

The meteoland reference book

true

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Preface

This is a reference book for the data structures and functions implemented in **meteoland**, an R package that provides functions to estimate daily weather at any position over given terrains.

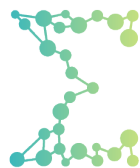
How to use this book

This reference book is meant to help you understand the data structures and functions included in package **meteoland** (ver. **2.0.1**). Hands-on user guides can be found as package vignettes within the package. As any reference book, you are not expected to read the book linearly, but to jump to sections whenever you have doubts about the design of the package or implementation of certain calculations.

The first two chapters of the book present the package, its data structures and main function. Chapter 3 focuses on the functions supplied for interpolating weather records and chapter 4 explains how solar radiation is estimated. Chapter 5 is devoted to statistical correction of weather series (i.e. bias correction). The remaining chapters detail other functions meant to complete the package.

In this book we use **objectname** or **variablename** to indicate R code or to refer to an R objects or a variable within data frames, and **functionname()** to refer to a package function. Whenever relevant, we indicate the correspondence between mathematical symbols, their units and the names used within the R package.

The reference book describes in detail the design and functioning of the package. An introduction to the package was provided by De Cáceres et al. (2018) at the time of its presentation, but this reference book should be preferred for an up-to-date description of the package. Our aim is to update this reference book along with package developments, so that users have detailed and up-to-date information about the models at the time functions are run. As the book will not be static, after a given application we recommend users to store a **PDF version** of the reference book to be sure it matches the version the package reported in their application report or article.



Chapter 1

Introduction

1.1 Purpose

Reliable meteorological data are a basic requirement for hydrological and ecological studies at the landscape scale. Given the large variation of weather over complex terrains, meteorological records from a single weather station are often not representative of entire landscapes. Studies made on multiple sites over a landscape require different meteorological series for each site; and other studies may require meteorological data series for all grid cells of a landscape, in a continuous way. In these cases, spatial correlation between the meteorology series of different sites or cells must be taken into account. For example, the sequence of days with rain of contiguous cells will normally be the same or very similar, even if precipitation amounts may differ substantially. Finally, studies addressing the impacts of climate change on forested landscapes require downscaling and bias-correcting coarse-scale predictions of global or regional climate models to the landscape scale. When downscaling predictions for several locations in a landscape, spatial correlation of predictions is also important.

With the aim to assist research of climatic impacts, the R package **meteoland** (De Cáceres et al. 2018) provides utilities to estimate daily weather variables at any position over complex terrains. The package was designed to provide functions to assist the following tasks:

- Spatial interpolation of daily weather records from meteorological stations.
- Statistical correction of meteorological data series (e.g. from climate models).
- Multisite and multivariate stochastic weather generation.

Spatial interpolation is required when meteorology for the area and period of interest cannot be obtained from local sensors. The nearest weather station may

not have data for the period of interest or it may be located too far away to be representative of the target area. Correcting the biases of a meteorological data series containing biases using a more accurate meteorological series is necessary when the more accurate series does not cover the period of interest and the less accurate series does. The less accurate series may be at coarser scale, as with climate model predictions or climate reanalysis data. In this case one can speak of statistical correction and downscaling. However, one may also correct the predictions of climate models using reanalysis data estimated at the same spatial resolution. Finally, stochastic weather generators are algorithms that produce series of synthetic daily weather data. The parameters of the model are conditioned on existing meteorological records to ensure the characteristics of input weather series emerge in the daily stochastic process.

IMPORTANT NOTE: Strong modifications of the spatial data structures in the package made starting in **ver. 2.0** have led to a completely new set of functions for **spatial interpolation**, which is the main use of the package. At the same time, previous functions for **statistical correction** and **weather generation** have been deprecated. Although the theory underlying these latter tasks is still described in this manual, and the future evolution of the package may lead to new functions being developed, users intending to perform those tasks should resort on other packages at present.

1.2 Package installation

Package **meteoland** is officially distributed via CRAN. Hence, it can be installed using:

```
install.packages("meteoland")
```

Users can also download and install the latest stable versions GitHub as follows (required package **remotes** should be installed/updated first):

```
remotes::install_github("emf-creaf/meteoland")
```


Chapter 2

Data structures and main functions

2.1 Meteorological variables

Package **meteoland** assists in the estimation of the following daily variables over landscapes (units in parentheses):

- **DOY**: Day of the year ([1-366]).
- **MeanTemperature**: Mean daily temperature (in degrees Celsius).
- **MinTemperature**: Minimum daily temperature (in degrees Celsius).
- **MaxTemperature**: Maximum daily temperature (in degrees Celsius).
- **Precipitation**: Daily precipitation (in mm of water).
- **MeanRelativeHumidity**: Mean daily relative humidity (in percent).
- **MinRelativeHumidity**: Minimum daily relative humidity (in percent).
- **MaxRelativeHumidity**: Maximum daily relative humidity (in percent).
- **Radiation**: Incoming radiation (in MJ/m²).
- **WindSpeed**: Wind speed (in m/s).
- **WindDirection**: Wind direction (in degrees from North).
- **PET**: Potential evapo-transpiration (in mm of water).

