tb_limpetBH()`, `Tb_limpet()`, `Tb_lizard_Fei()`, `Tb_lizard()`, `Tb_mussel()`, `Tb_salamander_humid()`, `Tb_snail()`, `Tbed_mussel()`, `Tsoil()`, `actual_vapor_pressure()`, `boundary_layer_resistance()`, `external_resistance_to_water_vapor_transfer()`, `free_or_forced_convection()`, `heat_transfer_coefficient_approximation()`, `heat_transfer_coefficient_simple()`, `heat_transfer_coefficient_saturation_vapor_pressure()`, `saturation_vapor_pressure()`, `saturation_water_vapor_pressure()`

Examples

```
Tb_Gates2(A      = 1,
          D      = 0.001,
          T_g    = 300,
          T_a    = 310,
          Qabs   = 2,
          V      = 0.1,
          epsilon = 1)
```

Tb_grasshopper

Operative Environmental Temperature of a Grasshopper

Description

The function estimates body temperatures (C, operative environmental temperatures) of a grasshopper based on Lactin and Johnson (1998). Part of the model is based on Swinbank (1963), following Gates (1962) in Kingsolver (1983).

Usage

```
Tb_grasshopper(
  T_a,
  T_g,
  u,
  H,
  K_t,
  psi,
  l,
  Acondfact = 0.25,
  z = 0.001,
  abs = 0.7,
  r_g = 0.3
)
```

Arguments

T_a	numeric air temperature (C).
T_g	numeric surface temperature (C). Kingsolver (1983) assumes $T_g - T_a = 8.4$.
u	numeric wind speed (ms^{-1}).
H	numeric total (direct + diffuse) solar radiation flux (Wm^{-2}).
K_t	numeric clearness index (dimensionless), which is the ratio of the global solar radiation measured at the surface to the total solar radiation at the top of the atmosphere.
psi	numeric solar zenith angle (degrees).
l	numeric grasshopper length (m).
Acondfact	numeric the proportion of the grasshopper surface area that is in contact with the ground.
z	numeric distance from the ground to the grasshopper (m).
abs	numeric absorptivity of the grasshopper to solar radiation (proportion). See Anderson et al. (1979).
r_g	numeric substrate solar reflectivity (proportion). See Kingsolver (1983).

Details

Total radiative flux is calculated as thermal radiative heat flux plus convective heat flux, following Kingsolver (1983), with the Erbs et al. (1982) model from Wong and Chow (2001).

Energy balance is based on Kingsolver (1983).

Radiation is calculated without area dependence (Anderson et al. 1979).

The body of a grasshopper female is approximated by a rotational ellipsoid with half the body length as the semi-major axis (Samietz et al. 2005).

The diffuse fraction is corrected following Olyphant (1984).

Value

numeric predicted body (operative environmental) temperature (C).

References

Anderson RV, Tracy CR, Abramsky Z (1979). "Habitat Selection in Two Species of Short-Horned Grasshoppers. The Role of Thermal and Hydric Stresses." *Oecologia*, **38**(3), 359–374. doi: [10.1007/BF00345194](https://doi.org/10.1007/BF00345194).

Erbs D, Klein S, Duffie J (1982). "Estimation of the diffuse radiation fraction for hourly, daily and monthly-average global radiation." *Solar Energy*, **28**, 293-302.

Gates DM (1962). "Leaf temperature and energy exchange." *Archiv fur Meteorologie, Geophysik*

und Bioklimatologie, Serie B volume, **12**, 321-336.

Kingsolver JG (1983). “Thermoregulation and Flight in Colias Butterflies: Elevational Patterns and Mechanistic Limitations.” *Ecology*, **64**(3), 534-545. doi: [10.2307/1939973](https://doi.org/10.2307/1939973).

Lactin DJ, Johnson DL (1998). “Convective heat loss and change in body temperature of grasshopper and locust nymphs: Relative importance of wind speed, insect size and insect orientation.” *Journal of Thermal Biology*, **23**(1), 5-13. ISSN 0306-4565, doi: [10.1016/S03064565\(97\)000375](https://doi.org/10.1016/S03064565(97)000375), <https://www.sciencedirect.com/science/article/pii/S0306456597000375>.

Olyphant G (1984). “Insolation Topoclimates and Potential Ablation in Alpine Snow Accumulation Basins: Front Range, Colorado.” *Water Resources Research*, **20**(4), 491-498.

Samietz J, Salser MA, Dingle H (2005). “Altitudinal variation in behavioural thermoregulation: local adaptation vs. plasticity in California grasshoppers.” *Journal of Evolutionary Biology*, **18**(4), 1087-1096. doi: [10.1111/j.14209101.2005.00893.x](https://doi.org/10.1111/j.14209101.2005.00893.x).

Swinbank WC (1963). “Long-wave radiation from clear skies.” *Quarterly Journal of the Royal Meteorological Society*, **89**, 339-348.

Wong LT, Chow WK (2001). “Solar radiation model.” *Applied Energy*, **69**(3), 191-224. ISSN 0306-2619, doi: [10.1016/S03062619\(01\)000125](https://doi.org/10.1016/S03062619(01)000125), <https://www.sciencedirect.com/science/article/pii/S0306261901000125>.

See Also

Other biophysical models: [Grashof_number_Gates\(\)](#), [Grashof_number\(\)](#), [Nusselt_from_Grashof\(\)](#), [Nusselt_from_Reynolds\(\)](#), [Nusselt_number\(\)](#), [Prandtl_number\(\)](#), [Qconduction_animal\(\)](#), [Qconduction_substrate\(\)](#), [Qconvection\(\)](#), [Qemitted_thermal_radiation\(\)](#), [Qevaporation\(\)](#), [Qmetabolism_from_mass_temp\(\)](#), [Qmetabolism_from_mass\(\)](#), [Qnet_Gates\(\)](#), [Qradiation_absorbed\(\)](#), [Qthermal_radiation_absorbed\(\)](#), [Reynolds_number\(\)](#), [Tb_CampbellNorman\(\)](#), [Tb_Gates2\(\)](#), [Tb_Gates\(\)](#), [Tb_butterfly\(\)](#), [Tb_limpetBH\(\)](#), [Tb_limpet\(\)](#), [Tb_lizard_Fei\(\)](#), [Tb_lizard\(\)](#), [Tb_mussel\(\)](#), [Tb_salamander_humid\(\)](#), [Tb_snail\(\)](#), [Tbed_mussel\(\)](#), [Tsoil\(\)](#), [actual_vapor_pressure\(\)](#), [boundary_layer_resistance\(\)](#), [external_resistance_to_water_vapor_transfer\(\)](#), [free_or_forced_convection\(\)](#), [heat_transfer_coefficient_approximation\(\)](#), [heat_transfer_coefficient_simple\(\)](#), [heat_transfer_coefficient_saturated_vapor_pressure\(\)](#), [saturation_vapor_pressure\(\)](#), [saturation_water_vapor_pressure\(\)](#)

Examples

```
Tb_grasshopper(T_a      = 25,
               T_g      = 25,
               u        = 0.4,
               H        = 400,
               K_t      = 0.7,
               psi      = 30,
               l        = 0.02,
               Acondfact = 0.25,
               z        = 0.001,
               abs      = 0.7,
               r_g      = 0.3)
```

Tb_limpet *Operative Environmental Temperature of a Limpet*

Description

The function estimates body temperatures (C, operative environmental temperatures) of a limpet based on Denny and Harley (2006).

Usage

```
Tb_limpet(T_a, T_r, l, h, I, u, psi, c, position = "anterior")
```

Arguments

T_a	numeric air temperature (C).
T_r	numeric rock surface temperature (C) in the sunlight.
l	numeric limpet length (anterior/posterior axis, m).
h	numeric limpet height (dorsal/ventral axis, m).
I	numeric solar irradiance (Wm^{-2}).
u	numeric wind speed (ms^{-1}).
psi	numeric solar zenith angle (degrees). Can be calculated from zenith_angle function.
c	numeric fraction of the sky covered by cloud (proportion).
position	character direction of the limpet that is facing upwind. Options are "anterior", "posterior", and "broadside".

Details

The original equation uses a finite-difference approach where they divide the rock into series of chunks, and calculate the temperature at each node to derive the conductive heat. For simplification, here it takes the rock temperature as a parameter, and conductive heat is calculated as a product of the area, thermal conductivity of rock and the temperature difference between the rock and the body.

Limpets are simulated as cones following and using solar emissivity values from Campbell and Norman (1998).

The area of the limpet's shell (m^2) is projected according to the direction at which sunlight strikes the organism (Pennell and Deignan 1989).

Air conductivity values ($Wm^{-1}K^{-1}$) are calculated following Denny and Harley (2006).

Value

numeric predicted body (operative environmental) temperature (C).

References

Campbell GS, Norman JM (1998). *Introduction to environmental biophysics*, 2nd ed. edition. Springer, New York. ISBN 0387949372.

Denny MW, Harley CDG (2006). "Hot limpets: predicting body temperature in a conductance-mediated thermal system." *Journal of Experimental Biology*, **209**(13), 2409-2419. ISSN 0022-0949, doi: [10.1242/jeb.02356](https://doi.org/10.1242/jeb.02356).