2.2 Spatial classes

With the retirement of **rgdal**, **rgeos** and **maptools** R packages, a complete update of **meteoland** was necessary to remove the hard dependency that the package had with **sp** and **raster** R packages. Starting with **version 2.0.0** of **meteoland**, now **sf** and **stars** packages are internally used for working with simple features and raster data, respectively.

2.2.1 Topography

Spatial variation of topography should be represented in **sf** and **stars** objects by the variables: **elevation** (in meters), **slope** (in degrees from the horizontal plane) and **aspect** (in degrees from North).

2.2.2 Meteorology

When using **sf** data structures, daily weather variables can be represented as columns of the corresponding data frame, whereas dates (i.e. **Date** or **POSIXct** objects) are specified in a column called **dates**. Interpolation results use also **sf** objects, but where weather data series for all variables are supplied in a column called **interpolated_data**.

When using **stars** data structures, daily weather variables are represented as attributes and dates are represented as a time dimension.

2.2.3 Interpolator objects

Since **ver. 2.0.0**, reference weather data is represented by interpolator objects of class **stars**, where the interpolation parameter list is included as an attribute **params**. Interpolator objects can be created using function **create_meteo_interpolator()**, and interpolation parameters are retrieved or modified using functions **get_interpolation_params()** and **set_interpolation_params()**, respectively.

2.3 Reading and writing meteorological data

Since **ver. 2.0.0**, reading and writing meteorological data is no longer dealt within the package, but can be dealt with using the corresponding functions in packages **sf** and **stars**. The only exception are interpolator objects, which are stored as NetCDFs and have their own functions **read_interpolator()** and **write_interpolator()**.

2.4 Subsetting, merging and reshaping data

Since **ver. 2.0.0**, subsetting, merging and reshaping weather data is done using functions provided by packages **sf** and **stars**.

2.5 Summarizing meteorological data

Since **ver. 2.0.0** spatial or temporal summaries can be done using functions of packages **sf** and **stars**. Additionally, **meteoland** provides a helper function called `summarise_interpolated_data()` that accepts the objects returned by function `interpolation_data()`.

2.6 Meteorology interpolation

Since **ver. 2.0.0**, package **meteoland** provides one single functions for interpolating meteorological data over landscapes. Function `interpolate_data()` interpolates weather for a set of locations, and accepts both **sf** and **stars** structures as input, but necessitates an interpolator object with the reference weather station data.

Functions `interpolator_calibration()` and `interpolation_cross_validation()` are included in **meteoland** to calibrate interpolation parameters and evaluate predictive performance of interpolation routines before using them. Details of interpolation routines are described in chapter 3.

Chapter 3

Spatial interpolation of weather records

3.1 Overview

Ecological research studies conducted for historical periods can be performed using meteorological records obtained from surface weather stations of the area under study. The general procedure for interpolation is very similar to the one that underpins the U.S. DAYMET dataset (<https://daymet.ornl.gov/>). For any target point, minimum temperature, maximum temperature and precipitation are interpolated from weather records using truncated Gaussian filters, while accounting for the relationship between these variables and elevation (Peter E. Thornton, Running, and White 1997). Relative humidity can be either interpolated (in fact, dew-point temperature is the variable being interpolated) or predicted from temperature estimates, depending on whether it has been measured in weather stations or not. Potential (i.e. top-of-atmosphere) solar radiation is estimated taking into account latitude, seasonality, aspect and slope, following Garnier and Ohmura (1968). Potential solar radiation is then corrected to account for atmosphere transmittance using the predictions of temperature range, relative humidity and precipitation (P. E. Thornton and Running 1999). Finally, the wind vector (wind direction and wind speed) is interpolated by using weather station records and static wind fields.

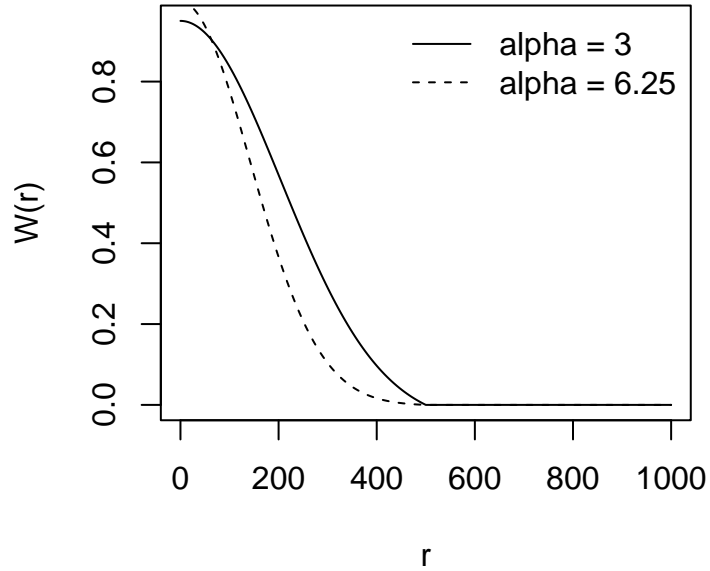
In the following sections we detail the general algorithm used to obtain interpolation weights and the interpolation procedure for temperature, precipitation, relative humidity and wind. The estimation of potential and actual solar radiation is explained in the next chapter.

3.2 Interpolation weights

Peter E. Thornton, Running, and White (1997) suggested interpolating meteorological data using a truncated Gaussian filter. Its form with respect to a central point p is:

$$W(r) = e^{-\alpha \cdot (r/R_p)^2} - e^{-\alpha} \quad (3.1)$$

if $r \leq R_p$ and $W(r) = 0$ otherwise. Here r is the radial distance from p , R_p is the truncation distance and α is the shape parameter. The spatial convolution of this filter with a set of weather station locations results, for each target point, in a vector of weights associated with observations. The following figure illustrates the Gaussian filter for $R_p = 500$ and either $\alpha = 3.0$ (continuous line) or $\alpha = 6.25$ (dashed line):



R_p is automatically adjusted so that it has lower values in data-rich regions and is increased in data-poor regions. The method, however, requires the user to specify N , the average number of observations to be included for each target point. R_p is then varied as a smooth function of the local density in such a way that this average is achieved over the spatial domain. Estimation of R_p is as follows:

1. A user-specified value is used to initialize R_p .
2. Interpolation weights W_i are calculated for all $i = (1, \dots, n)$ stations, and the local station density is calculated as:

$$D_p = \frac{\sum_{i=1}^n (W_i / \hat{W})}{\pi \cdot R_p^2} \quad (3.2)$$

where \hat{W} is the average weight over the untruncated region of the kernel, calculated as:

$$\hat{W} = \left(\frac{1 - e^{-\alpha}}{\alpha} \right) - e^{-\alpha} \quad (3.3)$$

3. A new R_p value is calculated as a function of N and D_p , as:

$$R_p = \sqrt{\frac{N^*}{D_p \cdot \pi}} \quad (3.4)$$

where $N^* = 2N$ for the first $I - 1$ iterations, and $N^* = N$ for the final iteration.

4. The new R_p is substituted in step (2) and steps (2-4) are iterated a specified number of times I . The final R_p value is used to generate interpolation weights W_i .

Peter E. Thornton, Running, and White (1997) suggested to use this algorithm only once per point (and variable to be estimated), but since missing meteorological values can occur only in some days, we apply the algorithm for each target point and day. The interpolation method for a given set of observations is defined by four parameters R , I , N and α . Following Peter E. Thornton, Running, and White (1997), we set $R = 140000$ meters and $I = 3$ by default (see parameters `initial_Rp` and `iterations` given in function `defaultInterpolationParams()`). The other parameters (N and α) depend on the variable to be interpolated.

3.3 Temperature

Predictions for minimum temperature and maximum temperature are done in the same way, so we refer to a general variable T . We focus on the prediction of T_p , the temperature at a single target point p and for a single day, based on observations T_i and interpolation weights W_i for the $i = (1, \dots, n)$ weather stations. Prediction of T_p requires a correction for the effects of elevation differences between observation points z_1, \dots, z_n and the prediction point z_p . Peter E. Thornton, Running, and White (1997) established the relationship between elevation and temperature using transformed variables (temporal or spatial moving window averages) for temperature and elevation, instead of the original variables, but we did not implement this feature here. A weighted least-squares regression is used to assess the relationship between temperature and elevation. Instead of regressing z_i on T_i , the independent variable is the difference in elevations associated with a pair of stations, and the dependent variable is the corresponding difference in temperatures. This gives a regression of the form:

$$(T_1 - T_2) = \beta_0 + \beta_1 \cdot (z_1 - z_2) \quad (3.5)$$

where subscripts 1 and 2 indicate the two stations of a pair and β_0 and β_1 are the regression coefficients. Regression is performed using all possible pairs of stations and the regression weight associated with each point is the product of the interpolation weights associated with the stations in a pair. The temperature for the target point, T_p is finally predicted as follows:

$$T_p = \frac{\sum_{i=1}^n W_i \cdot (T_i + \beta_0 + \beta_1 \cdot (z_p - z_i))}{\sum_{i=1}^n W_i} \quad (3.6)$$

where z_p is the elevation of the target point and z_i is the elevation of the weather station.