Pennell S, Deignan J (1989). "Computing the Projected Area of a Cone." *SIAM Review*, **31**, 299-302. <https://epubs.siam.org/doi/10.1137/1031052>.

See Also

Other biophysical models: [Grashof_number_Gates\(\)](#), [Grashof_number\(\)](#), [Nusselt_from_Grashof\(\)](#), [Nusselt_from_Reynolds\(\)](#), [Nusselt_number\(\)](#), [Prandtl_number\(\)](#), [Qconduction_animal\(\)](#), [Qconduction_substrate\(\)](#), [Qconvection\(\)](#), [Qemitted_thermal_radiation\(\)](#), [Qevaporation\(\)](#), [Qmetabolism_from_mass_temp\(\)](#), [Qmetabolism_from_mass\(\)](#), [Qnet_Gates\(\)](#), [Qradiation_absorbed\(\)](#), [Qthermal_radiation_absorbed\(\)](#), [Reynolds_number\(\)](#), [Tb_CampbellNorman\(\)](#), [Tb_Gates2\(\)](#), [Tb_Gates\(\)](#), [Tb_butterfly\(\)](#), [Tb_grasshopper\(\)](#), [Tb_limpetBH\(\)](#), [Tb_lizard_Fei\(\)](#), [Tb_lizard\(\)](#), [Tb_mussel\(\)](#), [Tb_salamander_humid\(\)](#), [Tb_snail\(\)](#), [Tbed_mussel\(\)](#), [Tsoil\(\)](#), [actual_vapor_pressure\(\)](#), [boundary_layer_resistance\(\)](#), [external_resistance_to_water_vapor_transfer\(\)](#), [free_or_forced_convection\(\)](#), [heat_transfer_coefficient_approximation\(\)](#), [heat_transfer_coefficient_simple\(\)](#), [heat_transfer_coefficient_saturation_vapor_pressure\(\)](#), [saturation_vapor_pressure\(\)](#), [saturation_water_vapor_pressure\(\)](#)

Examples

```
Tb_limpet(T_a      = 25,
          T_r      = 30,
          l        = 0.0176,
          h        = 0.0122,
          I        = 1300,
          u        = 1,
          psi      = 30,
          c        = 1,
          position = "anterior")
```

Tb_limpetBH

*Operative Environmental Temperature of a Limpet Based on a Model
by Helmuth*

Description

The function predicts body temperatures (C, operative environmental temperatures) of a limpet. The function was provided by Brian Helmuth – although radiation and convection are altered from his original model – and based on Denny and Harley (2006).

Usage

Tb_limpetBH(T_a, T_r, l, h, I, u, s_aspect, s_slope, c)

Arguments

T_a	numeric air temperature (C).
T_r	numeric rock surface temperature (C) in the sunlight.
l	numeric limpet length (anterior/posterior axis) (m).
h	numeric limpet height (dorsal/ventral axis) (m).
I	numeric solar irradiance (Wm^{-2}).
u	numeric wind speed (ms^{-1}).
s_aspect	numeric solar aspect angle (degree), the angle between the limpet's length dimension and the vector to the Sun. Generally between 70 and 110 degrees.
s_slope	numeric solar elevation angle (degree), the altitude of the sun, which is the angle between the horizon and the sun.
c	numeric fraction of the sky covered by clouds.

Details

The original equation uses a finite-difference approach where they divide the rock into series of chunks, and calculate the temperature at each node to derive the conductive heat. For simplification, here it takes the rock temperature as a parameter, and conductive heat is calculated by the product of the area, thermal conductivity of rock and the difference in temperatures of the rock and the body.

Limpets are simulated as cones following and using solar emissivity values from Campbell and Norman (1998).

The area of the limpet's shell (m^2) is projected in the direction at which sunlight strikes the organism Pennell and Deignan (1989).

Air conductivity values ($Wm^{-1}K^{-1}$) are calculated following Denny and Harley (2006).

Value

numeric predicted body (operative environmental) temperature (C).

Author(s)

Brian Helmuth et al.

References

Campbell GS, Norman JM (1998). *Introduction to environmental biophysics*, 2nd ed. edition. Springer, New York. ISBN 0387949372.

Denny MW, Harley CDG (2006). “Hot limpets: predicting body temperature in a conductance-mediated thermal system.” *Journal of Experimental Biology*, **209**(13), 2409-2419. ISSN 0022-0949, doi: [10.1242/jeb.02356](https://doi.org/10.1242/jeb.02356).

Pennell S, Deignan J (1989). “Computing the Projected Area of a Cone.” *SIAM Review*, **31**, 299-302. <https://epubs.siam.org/doi/10.1137/1031052>.

See Also

Other biophysical models: [Grashof_number_Gates\(\)](#), [Grashof_number\(\)](#), [Nusselt_from_Grashof\(\)](#), [Nusselt_from_Reynolds\(\)](#), [Nusselt_number\(\)](#), [Prandtl_number\(\)](#), [Qconduction_animal\(\)](#), [Qconduction_substrate\(\)](#), [Qconvection\(\)](#), [Qemitted_thermal_radiation\(\)](#), [Qevaporation\(\)](#), [Qmetabolism_from_mass_temp\(\)](#), [Qmetabolism_from_mass\(\)](#), [Qnet_Gates\(\)](#), [Qradiation_absorbed\(\)](#), [Qthermal_radiation_absorbed\(\)](#), [Reynolds_number\(\)](#), [Tb_CampbellNorman\(\)](#), [Tb_Gates2\(\)](#), [Tb_Gates\(\)](#), [Tb_butterfly\(\)](#), [Tb_grasshopper\(\)](#), [Tb_limpet\(\)](#), [Tb_lizard_Fei\(\)](#), [Tb_lizard\(\)](#), [Tb_mussel\(\)](#), [Tb_salamander_humid\(\)](#), [Tb_snail\(\)](#), [Tbed_mussel\(\)](#), [Tsoil\(\)](#), [actual_vapor_pressure\(\)](#), [boundary_layer_resistance\(\)](#), [external_resistance_to_water_vapor_transfer\(\)](#), [free_or_forced_convection_heat_transfer_coefficient_approximation\(\)](#), [heat_transfer_coefficient_simple\(\)](#), [heat_transfer_coefficient_saturation_vapor_pressure\(\)](#), [saturation_vapor_pressure\(\)](#), [saturation_water_vapor_pressure\(\)](#)

Examples

```
Tb_limpetBH(T_a = 25,
            T_r = 30,
            l = 0.0176,
            h = 0.0122,
            I = 1300,
            u = 1,
            s_aspect = 90,
            s_slope = 60,
            c = 1)
```

Tb_lizard

Operative Environmental Temperature of a Lizard

Description

The function estimates body temperature (C, operative environmental temperature) of a lizard based on Campbell and Norman (1998). The function was designed for Sceloporus lizards and described in Buckley (2008).

Usage

```
Tb_lizard(
  T_a,
  T_g,
  u,
```

```

svl,
m,
psi,
rho_S,
elev,
doy,
sun = TRUE,
surface = TRUE,
alpha_S = 0.9,
alpha_L = 0.965,
epsilon_s = 0.965,
F_d = 0.8,
F_r = 0.5,
F_a = 0.5,
F_g = 0.5
)

```

Arguments

T_a	numeric air temperature (C).
T_g	numeric surface temperature (C).
u	numeric wind speed (ms^{-1}).
svl	numeric lizard snout vent length (mm).
m	numeric lizard mass (g); note that it can be estimated as in mass_from_length : $3.55 * 10^{-5} * length^3$
psi	numeric solar zenith angle (degrees).
rho_S	numeric surface albedo (proportion). ~ 0.25 for grass, ~ 0.1 for dark soil, > 0.75 for fresh snow (Campbell and Norman 1998).
elev	numeric elevation (m).
doy	numeric day of year (1-366).
sun	logical indicates whether lizard is in sun (TRUE) or shade (FALSE).
surface	logical indicates whether lizard is on ground surface (TRUE) or above the surface (FALSE, e.g. in a tree).
alpha_S	numeric lizard solar absorptivity (proportion), alpha_S = 0.9 (Gates 1980) (Table 11.4).
alpha_L	numeric lizard thermal absorptivity (proportion), alpha_L = 0.965 (Bartlett and Gates 1967).
epsilon_s	numeric surface emissivity of lizards (proportion), epsilon_s = 0.965 (Bartlett and Gates 1967).
F_d	numeric the view factor between the surface of the lizard and diffuse solar radiation (proportion). i.e., the portion of the lizard surface that is exposed to diffuse solar radiation (Bartlett and Gates 1967).
F_r	numeric the view factor between the surface of the lizard and reflected solar radiation (proportion).

F_a	numeric the view factor between the surface of the lizard and atmospheric radiation (proportion).
F_g	numeric the view factor between the surface of the lizard and ground thermal radiation (proportion).

Details

The proportion of radiation that is direct is determined following Sears et al. (2011).

Boundary conductance uses a factor of 1.4 to account for increased convection (Mitchell 1976).

Value

T_e numeric predicted body (operative environmental) temperature (C).

References

Bartlett PN, Gates DM (1967). "The energy budget of a lizard on a tree trunk." *Ecology*, **48**, 316-322.

Buckley LB (2008). "Linking traits to energetics and population dynamics to predict lizard ranges in changing environments." *American Naturalist*, **171**(1), E1 - E19. doi: [10.1086/523949](https://pubmed.ncbi.nlm.nih.gov/18171140/), <https://pubmed.ncbi.nlm.nih.gov/18171140/>.

Campbell GS, Norman JM (1998). *Introduction to environmental biophysics*, 2nd ed. edition. Springer, New York. ISBN 0387949372.

Gates DM (1980). *Biophysical Ecology*. Springer-Verlag, New York, NY, USA.

Mitchell JW (1976). "Heat transfer from spheres and other animal forms." *Biophysical Journal*, **16**(6), 561-569. ISSN 0006-3495, doi: [10.1016/S00063495\(76\)857116](https://www.sciencedirect.com/science/article/pii/S0006349576857116), <https://www.sciencedirect.com/science/article/pii/S0006349576857116>.

Sears MW, Raskin E, Angilletta Jr. MJ (2011). "The World Is not Flat: Defining Relevant Thermal Landscapes in the Context of Climate Change." *Integrative and Comparative Biology*, **51**(5), 666-675. ISSN 1540-7063, doi: [10.1093/icb/icr111](https://academic.oup.com/icb/article-pdf/51/5/666/1757893/icr111.pdf), <https://academic.oup.com/icb/article-pdf/51/5/666/1757893/icr111.pdf>.

See Also

Other biophysical models: [Grashof_number_Gates\(\)](#), [Grashof_number\(\)](#), [Nusselt_from_Grashof\(\)](#), [Nusselt_from_Reynolds\(\)](#), [Nusselt_number\(\)](#), [Prandtl_number\(\)](#), [Qconduction_animal\(\)](#), [Qconduction_substrate\(\)](#), [Qconvection\(\)](#), [Qemitted_thermal_radiation\(\)](#), [Qevaporation\(\)](#), [Qmetabolism_from_mass_temp\(\)](#), [Qmetabolism_from_mass\(\)](#), [Qnet_Gates\(\)](#), [Qradiation_absorbed\(\)](#), [Qthermal_radiation_absorbed\(\)](#), [Reynolds_number\(\)](#), [Tb_CampbellNorman\(\)](#), [Tb_Gates2\(\)](#), [Tb_Gates\(\)](#), [Tb_butterfly\(\)](#), [Tb_grasshopper\(\)](#), [Tb_limpetBH\(\)](#), [Tb_limpet\(\)](#), [Tb_lizard_Fei\(\)](#), [Tb_mussel\(\)](#), [Tb_salamander_humid\(\)](#), [Tb_snail\(\)](#), [Tbed_mussel\(\)](#), [Tsoil\(\)](#), [actual_vapor_pressure\(\)](#), [boundary_layer_resistance\(\)](#), [external_resistance_to_water_vapor_transfer\(\)](#), [free_or_forced_convection\(\)](#), [heat_transfer_coefficient_approximation\(\)](#), [heat_transfer_coefficient_simple\(\)](#), [heat_transfer_coefficient_saturation_vapor_pressure\(\)](#), [saturation_vapor_pressure\(\)](#), [saturation_water_vapor_pressure\(\)](#)

Examples

```
Tb_lizard(T_a      = 25,
          T_g      = 30,
          u        = 0.1,
          svl      = 60,
          m        = 10,
          psi      = 34,
          rho_S    = 0.24,
          elev     = 500,
          doy      = 200,
          sun      = TRUE,
          surface  = TRUE,
          alpha_S  = 0.9,
          alpha_L  = 0.965,
          epsilon_s = 0.965,
          F_d      = 0.8,
          F_r      = 0.5,
          F_a      = 0.5,
          F_g      = 0.5)
```

Tb_lizard_Fei

Operative Temperature of a Lizard Using Fei et al. (2012)

Description

The function predicts body temperature (K, operative environmental temperature) of a lizard based on Fei et al. (2012).

Usage

```
Tb_lizard_Fei(T_a, T_g, H, lw, shade, m, Acondfact, Agradfact)
```

Arguments

T_a	numeric air temperature at lizard height (K).
T_g	numeric surface temperature (K).
H	numeric total (direct + diffuse) solar radiation flux (Wm^{-2}).
lw	numeric downward flux of near-infrared radiation (Wm^{-2}).
shade	numeric proportion of shade.
m	numeric lizard mass (g).
Acondfact	numeric proportion of the lizard projected area that is in contact with the ground. Acondfact = 0.1 for standing and Acondfact = 0.4 for lying on ground.
Agradfact	numeric proportion of the lizard projected area exposed to radiation from the ground. Agradfact = 0.3 for standing and Agradfact = 0.0 for lying on ground.

Details

Thermal radiative flux is calculated following Fei et al. (2012) based on Bartlett and Gates (1967) and Porter et al. (1973).

Value

numeric predicted body (operative environmental) temperature (K).

Author(s)

Ofir Levy

References

Bartlett PN, Gates DM (1967). "The energy budget of a lizard on a tree trunk." *Ecology*, **48**, 316-322.

Fei T, Skidmore AK, Venus V, Wang T, Schlerf M, Toxopeus B, van Overjijk S, Bian M, Liu Y (2012). "A body temperature model for lizards as estimated from the thermal environment." *Journal of Thermal Biology*, **37**(1), 56-64. ISSN 0306-4565, doi: [10.1016/j.jtherbio.2011.10.013](https://doi.org/10.1016/j.jtherbio.2011.10.013), <https://www.sciencedirect.com/science/article/pii/S0306456511001513>.

Porter WP, Mitchell JW, Bekman A, DeWitt CB (1973). "Behavioral implications of mechanistic ecology: thermal and behavioral modeling of desert ectotherms and their microenvironments." *Oecologia*, **13**, 1-54.

See Also

Other biophysical models: [Grashof_number_Gates\(\)](#), [Grashof_number\(\)](#), [Nusselt_from_Grashof\(\)](#), [Nusselt_from_Reynolds\(\)](#), [Nusselt_number\(\)](#), [Prandtl_number\(\)](#), [Qconduction_animal\(\)](#), [Qconduction_substrate\(\)](#), [Qconvection\(\)](#), [Qemitted_thermal_radiation\(\)](#), [Qevaporation\(\)](#), [Qmetabolism_from_mass_temp\(\)](#), [Qmetabolism_from_mass\(\)](#), [Qnet_Gates\(\)](#), [Qradiation_absorbed\(\)](#), [Qthermal_radiation_absorbed\(\)](#), [Reynolds_number\(\)](#), [Tb_CampbellNorman\(\)](#), [Tb_Gates2\(\)](#), [Tb_Gates\(\)](#), [Tb_butterfly\(\)](#), [Tb_grasshopper\(\)](#), [Tb_limpetBH\(\)](#), [Tb_limpet\(\)](#), [Tb_lizard\(\)](#), [Tb_mussel\(\)](#), [Tb_salamander_humid\(\)](#), [Tb_snail\(\)](#), [Tbed_mussel\(\)](#), [Tsoil\(\)](#), [actual_vapor_pressure\(\)](#), [boundary_layer_resistance\(\)](#), [external_resistance_to_water_vapor_transfer\(\)](#), [free_or_forced_convection\(\)](#), [heat_transfer_coefficient_approximation\(\)](#), [heat_transfer_coefficient_simple\(\)](#), [heat_transfer_coefficient_saturation_vapor_pressure\(\)](#), [saturation_vapor_pressure\(\)](#), [saturation_water_vapor_pressure\(\)](#)

Examples

```
Tb_lizard_Fei(T_a      = 293,
              T_g      = 300,
              H        = 1300,
              lw       = 60,
              shade    = 0.5,
              m        = 10.5,
              Acondfact = 0.1,
              Agradfact = 0.3)
```

Tb_mussel

*Operative Environmental Temperature of a Mussel***Description**

The function estimates body temperature (C, operative environmental temperature) of a mussel. The function implements a steady-state model, which assumes unchanging environmental conditions.

Usage

```
Tb_mussel(l, h, T_a, T_g, S, k_d, u, psi, cl, evap = FALSE, group = "solitary")
```

Arguments

l	numeric mussel length (anterior/posterior axis, m).
h	numeric mussel height (dorsal/ventral axis, m). It is reasonable to assume $h = 0.5 * l$.
T_a	numeric air temperature (C).
T_g	numeric ground temperature (C).
S	numeric direct solar flux density (Wm^{-2}).
k_d	numeric diffuse fraction, proportion of solar radiation that is diffuse.
u	numeric wind speed (ms^{-1}).
psi	numeric solar zenith angle (degrees): can be calculated from zenith_angle .
cl	numeric fraction of the sky covered by cloud.
evap	logical Whether mussel is gaping to evaporatively cool. If TRUE, the function assumes a constant mass loss rate of 5 percent of the initial body mass per hour.
group	character; options are "aggregated": mussels living in beds; "solitary": solitary individual, anterior or posterior end facing upwind; and "solitary_valve": solitary individual, valve facing upwind.