3.4 Relative humidity

Relative humidity is a parameter not always recorded in weather stations. When input station weather data does not include relative humidity, **meteoland** estimates it directly from minimum and maximum temperature (Peter E. Thornton, Running, and White 1997). Assuming that minimum daily air temperature $T_{min,p}$ at the target point is a good surrogate of dew-point temperature $T_{d,p}$ (i.e. $T_{d,p} = T_{min,p}$; note that this assumption may not be valid in arid climates), one can estimate actual vapor pressure e_p (in kPa) as:

$$e_p = 0.61078 \cdot e^{\left(\frac{17.269 \cdot T_{d,p}}{237.3 + T_{d,p}}\right)} \quad (3.7)$$

and saturated vapor pressure $e_{s,p}$ (in Pa) as:

$$e_{s,p} = 0.61078 \cdot e^{\left(\frac{17.269 \cdot T_{a,p}}{237.3 + T_{a,p}}\right)} \quad (3.8)$$

where $T_{a,p} = 0.606 \cdot T_{max,p} + 0.394 \cdot T_{min,p}$ is the average daily temperature. Finally, relative humidity RH_p (in percentage) is calculated as:

$$RH_p = 100 \cdot \frac{e_p}{e_{s,p}} \quad (3.9)$$

When relative humidity has been measured at weather stations, interpolation should be preferred to estimation from minimum and maximum temperature. However, because relative humidity depends on temperature, relative humidity RH_i of each weather station i has to be converted to dew-point temperature $T_{d,i}$ before interpolation (Tymstra et al. 2010). To obtain the dew-point temperature one first needs to calculate vapor pressure:

$$e_i = e_{s,i} \cdot (RH_i/100) \quad (3.10)$$

where $e_{s,i}$ is the saturated water vapor pressure of station i , calculated as indicated above. Then, dew-point temperature of station i is obtained from:

$$T_{d,i} = \frac{237.3 \cdot \ln(e_i/0.61078)}{17.269 - \ln(e_i/0.61078)} \quad (3.11)$$

Unlike temperature, interpolation of dew temperature is not corrected for elevation differences. The dew-point temperature for the target point, $T_{d,p}$ is predicted as:

$$T_{d,p} = \frac{\sum_{i=1}^n W_i \cdot T_{d,i}}{\sum_{i=1}^n W_i} \quad (3.12)$$

From the interpolated dew-point temperature one can obtain actual vapour pressure e_p and, together with saturated vapour pressure at point p , one calculates relative humidity as indicated above. If saturated vapour pressure is referred to average temperature $T_{a,p}$, then relative humidity is average relative humidity $RH_{a,p}$. If, instead, one refers saturated vapour pressure to minimum and maximum daily temperatures one obtains, respectively, maximum and minimum relative humidity values ($RH_{max,p}$, $RH_{min,p}$). After their estimation, the routine checks that the predicted maximum and minimum relative humidity values stay within the physical limits 0% and 100%. Although interpolation of dew-point temperature does not account for elevation differences, interpolated values of relative humidity will normally exhibit a pattern following elevation differences because temperature is involved in the calculation of relative humidity.

3.5 Precipitation

Predictions of precipitation are complicated by the need to predict both daily occurrence and, conditioned on this, daily precipitation amount. Peter E. Thornton, Running, and White (1997) define a binomial predictor of spatial precipitation occurrence as a function of the weighted occurrence at surrounding stations. The precipitation occurrence probability POP_p is:

$$POP_p = \frac{\sum_{i=1}^n W_{o,i} \cdot PO_i}{\sum_{i=1}^n W_{o,i}} \quad (3.13)$$

where PO_i is the binomial precipitation occurrence in station i (i.e., $PO_i = 0$ if $P_i = 0$ and $PO_i = 1$ if $P_i > 0$) and $W_{o,i}$ is the interpolation weight for precipitation occurrence. Once POP_p is calculated, then precipitation occurs if POP_p is smaller than a critical value (i.e. $PO_p = 1$ if $POP_p < POP_{crit}$ and $PO_p = 0$ otherwise).

Conditional on precipitation occurrence we calculate the prediction of daily total precipitation, P_p . Like with temperature, Peter E. Thornton, Running, and White (1997) established the relationship between elevation and precipitation using transformed variables (temporal or spatial moving window averages) for precipitation and elevation. Following their results, we transform precipitation values using a temporal window with side of 5 days. Weighted least-squares, where the weight associated with each point is the product of the interpolation weights associated with the stations in a pair, is used to account for elevation effects on precipitation. Unlike Peter E. Thornton, Running, and White (1997),

who use the same set of interpolation weights (i.e. $W_{o,i}$) for precipitation occurrence and regression, we use a second set of interpolation weights $W_{r,i}$ for the calculation of regression weights. The dependent variable in the regression function is defined as the normalized difference of the precipitation observations P_i for any given pair of stations:

$$\left(\frac{P_1 - P_2}{P_1 + P_2} \right) = \beta_0 + \beta_1 \cdot (z_1 - z_2) \quad (3.14)$$

To obtain the predicted daily total P_p we use the following equation:

$$P_p = \frac{\sum_{i=1}^n W_{o,i} \cdot P_i \cdot PO_i \cdot \left(\frac{1+f}{1-f} \right)}{\sum_{i=1}^n W_{o,i} \cdot PO_i} \quad (3.15)$$

where $f = \beta_0 + \beta_1 \cdot (z_p - z_i)$. Note the usage of interpolation weight $W_{o,i}$ (and not $W_{r,i}$). The form of prediction requires that $|f| < 1$. A parameter f_{max} (with default $f_{max} = 0.95$) is introduced to force $|f| = f_{max}$ whenever $|f| > f_{max}$.