Details

Thermal radiative flux is calculated following Helmuth (1998), Helmuth (1999), and Idso and Jackson (1969).

Value

numeric predicted body (operative environmental) temperature (C).

References

Helmuth B (1999). “Thermal biology of rocky intertidal mussels: quantifying body temperatures using climatological data.” *Ecology*, **80**(1), 15-34. <https://esajournals.onlinelibrary.wiley.com/doi/abs/10.1890/0012-9658%281999%29080%5B0015%3ATBORIM%5D2.0.CO%3B2>.

Helmuth BST (1998). “Intertidal Mussel Microclimates: Predicting the Body Temperature of a Sessile Invertebrate.” *Ecological Monographs*, **68**(1), 51–74. ISSN 00129615, doi: [10.2307/2657143](https://doi.org/10.2307/2657143).

Idso SB, Jackson RD (1969). “Thermal radiation from the atmosphere.” *Journal of Geophysical Research (1896-1977)*, **74**(23), 5397-5403. doi: [10.1029/JC074i023p05397](https://doi.org/10.1029/JC074i023p05397).

See Also

Other biophysical models: [Grashof_number_Gates\(\)](#), [Grashof_number\(\)](#), [Nusselt_from_Grashof\(\)](#), [Nusselt_from_Reynolds\(\)](#), [Nusselt_number\(\)](#), [Prandtl_number\(\)](#), [Qconduction_animal\(\)](#), [Qconduction_substrate\(\)](#), [Qconvection\(\)](#), [Qemitted_thermal_radiation\(\)](#), [Qevaporation\(\)](#), [Qmetabolism_from_mass_temp\(\)](#), [Qmetabolism_from_mass\(\)](#), [Qnet_Gates\(\)](#), [Qradiation_absorbed\(\)](#), [Qthermal_radiation_absorbed\(\)](#), [Reynolds_number\(\)](#), [Tb_CampbellNorman\(\)](#), [Tb_Gates2\(\)](#), [Tb_Gates\(\)](#), [Tb_butterfly\(\)](#), [Tb_grasshopper\(\)](#), [Tb_limpetBH\(\)](#), [Tb_limpet\(\)](#), [Tb_lizard_Fei\(\)](#), [Tb_lizard\(\)](#), [Tb_salamander_humid\(\)](#), [Tb_snail\(\)](#), [Tbed_mussel\(\)](#), [Tsoil\(\)](#), [actual_vapor_pressure\(\)](#), [boundary_layer_resistance\(\)](#), [external_resistance_to_water_vapor_transfer\(\)](#), [free_or_forced_convection](#), [heat_transfer_coefficient_approximation\(\)](#), [heat_transfer_coefficient_simple\(\)](#), [heat_transfer_coefficient](#), [saturation_vapor_pressure\(\)](#), [saturation_water_vapor_pressure\(\)](#)

Examples

```
Tb_mussel(l = 0.1,
          h = 0.05,
          T_a = 25,
          T_g = 30,
          S = 500,
          k_d = 0.2,
          u = 2,
          psi = 30,
          evap = FALSE,
          cl = 0.5,
          group = "solitary")
```

Tb_salamander_humid *Humid Operative Environmental Temperature of a Salamander*

Description

The function estimates the humid body temperature (C, operative environmental temperature) using an adaptation of Campbell and Norman (1998) described in Riddell et al. (2018).

Usage

Tb_salamander_humid(r_i, r_b, D, T_a, elev, e_a, e_s, Qabs, epsilon = 0.96)

Arguments

r_i	numeric internal (skin) resistance (scm^{-1}).
r_b	numeric boundary layer resistance (scm^{-1}).
D	numeric body diameter (m); can estimate as diameter = 0.0016*log(mass) + 0.0061 for mass(g).
T_a	numeric ambient temperature (C).
elev	numeric elevation (m).
e_a	numeric actual vapor pressure (kPa).
e_s	numeric saturation vapor pressure (kPa).
Qabs	numeric Solar and thermal radiation absorbed (W).
epsilon	numeric emissivity of salamander skin (proportion).

Value

numeric humid operative temperature (C).

Author(s)

Eric Riddell

References

Campbell GS, Norman JM (1998). *Introduction to environmental biophysics*, 2nd ed. edition. Springer, New York. ISBN 0387949372.

Riddell EA, Odom JP, Damm JD, Sears MW (2018). "Plasticity reveals hidden resistance to extinction under climate change in the global hotspot of salamander diversity." *Science Advances*, **4**(4). doi: [10.1126/sciadv.aar5471](https://doi.org/10.1126/sciadv.aar5471).

See Also

Other biophysical models: [Grashof_number_Gates\(\)](#), [Grashof_number\(\)](#), [Nusselt_from_Grashof\(\)](#), [Nusselt_from_Reynolds\(\)](#), [Nusselt_number\(\)](#), [Prandtl_number\(\)](#), [Qconduction_animal\(\)](#), [Qconduction_substrate\(\)](#), [Qconvection\(\)](#), [Qemitted_thermal_radiation\(\)](#), [Qevaporation\(\)](#), [Qmetabolism_from_mass_temp\(\)](#), [Qmetabolism_from_mass\(\)](#), [Qnet_Gates\(\)](#), [Qradiation_absorbed\(\)](#), [Qthermal_radiation_absorbed\(\)](#), [Reynolds_number\(\)](#), [Tb_CampbellNorman\(\)](#), [Tb_Gates2\(\)](#), [Tb_Gates\(\)](#), [Tb_butterfly\(\)](#), [Tb_grasshopper\(\)](#), [Tb_limpetBH\(\)](#), [Tb_limpet\(\)](#), [Tb_lizard_Fei\(\)](#), [Tb_lizard\(\)](#), [Tb_mussel\(\)](#), [Tb_snail\(\)](#), [Tbed_mussel\(\)](#), [Tsoil\(\)](#), [actual_vapor_pressure\(\)](#), [boundary_layer_resistance\(\)](#), [external_resistance_to_water_vapor_transfer\(\)](#), [free_or_forced_convection\(\)](#), [heat_transfer_coefficient_approximation\(\)](#), [heat_transfer_coefficient_simple\(\)](#), [heat_transfer_coefficient_saturated_vapor_pressure\(\)](#), [saturation_vapor_pressure\(\)](#), [saturation_water_vapor_pressure\(\)](#)

Examples

```
Tb_salamander_humid(r_i = 4,
                    r_b = 1,
                    D = 0.01,
                    T_a = 20,
                    elev = 500,
                    e_a = 2.0,
                    e_s = 2.5,
                    Qabs = 400,
                    epsilon = 0.96)
```

Tb_snail

*Operative Environmental Temperature of a Marine Snail***Description**

The function estimates body temperature (C, operative environmental temperature) of a marine snail. The function implements a steady-state model, which assumes unchanging environmental conditions and is based on (Iacarella and Helmuth 2012). Body temperature and desiccation constrain the activity of *Littoraria irrorata* within the *Spartina alterniflora* canopy. The function was provided by Brian Helmuth and is a simplified version of the published model.

Usage

```
Tb_snail(temp, l, solar, WS, CC, WL, WSH)
```

Arguments

temp	numeric air temperature (C).
l	numeric snail length (m).
solar	numeric direct solar flux density (Wm^{-2}).
WS	numeric wind speed (ms^{-1}).
CC	numeric fraction of the sky covered by cloud (0-1).
WL	numeric water loss rate ($kg s^{-1}$), 5 percent loss of body mass over one hour is a reasonable maximum level (Helmuth 1999).
WSH	numeric wind sensor height (m).

Details

Thermal radiative flux is calculated following Helmuth (1998), Helmuth (1999), and Idso and Jackson (1969).

Value

numeric predicted body (operative environmental) temperature (C).

Author(s)

Brian Helmuth et al.

References

Helmuth B (1999). “Thermal biology of rocky intertidal mussels: quantifying body temperatures using climatological data.” *Ecology*, **80**(1), 15-34. <https://esajournals.onlinelibrary.wiley.com/doi/abs/10.1890/0012-9658%281999%29080%5B0015%3ATBORIM%5D2.0.CO%3B2>.

Helmuth BST (1998). “Intertidal Mussel Microclimates: Predicting the Body Temperature of a Sessile Invertebrate.” *Ecological Monographs*, **68**(1), 51–74. ISSN 00129615, doi: [10.2307/2657143](https://doi.org/10.2307/2657143).

Iacarella J, Helmuth B (2012). “Body temperature and desiccation constrain the activity of *Littoraria irrorata* within the *Spartina alterniflora* canopy.” *Journal of Thermal Biology*, **37**(1). doi: [10.1016/j.jtherbio.2011.10.003](https://doi.org/10.1016/j.jtherbio.2011.10.003), https://www.researchgate.net/publication/238501940_Body_temperature_and_desiccation_constrain_the_activity_of_Littoraria_irrorata_within_the_Spartina_alterniflora_canopy.

Idso SB, Jackson RD (1969). “Thermal radiation from the atmosphere.” *Journal of Geophysical Research (1896-1977)*, **74**(23), 5397-5403. doi: [10.1029/JC074i023p05397](https://doi.org/10.1029/JC074i023p05397).

See Also

Other biophysical models: `Grashof_number_Gates()`, `Grashof_number()`, `Nusselt_from_Grashof()`, `Nusselt_from_Reynolds()`, `Nusselt_number()`, `Prandtl_number()`, `Qconduction_animal()`, `Qconduction_substrate()`, `Qconvection()`, `Qemitted_thermal_radiation()`, `Qevaporation()`, `Qmetabolism_from_mass_temp()`, `Qmetabolism_from_mass()`, `Qnet_Gates()`, `Qradiation_absorbed()`, `Qthermal_radiation_absorbed()`, `Reynolds_number()`, `Tb_CampbellNorman()`, `Tb_Gates2()`, `Tb_Gates()`, `Tb_butterfly()`, `Tb_grasshopper()`, `Tb_limpetBH()`, `Tb_limpet()`, `Tb_lizard_Fei()`, `Tb_lizard()`, `Tb_mussel()`, `Tb_salamander_humid()`, `Tbed_mussel()`, `Tsoil()`, `actual_vapor_pressure()`, `boundary_layer_resistance()`, `external_resistance_to_water_vapor_transfer()`, `free_or_forced_convection`, `heat_transfer_coefficient_approximation()`, `heat_transfer_coefficient_simple()`, `heat_transfer_coefficient`, `saturation_vapor_pressure()`, `saturation_water_vapor_pressure()`

Examples

```
Tb_snail(temp = 25,
         l = 0.012,
         solar = 800,
         WS = 1,
         CC = 0.5,
         WL = 0,
         WSH = 10)
```

temperature conversions

Convert Among Temperature Scales

Description

The function converts temperatures among Celsius, Fahrenheit, and Kelvin (J. Blischak et al. 2016).

Usage

```
fahrenheit_to_kelvin(temperature)
```

```
kelvin_to_celsius(temperature)
```

```
celsius_to_kelvin(temperature)
```

```
fahrenheit_to_celsius(temperature)
```

Arguments

temperature numeric temperature (Celsius, Fahrenheit, or Kelvin).

Value

numeric temperature (Celsius, Fahrenheit, or Kelvin).

References

J. Blischak, D. Chen, H. Dashnow, Haine D (2016). *Software Carpentry: Programming with R*. doi: [10.5281/zenodo.57541](https://doi.org/10.5281/zenodo.57541), Version 2016.06, June 2016.

See Also

Other utility functions: [airpressure_from_elev\(\)](#), [azimuth_angle\(\)](#), [day_of_year\(\)](#), [daylength\(\)](#), [dec_angle\(\)](#), [solar_noon\(\)](#), [zenith_angle\(\)](#)

Examples

```
kelvin_to_celsius(temperature = 270)
fahrenheit_to_kelvin(temperature = 85)
fahrenheit_to_celsius(temperature = 85)
celsius_to_kelvin(temperature = -10)
```

TPC

Gaussian-Quadratic Function Thermal Performance Curve

Description

The function constructs a thermal performance curve by combining as a Gaussian function to describe the rise in performance up to the optimal temperature and a quadratic decline to zero performance at critical thermal maxima and higher temperatures (Deutsch et al. 2008).

Usage

```
TPC(T_b, T_opt, CT_min, CT_max)
```

Arguments

T_b numeric vector of temperature range (C).
T_opt numeric thermal optima (C), the temperature at which peak performance occurs.
CT_min, CT_max numeric critical thermal minimum and maximum (C), the lower and upper temperature limits for performance.

Value

performance

References

Deutsch CA, Tewksbury JJ, Huey RB, Sheldon KS, Ghalambor CK, Haak DC, Martin PR (2008). “Impacts of climate warming on terrestrial ectotherms across latitude.” *Proceedings of the National Academy of Science of the United States of America*, **105**, 6668-6672. doi: [10.1073/pnas.0709472105](https://doi.org/10.1073/pnas.0709472105).

Examples

```
TPC(T_b = 0:60,  
     T_opt = 30,  
     CT_min = 10,  
     CT_max = 40)
```

 TPC_beta

Beta Function Thermal Performance Curve

Description

The function constructs a thermal performance curve based on a beta function (Asbury and Angilletta 2010).

Usage

```
TPC_beta(T_b, shift = -1, breadth = 0.1, aran = 0, tolerance = 43, skew = 0.7)
```

Arguments

T_b	numeric temperature (C).
shift	numeric mode of the thermal performance curve.
breadth	numeric breadth of the thermal performance curve.
aran	numeric scale performance value. If 0, no scaling; if 1, include a thermodynamic effect on mean performance.
tolerance	numeric maximal breath (C) of the thermal performance curve.
skew	numeric skewness of the thermal performance curve (0-1).

Value

numeric performance.

References

Asbury DA, Angilletta MJ (2010). “Thermodynamic effects on the evolution of performance curves.” *American Naturalist*, **176**(2), E40-E49. doi: [10.1086/653659](https://doi.org/10.1086/653659).

Examples

```
TPC_beta(T_b      = 0:60,
          shift    = -1,
          breadth  = 0.1,
          aran     = 0,
          tolerance = 43,
          skew     = 0.7)
```

TrenchR

Tools for Microclimate and Biophysical Ecology

Description

Tools for translating environmental change into organismal response. Microclimate models to vertically scale weather station data to organismal heights. The biophysical modeling tools include both general models for heat flows and specific models to predict body temperatures for a variety of ectothermic taxa. Additional functions model and temporally partition air and soil temperatures and solar radiation. Utility functions estimate the organismal and environmental parameters needed for biophysical ecology. 'TrenchR' focuses on relatively simple and modular functions so users can create transparent and flexible biophysical models. Many functions are derived from Gates (1980) and Campbell and Norman (1988).

Tsoil

Approximate Soil Temperature

Description

The function estimates soil temperature (C) at a given depth and hour by approximating diurnal variation as sinusoidal. The function is adapted from Campbell and Norman (1998) and described in Riddell et al. (2018).

Usage

```
Tsoil(T_g_max, T_g_min, hour, depth)
```

Arguments

T_g_max	numeric daily maximum soil surface temperature (C).
T_g_min	numeric daily minimum soil surface temperature (C).
hour	numeric hour of the day.
depth	numeric depth (cm).

Value

numeric soil temperature (C).

Author(s)

Eric Riddell

References

Campbell GS, Norman JM (1998). *Introduction to environmental biophysics*, 2nd ed. edition. Springer, New York. ISBN 0387949372.

Riddell EA, Odom JP, Damm JD, Sears MW (2018). “Plasticity reveals hidden resistance to extinction under climate change in the global hotspot of salamander diversity.” *Science Advances*, **4**(4). doi: [10.1126/sciadv.aar5471](https://doi.org/10.1126/sciadv.aar5471).

See Also

Other biophysical models: [Grashof_number_Gates\(\)](#), [Grashof_number\(\)](#), [Nusselt_from_Grashof\(\)](#), [Nusselt_from_Reynolds\(\)](#), [Nusselt_number\(\)](#), [Prandtl_number\(\)](#), [Qconduction_animal\(\)](#), [Qconduction_substrate\(\)](#), [Qconvection\(\)](#), [Qemitted_thermal_radiation\(\)](#), [Qevaporation\(\)](#), [Qmetabolism_from_mass_temp\(\)](#), [Qmetabolism_from_mass\(\)](#), [Qnet_Gates\(\)](#), [Qradiation_absorbed\(\)](#), [Qthermal_radiation_absorbed\(\)](#), [Reynolds_number\(\)](#), [Tb_CampbellNorman\(\)](#), [Tb_Gates2\(\)](#), [Tb_Gates\(\)](#), [Tb_butterfly\(\)](#), [Tb_grasshopper\(\)](#), [Tb_limpetBH\(\)](#), [Tb_limpet\(\)](#), [Tb_lizard_Fei\(\)](#), [Tb_lizard\(\)](#), [Tb_mussel\(\)](#), [Tb_salamander_humid\(\)](#), [Tb_snail\(\)](#), [Tbed_mussel\(\)](#), [actual_vapor_pressure\(\)](#), [boundary_layer_resistance\(\)](#), [external_resistance_to_water_vapor_transfer\(\)](#), [free_or_forced_convection\(\)](#), [heat_transfer_coefficient_approximation\(\)](#), [heat_transfer_coefficient_simple\(\)](#), [heat_transfer_coefficient_saturated_vapor_pressure\(\)](#), [saturation_vapor_pressure\(\)](#), [saturation_water_vapor_pressure\(\)](#)

Examples

```
Tsoil(T_g_max = 30,
      T_g_min = 15,
      hour    = 12,
      depth   = 5)
```

VAPPRS

Saturation Vapor Pressure

Description

The function calculates saturation vapor pressure for a given air temperature. The program is based on equations from List (1971) and code implementation from NicheMapR (Kearney and Porter 2017; Kearney and Porter 2020).