3.6 Wind

Interpolation of wind characteristics depends on the amount of information available:

- Interpolation of wind speed only
- Interpolation of wind vectors (speed and direction)
- Interpolation of wind vectors using wind fields

The following subsections detail the calculations in each case.

3.6.1 Interpolation of wind speed

The predicted wind speed u_p for a target point p is the weighted average of station wind speed values $\{u_i\}$ $i = (1, \dots, n)$ using the interpolation weights W_i determined from the truncated Gaussian filter:

$$u_p = \frac{\sum_{i=1}^n W_i \cdot u_i}{\sum_{i=1}^n W_i} \quad (3.16)$$

3.6.2 Interpolation of wind vectors

Interpolation of wind vectors for a target point p is as follows. Let \mathbf{v}_i be the wind vector in weather station i . \mathbf{v}_i is initially expressed using polar coordinates.

Indeed, we have u_i and θ_i , the wind speed and wind direction, respectively. If we express \mathbf{v}_i in cartesian coordinates we have:

$$x_i = u_i \cdot \sin(\theta_i) \quad y_i = u_i \cdot \cos(\theta_i) \quad (3.17)$$

The predicted wind vector \mathbf{v}_p is the weighted average of the wind vectors $\{\mathbf{v}_i\}$ $i = (1, \dots, n)$ predicted for point p using the interpolation weights W_i determined from the truncated Gaussian filter:

$$x_p = \frac{\sum_{i=1}^n W_i \cdot x_i}{\sum_{i=1}^n W_i} \quad y_p = \frac{\sum_{i=1}^n W_i \cdot y_i}{\sum_{i=1}^n W_i} \quad (3.18)$$

The polar coordinates of the predicted wind vector \mathbf{v}_p are:

$$u_p = \sqrt{x_p^2 + y_p^2} \quad \theta_p = \tan^{-1}(x_p/y_p) \quad (3.19)$$

3.6.3 Interpolation of wind vectors using wind fields

More precise wind interpolation of wind vectors requires a set of static wind fields covering the landscape of interest. Each of these wind fields has been calculated assuming a domain-level combination of wind speed and wind direction. The set of domain-level combinations should cover all possible winds in the landscape under study. For example, one could decide to include the combinations of eight different wind directions (i.e., N, NE, E, SE, ...) and three wind speed classes. The wind estimation of a given target point depends on both the wind observations at weather stations and these static wind fields.

In a given day (and before processing target points) we begin by identifying, for each weather station $i = (1, \dots, n)$, the wind field m_i corresponding to a minimum difference between the observed wind vector \mathbf{v}_i and the wind vector of the station in the wind field (i.e., minimum distance between the corresponding cartesian coordinates). The set of wind fields $\{m_i\}$ $i = (1, \dots, n)$ chosen for each weather station conform the information for wind interpolation in a given day.

Actual wind interpolation details for a target point p are as follows. We first draw for each $i = (1, \dots, n)$ the wind vector $\mathbf{v}_{m_i,p}$ corresponding to the location of the target point p in wind fields m_i . Let $u_{m_i,p}$ and $\theta_{m_i,p}$ be the wind speed and wind direction of $\mathbf{v}_{m_i,p}$, respectively. The cartesian coordinates of $\mathbf{v}_{m_i,p}$ are:

$$x_{m_i,p} = u_{m_i,p} \cdot \sin(\theta_{m_i,p}) \quad y_{m_i,p} = u_{m_i,p} \cdot \cos(\theta_{m_i,p}) \quad (3.20)$$

The predicted wind vector \mathbf{v}_p is the weighted average of the wind vectors $\{\mathbf{v}_{m_i,p}\}$ $i = (1, \dots, n)$ predicted for point p using the interpolation weights W_i determined from the truncated Gaussian filter:

$$x_p = \frac{\sum_{i=1}^n W_i \cdot x_{m_i,p}}{\sum_{i=1}^n W_i} \quad y_p = \frac{\sum_{i=1}^n W_i \cdot y_{m_i,p}}{\sum_{i=1}^n W_i} \quad (3.21)$$

The polar coordinates of the predicted wind vector \mathbf{v}_p are found as before.

Chapter 4

Estimation of solar radiation

Incident daily solar radiation is not interpolated, but estimated from topography and measurements of temperature, humidity and precipitation.

4.1 Solar declination and solar constant

The declination of the sun δ is the angle between the rays of the sun and the plan of the Earth's equator. Solar declination varies with years and seasons. However, the Earth's axial tilt changes slowly over thousands of years but it is nearly constant for shorter periods, so the change in solar declination during one year is nearly the same as during the next year. Solar constant (I_0) is normally given a nominal value of $1.361 \text{ kW} \cdot \text{m}^{-2}$ but in fact it also varies through the year and over years. Both can be calculated from Julian day (J), the number of days number of days since January 1, 4713 BCE at noon UTC. from Julian day. In **meteoland**, julian days, solar declination and solar constant are calculated using an adaptation of the code as in package **insol** by J.G. Corripio, which is based on Danby (1988) and Reda and Nrel (2008).