Usage

```
VAPPRS(db)
```

Arguments

db numeric Dry bulb temperature (C)

Value

esat numeric Saturation vapor pressure (Pa)

References

Kearney MR, Porter WP (2017). “NicheMapR - an R package for biophysical modelling: the microclimate model.” *Ecography*, **40**, 664-674. doi: [10.1111/ecog.02360](https://doi.org/10.1111/ecog.02360).

Kearney MR, Porter WP (2020). “NicheMapR - an R package for biophysical modelling: the ecotherm and Dynamic Energy Budget models.” *Ecography*, **43**(1), 85-96. doi: [10.1111/ecog.04680](https://doi.org/10.1111/ecog.04680).

List RJ (1971). “Smithsonian Meteorological Tables.” *Smithsonian Miscellaneous Collections*, **114**(1), 1-527. <https://repository.si.edu/handle/10088/23746>.

Examples

```
VAPPRS(db = 30)
```

volume_from_length	<i>Organism Volume from Length</i>
--------------------	------------------------------------

Description

The function estimates volume (m^3) from length (m) for a variety of taxa following Mitchell (1976).

Usage

```
volume_from_length(l, taxon)
```

Arguments

l	numeric length (m). Use snout-vent length for lizards and frogs.
taxon	character taxon of organism, current choices: "lizard", "frog", "sphere".

Details

Relationships come from

- Lizards: Norris (1965)
- Frogs: Tracy (1972)
- Sphere: Mitchell (1976)

Value

numeric volume (m^3).

References

Mitchell JW (1976). "Heat transfer from spheres and other animal forms." *Biophysical Journal*, **16**(6), 561-569. ISSN 0006-3495, doi: [10.1016/S00063495\(76\)857116](https://doi.org/10.1016/S00063495(76)857116), <https://www.sciencedirect.com/science/article/pii/S0006349576857116>.

Norris KS (1965). "Color adaptation in desert reptiles and its thermal relationships." In *Symposium on Lizard Ecology*, 162- 229. U. Missouri Press.

Tracy CR (1972). "Newton's Law: Its Application for Expressing Heat Losses from Homeotherms." *BioScience*, **22**(11), 656-659. ISSN 0006-3568, doi: [10.2307/1296267](https://doi.org/10.2307/1296267).

See Also

Other allometric functions: [mass_from_length\(\)](#), [proportion_silhouette_area_shapes\(\)](#), [proportion_silhouette_surface_area_from_length\(\)](#), [surface_area_from_mass\(\)](#), [surface_area_from_volume\(\)](#)

Examples

```
volume_from_length(l = 0.05,
                  taxon = "lizard")
volume_from_length(l = 0.05,
                  taxon = "frog")
volume_from_length(l = 0.05,
                  taxon = "sphere")
```

WETAIR

Properties of Wet Air

Description

The function calculates several properties of humid air described as output variables below. The program is based on equations from List (1971) and code implementation from NicheMapR (Kearney and Porter 2017; Kearney and Porter 2020).

WETAIR must be used in conjunction with [VAPPRS](#). Input variables are shown below. See Details.

Usage

```
WETAIR(db, wb = db, rh = 0, dp = 999, bp = 101325)
```

Arguments

db	numeric dry bulb temperature (C).
wb	numeric wet bulb temperature (C).
rh	numeric relative humidity (%).
dp	numeric dew point temperature (C).
bp	numeric barometric pressure (Pa).

Details

The user must supply known values for DB and BP (BP at one standard atmosphere is 101,325 pascals). Values for the remaining variables are determined by whether the user has either (1) psychrometric data (WB or RH), or (2) hygrometric data (DP):

- Psychrometric data: If WB is known but not RH, then set RH = -1 and DP = 999. If RH is known but not WB then set WB = 0 and DP = 999
- Hygrometric data: If DP is known, set WB = 0 and RH = 0

Value

Named list with elements

- e: numeric saturation vapor pressure (Pa)
- vd: numeric vapor density (kgm^{-3})
- rw: numeric mixing ratio ($kgkg^{-1}$)
- tvir: numeric virtual temperature (K)
- tvinc: numeric virtual temperature increment (K)
- denair: numeric density of the air (kgm^{-3})
- cp: numeric specific heat of air at constant pressure ($Jkg^{-1}K^{-1}$)
- wtrpot: numeric water potential (Pa)
- rh: numeric relative humidity (%)

References

Kearney MR, Porter WP (2017). “NicheMapR - an R package for biophysical modelling: the microclimate model.” *Ecography*, **40**, 664-674. doi: [10.1111/ecog.02360](https://doi.org/10.1111/ecog.02360).

Kearney MR, Porter WP (2020). “NicheMapR - an R package for biophysical modelling: the ecotherm and Dynamic Energy Budget models.” *Ecography*, **43**(1), 85-96. doi: [10.1111/ecog.04680](https://doi.org/10.1111/ecog.04680).

List RJ (1971). “Smithsonian Meteorological Tables.” *Smithsonian Miscellaneous Collections*, **114**(1), 1-527. <https://repository.si.edu/handle/10088/23746>.

Examples

```
WETAIR(db = 30,
       wb = 28,
       rh = 60,
       bp = 100 * 1000)
```

`wind_speed_profile_neutral`*Wind Speed at a Specific Height Under Neutral Conditions*

Description

The function calculates wind speed (ms^{-1}) at a specified height (m) within a boundary layer near the surface. The profile assumes neutral conditions. The velocity profile is the neutral profile described by Sellers (1965). Function is equations (2) and (3) of Porter et al. (1973).

Usage

```
wind_speed_profile_neutral(u_r, z_r, z0, z)
```

Arguments

<code>u_r</code>	numeric wind velocity (ms^{-1}) at reference height.
<code>z_r</code>	numeric initial reference height (m).
<code>z0</code>	numeric surface roughness (m).
<code>z</code>	numeric height to scale (m).

Value

numeric windspeed (ms^{-1}).

References

Porter WP, Mitchell JW, Bekman A, DeWitt CB (1973). "Behavioral implications of mechanistic ecology: thermal and behavioral modeling of desert ectotherms and their microenvironments." *Oecologia*, **13**, 1-54.

Sellers WD (1965). *Physical climatology*. University of Chicago Press, Chicago, IL, USA.

See Also

Other microclimate functions: [air_temp_profile_neutral\(\)](#), [air_temp_profile_segment\(\)](#), [air_temp_profile\(\)](#), [degree_days\(\)](#), [direct_solar_radiation\(\)](#), [diurnal_radiation_variation\(\)](#), [diurnal_temp_variation_sineexp\(\)](#), [diurnal_temp_variation_sinesqrt\(\)](#), [diurnal_temp_variation_sine\(\)](#), [monthly_solar_radiation\(\)](#), [partition_solar_radiation\(\)](#), [proportion_diffuse_solar_radiation\(\)](#), [solar_radiation\(\)](#), [surface_roughness\(\)](#), [wind_speed_profile_segment\(\)](#)

Examples

```
wind_speed_profile_neutral(u_r = 0.1,  
                           z_r = 0.1,  
                           z0 = 0.2,  
                           z = 0.15)
```

 wind_speed_profile_segment

Wind Speed at a Specified Height

Description

The function calculates wind speed (ms^{-1}) at a specified height (m). The function estimates a three segment velocity and temperature profile based on user-specified, experimentally determined values for 3 roughness heights and reference heights. Multiple heights are appropriate in heterogenous areas with, for example, a meadow, bushes, and rocks. Implements the MICROSEGMT routine from NicheMapR as described in Kearney and Porter (2017).

Usage

```
wind_speed_profile_segment(u_r, zr, z0, z)
```

Arguments

<code>u_r</code>	numeric a vector of wind speeds (ms^{-1}) at the 3 reference heights.
<code>zr</code>	numeric a vector of 3 reference heights (m).
<code>z0</code>	numeric a vector of 3 experimentally determined roughness heights (m).
<code>z</code>	numeric height to scale (m).

Value

numeric wind speed (ms^{-1}).

References

Kearney MR, Porter WP (2017). “NicheMapR - an R package for biophysical modelling: the microclimate model.” *Ecography*, **40**, 664-674. doi: [10.1111/ecog.02360](https://doi.org/10.1111/ecog.02360).

See Also

Other microclimate functions: [air_temp_profile_neutral\(\)](#), [air_temp_profile_segment\(\)](#), [air_temp_profile\(\)](#), [degree_days\(\)](#), [direct_solar_radiation\(\)](#), [diurnal_radiation_variation\(\)](#), [diurnal_temp_variation_sineexp\(\)](#), [diurnal_temp_variation_sinesqrt\(\)](#), [diurnal_temp_variation_sine\(\)](#), [monthly_solar_radiation\(\)](#), [partition_solar_radiation\(\)](#), [proportion_diffuse_solar_radiation\(\)](#), [solar_radiation\(\)](#), [surface_roughness\(\)](#), [wind_speed_profile_neutral\(\)](#)

Examples

```
wind_speed_profile_segment(u_r = c(0.01, 0.025, 0.05),
                          zr = c(0.05, 0.25, 0.5),
                          z0 = c(0.01, 0.15, 0.2),
                          z = 0.3)
```

zenith_angle	<i>Zenith Angle</i>
--------------	---------------------

Description

The function calculates the zenith angle, the location of the sun as an angle (in degrees) measured from vertical (Campbell and Norman 1998).