The following figures show the variation of solar declination and the value of solar constant over a year (see functions `radiation_solarDeclination()` and `radiation_solarConstant()`):

```
## Warning in axis(side, at = z, labels = labels, ...): conversion failure on 'd'abr. 2012' in
## 'mbcsToSbcs': dot substituted for <e2>
```

```
## Warning in axis(side, at = z, labels = labels, ...): conversion failure on 'd'abr. 2012' in
## 'mbcsToSbcs': dot substituted for <80>
```

```

## Warning in axis(side, at = z, labels = labels, ...): conversion failure on 'd'abr. 2
## 'mbsToSbs': dot substituted for <99>

## Warning in axis(side, at = z, labels = labels, ...): conversion failure on 'd'oct. 2
## 'mbsToSbs': dot substituted for <e2>

## Warning in axis(side, at = z, labels = labels, ...): conversion failure on 'd'oct. 2
## 'mbsToSbs': dot substituted for <80>

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## 'mbsToSbs': dot substituted for <e2>

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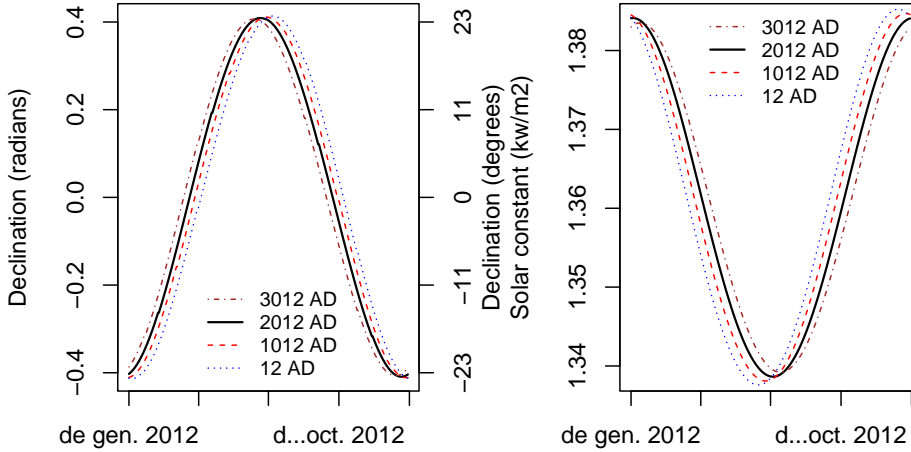
## Warning in axis(side, at = z, labels = labels, ...): conversion failure on 'd'oct. 2
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```

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## Warning in axis(side, at = z, labels = labels, ...): conversion failure on 'd'oct. 2012' in
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```

```
## Warning in axis(side, at = z, labels = labels, ...): conversion failure on 'd'oct. 2012' in
## 'mbsToSbcs': dot substituted for <99>
```



4.2 Day length

Calculation of sunrise and sunset on a horizontal surface is rather straightforward. The hour angles of sunrise and sunset (sr and ss , both in radians) for a horizontal surface of latitude ϕ on a day with declination δ (both expressed in radians) are:

$$sr = T_1 = \cos^{-1}(\max(\min(-\tan(\phi) \cdot \tan(\delta), 1), -1)) \quad (4.1)$$

$$ss = T_0 = -T_1 \quad (4.2)$$

Knowing that each hour corresponds to 15 degrees of rotation, hour angles can be transformed to solar hours. The following figures show the seasonal variation of sunrise and sunset hours, as well as day length, for horizontal surfaces in three latitudes (40North, equator and 40South) (see functions `radiation_sunRiseSet()` and `radiation_daylength()`):

```
## Warning in axis(side, at = z, labels = labels, ...): conversion failure on 'd'abr. 2012' in
## 'mbsToSbcs': dot substituted for <e2>
```

```
## Warning in axis(side, at = z, labels = labels, ...): conversion failure on 'd'abr. 2012' in
## 'mbsToSbcs': dot substituted for <80>
```

```

## Warning in axis(side, at = z, labels = labels, ...): conversion failure on 'd'abr. 2
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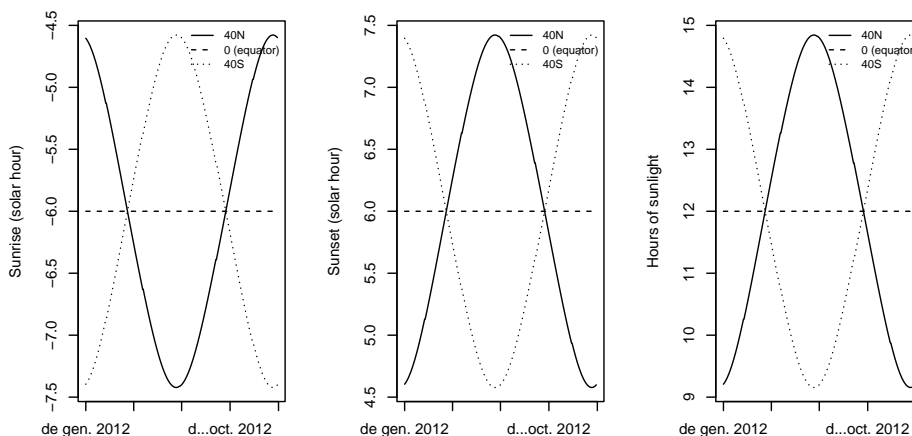
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## 'mbcsToSbcs': dot substituted for <80>