Usage

```
zenith_angle(doy, lat, lon, hour, offset = NA)
```

Arguments

doy	numeric day of year (1-366). This can be obtained from standard date via day_of_year .
lat	numeric latitude (decimal degrees).
lon	numeric longitude (decimal degrees).
hour	numeric hour of the day.
offset	numeric the number of hours to add to UTC (Coordinated Universal Time) to get local time (improves accuracy but not always necessary). Optional. Defaults to NA.

Value

numeric zenith angle (degrees)

References

Campbell GS, Norman JM (1998). *Introduction to environmental biophysics*, 2nd ed. edition. Springer, New York. ISBN 0387949372.

See Also

Other utility functions: [airpressure_from_elev\(\)](#), [azimuth_angle\(\)](#), [day_of_year\(\)](#), [daylength\(\)](#), [dec_angle\(\)](#), [solar_noon\(\)](#), [temperature conversions](#)

Examples

```
zenith_angle(doy = 112,  
             lat = 47.61,  
             lon = -122.33,  
             hour = 12)
```

Index

* allometric functions

mass_from_length, 32
proportion_silhouette_area, 41
proportion_silhouette_area_shapes,
42
surface_area_from_length, 69
surface_area_from_mass, 70
surface_area_from_volume, 72
volume_from_length, 104

* biophysical models

actual_vapor_pressure, 4
boundary_layer_resistance, 11
external_resistance_to_water_vapor_transfer,
24
free_or_forced_convection, 25
Grashof_number, 26
Grashof_number_Gates, 27
heat_transfer_coefficient, 28
heat_transfer_coefficient_approximation,
29
heat_transfer_coefficient_simple,
30
Nusselt_from_Grashof, 35
Nusselt_from_Reynolds, 36
Nusselt_number, 37
Prandtl_number, 39
Qconduction_animal, 43
Qconduction_substrate, 45
Qconvection, 46
Qemitted_thermal_radiation, 47
Qevaporation, 49
Qmetabolism_from_mass, 50
Qmetabolism_from_mass_temp, 51
Qnet_Gates, 52
Qradiation_absorbed, 53
Qthermal_radiation_absorbed, 55
Reynolds_number, 56
saturation_vapor_pressure, 57
saturation_water_vapor_pressure,

58

Tb_butterfly, 76
Tb_CampbellNorman, 78
Tb_Gates, 80
Tb_Gates2, 82
Tb_grasshopper, 83
Tb_limpet, 86
Tb_limpetBH, 87
Tb_lizard, 89
Tb_lizard_Fei, 92
Tb_mussel, 94
Tb_salamander_humid, 95
Tb_snail, 97
Tbed_mussel, 74
Tsoil, 102

* microclimate functions

air_temp_profile, 6
air_temp_profile_neutral, 7
air_temp_profile_segment, 8
degree_days, 15
direct_solar_radiation, 16
diurnal_radiation_variation, 18
diurnal_temp_variation_sine, 19
diurnal_temp_variation_sineexp, 20
diurnal_temp_variation_sinesqrt,
21
monthly_solar_radiation, 33
partition_solar_radiation, 38
proportion_diffuse_solar_radiation,
40
solar_radiation, 68
surface_roughness, 73
wind_speed_profile_neutral, 107
wind_speed_profile_segment, 108

* package

TrenchR, 102

* soil temperature functions

soil_conductivity, 59
soil_specific_heat, 60

- soil_temperature, 61
- soil_temperature_equation, 63
- soil_temperature_function, 65
- soil_temperature_integrand, 66
- * **utility functions**
- airpressure_from_elev, 5
- azimuth_angle, 10
- day_of_year, 14
- daylength, 13
- dec_angle, 14
- solar_noon, 67
- temperature_conversions, 99
- zenith_angle, 109

- actual_vapor_pressure, 4, 12, 24–26, 28–31, 35–37, 39, 44, 45, 47, 48, 50–54, 56–59, 75, 77, 79, 81, 83, 85, 87, 89, 91, 93, 95, 96, 98, 103
- air_temp_profile, 6, 7, 9, 16–19, 21, 22, 34, 38, 40, 69, 74, 107, 108
- air_temp_profile_neutral, 6, 7, 9, 16–19, 21, 22, 34, 38, 40, 69, 74, 107, 108
- air_temp_profile_segment, 6, 7, 8, 16–19, 21, 22, 34, 38, 40, 69, 74, 107, 108
- airpressure_from_elev, 5, 10, 13–15, 68, 99, 109
- angle_conversions, 9
- as.POSIXlt, 14
- azimuth_angle, 5, 10, 13–15, 68, 99, 109

- boundary_layer_resistance, 4, 11, 24–26, 28–31, 35–37, 39, 44, 45, 47, 48, 50–54, 56–59, 75, 77, 79, 81, 83, 85, 87, 89, 91, 93, 95, 96, 98, 103

- celsius_to_kelvin (temperature conversions), 99
- constants, 12

- day_of_year, 5, 10, 13, 14, 15, 68, 99, 109
- daylength, 5, 10, 13, 14, 15, 68, 99, 109
- dec_angle, 5, 10, 13, 14, 14, 68, 99, 109
- degree_days, 6, 7, 9, 15, 17–19, 21, 22, 34, 38, 40, 69, 74, 107, 108
- degrees_to_radians (angle conversions), 9
- direct_solar_radiation, 6, 7, 9, 16, 16, 18, 19, 21, 22, 34, 38, 40, 69, 74, 107, 108
- diurnal_radiation_variation, 6, 7, 9, 16, 17, 18, 19, 21, 22, 34, 38, 40, 69, 74, 107, 108
- diurnal_temp_variation_sine, 6, 7, 9, 16–18, 19, 21, 22, 34, 38, 40, 69, 74, 107, 108
- diurnal_temp_variation_sineexp, 6, 7, 9, 16–19, 20, 22, 34, 38, 40, 69, 74, 107, 108
- diurnal_temp_variation_sinesqrt, 6, 7, 9, 16–19, 21, 21, 34, 38, 40, 69, 74, 107, 108
- DRYAIR, 22, 26–30, 56, 58

- external_resistance_to_water_vapor_transfer, 4, 12, 24, 25, 26, 28–31, 35–37, 39, 44, 46–48, 50–54, 56–59, 75, 77, 79, 81, 83, 85, 87, 89, 91, 93, 95, 96, 98, 103

- fahrenheit_to_celsius (temperature conversions), 99
- fahrenheit_to_kelvin (temperature conversions), 99
- free_or_forced_convection, 4, 12, 24, 25, 26, 28–31, 35–37, 39, 44, 46–48, 50–54, 56–59, 75, 77, 79, 81, 83, 85, 87, 89, 91, 93, 95, 96, 98, 103

- Grashof_number, 4, 11, 24, 25, 26, 27, 29–31, 35–37, 39, 44, 45, 47, 48, 50–54, 56–59, 75, 77, 79, 81, 83, 85, 87, 89, 91, 93, 95, 96, 98, 103
- Grashof_number_Gates, 4, 11, 24–26, 27, 29–31, 35–37, 39, 44, 45, 47, 48, 50–54, 56–59, 75, 77, 79, 81, 83, 85, 87, 89, 91, 93, 95, 96, 98, 103

- heat_transfer_coefficient, 4, 12, 24–26, 28, 28, 30, 31, 35–37, 39, 44, 46–48, 50–54, 56–59, 76, 77, 79, 81, 83, 85, 87, 89, 91, 93, 95, 96, 98, 103
- heat_transfer_coefficient_approximation, 4, 12, 24–26, 28, 29, 29, 31, 35–37, 39, 44, 46–48, 50–54, 56–59, 76, 77, 79, 81, 83, 85, 87, 89, 91, 93, 95, 96, 98, 103
- heat_transfer_coefficient_simple, 4, 12, 24–26, 28–30, 30, 35–37, 39, 44,