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## 'mbcsToSbcs': dot substituted for <80>

## Warning in axis(side, at = z, labels = labels, ...): conversion failure on 'd'oct. 2012' in
## 'mbcsToSbcs': dot substituted for <99>
```



For inclined slopes, the calculation of day length is based on the concept of equivalent slopes, which are places on earth where the slope of earth's surface is equal to the slope of interest. The calculations start with the determination of the latitude L_1 of the equivalent slope:

$$L_1 = \sin^{-1}(\cos(Z_x) \cdot \sin(\phi) + \sin(Z_x) \cdot \cos(\phi) \cdot \cos(A)) \quad (4.3)$$

$$D = \cos(Z_x) \cdot \cos(\phi) - \sin(Z_x) \cdot \sin(\phi) \cdot \cos(A) \quad (4.4)$$

where ϕ is the latitude, A is the azimuth of the slope (aspect) and Z_x is the zenith angle of the vector normal to the slope (equal to the slope angle). Then L_2 is defined depending on the value of D . If $D < 0$ then:

$$L_2 = \tan^{-1} \left(\frac{\sin(Z_x) \cdot \sin(A)}{D} \right) + \pi \quad (4.5)$$

Otherwise, L_2 is calculated as:

$$L_2 = \tan^{-1} \left(\frac{\sin(Z_x) \cdot \sin(A)}{D} \right) \quad (4.6)$$

Once L_1 and L_2 are available, we can calculate solar hours on equivalent slopes:

$$T_7 = \cos^{-1}(\max(\min(-\tan(L_1) \cdot \tan(\delta), 1), -1)) - L_2 \quad (4.7)$$

$$T_6 = -\cos^{-1}(\max(\min(-\tan(L_1) \cdot \tan(\delta), 1), -1)) - L_2 \quad (4.8)$$

Being T_6 and T_7 the hour angle of sunrise and sunset on equivalent slopes, respectively. and the hour angles of sunrise (sr) and sunset (ss) on the slope (both in radians) are found comparing the hour angles on equivalent surfaces with the hour angles on the horizontal surface:

$$sr = \max(T_0, T_6) \quad (4.9)$$

$$ss = \min(T_1, T_7) \quad (4.10)$$

The following three figures show the seasonal variation of sunrise and sunset hours, as well as day length, for slopes of 30 inclination, facing to the four cardinal points. Curves for flat surfaces are shown for comparison. If the slopes are at latitude 40North:

```
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## Warning in axis(side, at = z, labels = labels, ...): conversion failure on 'd'abr. 2
## 'mbsToSbcs': dot substituted for <80>
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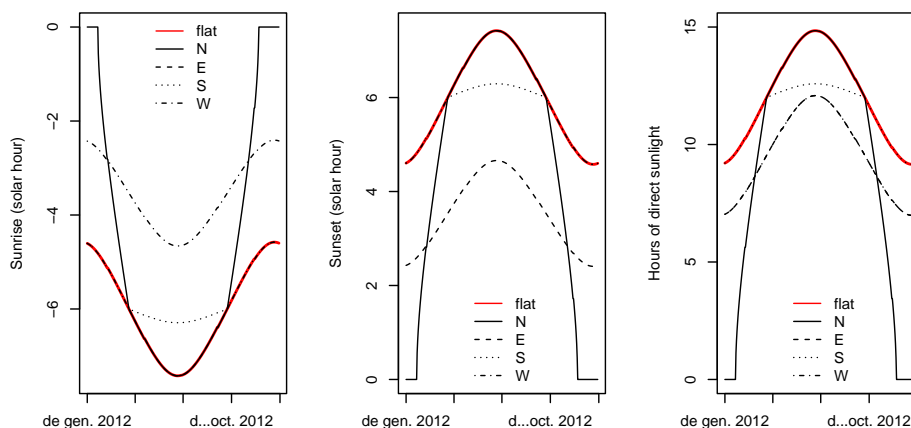
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## Warning in axis(side, at = z, labels = labels, ...): conversion failure on 'd'oct. 2
## 'mbcsToSbcs': dot substituted for <99>
```



whereas if they are at Equator (i.e. $\phi = 0$):

```
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## 'mbcsToSbcs': dot substituted for <e2>

## Warning in axis(side, at = z, labels = labels, ...): conversion failure on 'd'abr. 2012' in
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## 'mbcsToSbcs': dot substituted for <80>
```