- 46–48, 50–54, 56–59, 76, 77, 79, 81, 83, 85, 87, 89, 91, 93, 95, 96, 98, 103
- kelvin_to_celsius (temperature conversions), 99
- latent_heat_vaporization_h2o (constants), 12
- mass_from_length, 32, 42, 43, 70, 72, 73, 90, 105
- monthly_solar_radiation, 6, 7, 9, 16–19, 21, 22, 33, 38, 40, 69, 74, 107, 108
- Nusselt_from_Grashof, 4, 11, 24–27, 29–31, 35, 36, 37, 39, 44, 45, 47, 48, 50–54, 56–59, 75, 77, 79, 81, 83, 85, 87, 89, 91, 93, 95, 96, 98, 103
- Nusselt_from_Reynolds, 4, 11, 24–27, 29–31, 35, 36, 37, 39, 44, 45, 47, 48, 50–54, 56–59, 75, 77, 79, 81, 83, 85, 87, 89, 91, 93, 95, 96, 98, 103
- Nusselt_number, 4, 11, 24–27, 29–31, 35, 36, 37, 39, 44, 45, 47, 48, 50–54, 56–59, 75, 77, 79, 81, 83, 85, 87, 89, 91, 93, 95, 96, 98, 103
- partition_solar_radiation, 6, 7, 9, 16–19, 21, 22, 34, 38, 40, 69, 74, 107, 108
- Prandtl_number, 4, 11, 24–27, 29–31, 35–37, 39, 44, 45, 47, 48, 50–54, 56–59, 75, 77, 79, 81, 83, 85, 87, 89, 91, 93, 95, 96, 98, 103
- proportion_diffuse_solar_radiation, 6, 7, 9, 16–19, 21, 22, 34, 38, 40, 69, 74, 107, 108
- proportion_silhouette_area, 33, 41, 43, 70, 72, 73, 105
- proportion_silhouette_area_shapes, 33, 42, 42, 70, 72, 73, 105
- Qconduction_animal, 4, 11, 24–27, 29–31, 35–37, 39, 43, 45, 47, 48, 50–54, 56–59, 75, 77, 79, 81, 83, 85, 87, 89, 91, 93, 95, 96, 98, 103
- Qconduction_substrate, 4, 11, 24–27, 29–31, 35–37, 39, 44, 45, 47, 48, 50–54, 56–59, 75, 77, 79, 81, 83, 85, 87, 89, 91, 93, 95, 96, 98, 103
- Qconvection, 4, 11, 24–27, 29–31, 35–37, 39, 44, 45, 46, 48, 50–54, 56–59, 75, 77, 79, 81, 83, 85, 87, 89, 91, 93, 95, 96, 98, 103
- Qemitted_thermal_radiation, 4, 11, 24–27, 29–31, 35–37, 39, 44, 45, 47, 47, 50–54, 56–59, 75, 77, 79, 81, 83, 85, 87, 89, 91, 93, 95, 96, 98, 103
- Qevaporation, 4, 11, 24–27, 29–31, 35–37, 39, 44, 45, 47, 48, 49, 51–54, 56–59, 75, 77, 79, 81, 83, 85, 87, 89, 91, 93, 95, 96, 98, 103
- Qmetabolism_from_mass, 4, 11, 24–27, 29–31, 35–37, 39, 44, 45, 47, 48, 50, 50, 52–54, 56–59, 75, 77, 79, 81, 83, 85, 87, 89, 91, 93, 95, 96, 98, 103
- Qmetabolism_from_mass_temp, 4, 11, 24–27, 29–31, 35–37, 39, 44, 45, 47, 48, 50, 51, 51, 53, 54, 56–59, 75, 77, 79, 81, 83, 85, 87, 89, 91, 93, 95, 96, 98, 103
- Qnet_Gates, 4, 11, 24–27, 29–31, 35–37, 39, 44, 45, 47, 48, 50–52, 52, 54, 56–59, 75, 77, 79, 81, 83, 85, 87, 89, 91, 93, 95, 96, 98, 103
- Qradiation_absorbed, 4, 11, 24–27, 29–31, 35–37, 39, 44, 45, 47, 48, 50–53, 53, 56–59, 75, 77, 79, 81, 83, 85, 87, 89, 91, 93, 95, 96, 98, 103
- Qthermal_radiation_absorbed, 4, 11, 24–27, 29–31, 35–37, 39, 44, 45, 47, 48, 50–54, 55, 57–59, 75, 77, 79, 81, 83, 85, 87, 89, 91, 93, 95, 96, 98, 103
- radians_to_degrees (angle conversions), 9
- Reynolds_number, 4, 11, 24–27, 29–31, 35–37, 39, 44, 45, 47, 48, 50–54, 56, 56, 58, 59, 75, 77, 79, 81, 83, 85, 87, 89, 91, 93, 95, 96, 98, 103
- saturation_vapor_pressure, 4, 12, 24–26, 28–31, 35–37, 39, 44, 46–48, 50–54, 56, 57, 57, 59, 76, 77, 79, 81, 83, 85, 87, 89, 91, 93, 95, 96, 98, 103
- saturation_water_vapor_pressure, 4, 12, 24–26, 28–31, 35–37, 39, 44, 46–48, 50–54, 56–58, 58, 76, 77, 79, 81, 83, 85, 87, 89, 91, 93, 95, 96, 98, 103
- soil_conductivity, 59, 61, 63–65, 67

- soil_specific_heat, 60, 60, 63–65, 67
 soil_temperature, 60, 61, 61, 64, 65, 67
 soil_temperature_equation, 60, 61, 63, 63, 65–67
 soil_temperature_function, 60, 61, 63, 64, 65, 67
 soil_temperature_integrand, 60, 61, 63–65, 66
 solar_noon, 5, 10, 13–15, 17, 67, 99, 109
 solar_radiation, 6, 7, 9, 16–19, 21, 22, 34, 38, 40, 68, 74, 107, 108
 specific_heat_h2o (constants), 12
 stefan_boltzmann_constant (constants), 12
 surface_area_from_length, 33, 42, 43, 69, 72, 73, 105
 surface_area_from_mass, 33, 42, 43, 70, 70, 73, 105
 surface_area_from_volume, 33, 42, 43, 70, 72, 72, 105
 surface_roughness, 6, 7, 9, 16–19, 21, 22, 34, 38, 40, 69, 73, 107, 108

 Tb_butterfly, 4, 11, 24–27, 29–31, 35–37, 39, 44, 45, 47, 48, 50–54, 56–59, 75, 76, 79, 81, 83, 85, 87, 89, 91, 93, 95, 96, 98, 103
 Tb_CampbellNorman, 4, 11, 24–27, 29–31, 35–37, 39, 44, 45, 47, 48, 50–54, 56–59, 75, 77, 78, 81, 83, 85, 87, 89, 91, 93, 95, 96, 98, 103
 Tb_Gates, 4, 11, 24–27, 29–31, 35–37, 39, 44, 45, 47, 48, 50–54, 56–59, 75, 77, 79, 80, 83, 85, 87, 89, 91, 93, 95, 96, 98, 103
 Tb_Gates2, 4, 11, 24–27, 29–31, 35–37, 39, 44, 45, 47, 48, 50–54, 56–59, 75, 77, 79, 81, 82, 85, 87, 89, 91, 93, 95, 96, 98, 103
 Tb_grasshopper, 4, 11, 24–27, 29–31, 35–37, 39, 44, 45, 47, 48, 50–54, 56–59, 75, 77, 79, 81, 83, 83, 87, 89, 91, 93, 95, 96, 98, 103
 Tb_limpet, 4, 11, 24–26, 28–31, 35–37, 39, 44, 45, 47, 48, 50–54, 56–59, 75, 77, 79, 81, 83, 85, 86, 89, 91, 93, 95, 96, 98, 103
 Tb_limpetBH, 4, 11, 24–26, 28–31, 35–37, 39, 44, 45, 47, 48, 50–54, 56–59, 75, 77, 79, 81, 83, 85, 87, 87, 91, 93, 95, 96, 98, 103
 Tb_lizard, 4, 11, 24–26, 28–31, 35–37, 39, 44, 45, 47, 48, 50–54, 56–59, 75, 77, 79, 81, 83, 85, 87, 89, 89, 93, 95, 96, 98, 103
 Tb_lizard_Fei, 4, 11, 24–26, 28–31, 35–37, 39, 44, 45, 47, 48, 50–54, 56–59, 75, 77, 79, 81, 83, 85, 87, 89, 91, 92, 95, 96, 98, 103
 Tb_mussel, 4, 11, 24–26, 28–31, 35–37, 39, 44, 45, 47, 48, 50–54, 56–59, 75, 77, 79, 81, 83, 85, 87, 89, 91, 93, 94, 96, 98, 103
 Tb_salamander_humid, 4, 11, 24–26, 28–31, 35–37, 39, 44, 45, 47, 48, 50–54, 56–59, 75, 77, 79, 81, 83, 85, 87, 89, 91, 93, 95, 95, 98, 103
 Tb_snail, 4, 11, 24–26, 28–31, 35–37, 39, 44, 45, 47, 48, 50–54, 56–59, 75, 77, 79, 81, 83, 85, 87, 89, 91, 93, 95, 96, 97, 103
 Tbed_mussel, 4, 11, 24–26, 28–31, 35–37, 39, 44, 45, 47, 48, 50–54, 56–59, 74, 77, 79, 81, 83, 85, 87, 89, 91, 93, 95, 96, 98, 103
 temperature_conversions, 99
 TPC, 100
 TPC_beta, 101
 TrenchR, 102
 Tsoil, 4, 11, 24–26, 28–31, 35–37, 39, 44, 45, 47, 48, 50–54, 56–59, 75, 77, 79, 81, 83, 85, 87, 89, 91, 93, 95, 96, 98, 102

 VAPPRS, 103, 105
 volume_from_length, 33, 42, 43, 70, 72, 73, 104
 von_karman_constant (constants), 12

 WETAIR, 26–30, 56, 58, 105
 wind_speed_profile_neutral, 6, 7, 9, 16–19, 21, 22, 34, 38, 40, 69, 74, 107, 108
 wind_speed_profile_segment, 6, 7, 9, 16–19, 21, 22, 34, 38, 40, 69, 74, 107, 108

 zenith_angle, 5, 10, 13–15, 68, 86, 94, 99, 109