```

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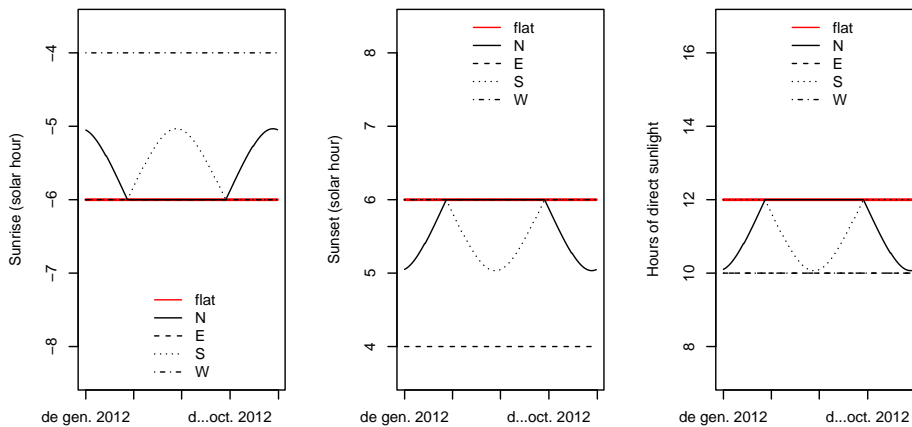
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## Warning in axis(side, at = z, labels = labels, ...): conversion failure on 'd'oct. 2
## 'mbsToSbs': dot substituted for <99>

```



and if they are at latitude 40South:

```
## Warning in axis(side, at = z, labels = labels, ...): conversion failure on 'd'abr. 2012' in
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```

```
## Warning in axis(side, at = z, labels = labels, ...): conversion failure on 'd'abr. 2012' in
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## Warning in axis(side, at = z, labels = labels, ...): conversion failure on 'd'abr. 2012' in
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```

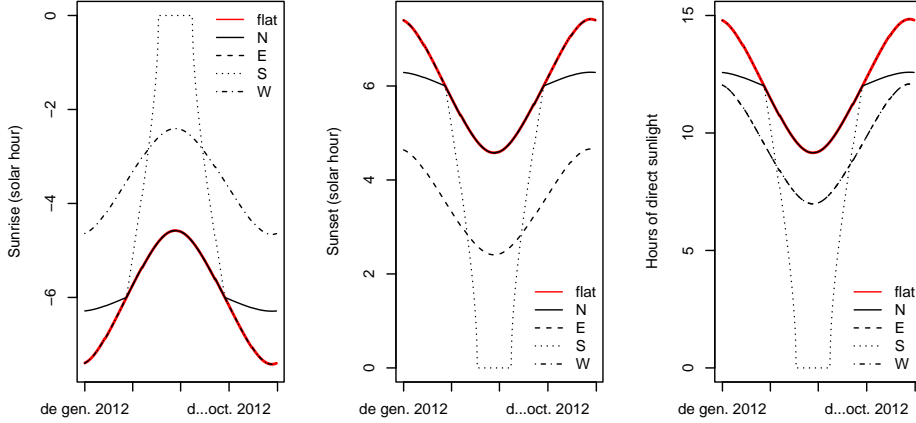


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## Warning in axis(side, at = z, labels = labels, ...): conversion failure on 'd'oct. 2012' in
## 'mbcsToSbcs': dot substituted for <99>
```



4.3 Potential radiation

Potential solar radiation is the radiation that a surface on earth would receive if atmosphere was not present (i.e. without the effects of cloud reflection, scattering, ...). In **meteoland**, potential solar radiation is estimated from solar declination, latitude, aspect and slope according to Garnier and Ohmura (1968). Daily potential radiation (R_{pot} , in $MJ \cdot m^{-2}$) is calculated by integrating instantaneous potential radiation $R_{pot,s}$ (in $kW \cdot m^{-2}$) over the day between sunrise (sr) and sunset (ss), using 10 min (i.e. 600 sec) intervals:

$$R_{pot} = \frac{1}{1000} \cdot \sum_{s=sr}^{ss} 600 \cdot R_{pot,s} \quad (4.11)$$

In turn, instantaneous potential solar radiation $R_{pot,s}$ is calculated using:

$$\begin{aligned} R_{pot,s} = & I_0 \cdot [(\sin \phi \cdot \cos H)(-\cos A \cdot \sin Z_x) - \sin H \cdot (\sin A \cdot \sin Z_x) \\ & + [(\cos \phi \cdot \cos H) \cdot \cos Z_x] \cdot \cos \delta \\ & + [\cos \phi \cdot (\cos A \cdot \sin Z_x) + \sin \phi \cdot \cos Z_x] \cdot \sin \delta] \end{aligned} \quad (4.12)$$

where I_0 is the solar constant, ϕ is the latitude, H is the hour angle measured from solar noon, positively towards the west, A is the azimuth of the slope (aspect), Z_x is the zenith angle of the vector normal to the slope (equal to the slope angle) and δ is the sun's declination. Note that in the case of a flat surface the previous equation reduces to:

$$R_{pot,s} = I_0 \cdot [\cos \phi \cdot \cos H \cdot \cos \delta + \sin \phi \cdot \sin \delta] = I_0 \cdot \sin \beta \quad (4.13)$$

where β is called the solar elevation angle.

The following figures illustrate seasonal variation of potential solar radiation for the horizontal inclined surfaces presented above (see function `radiation_potentialRadiation()`):

```
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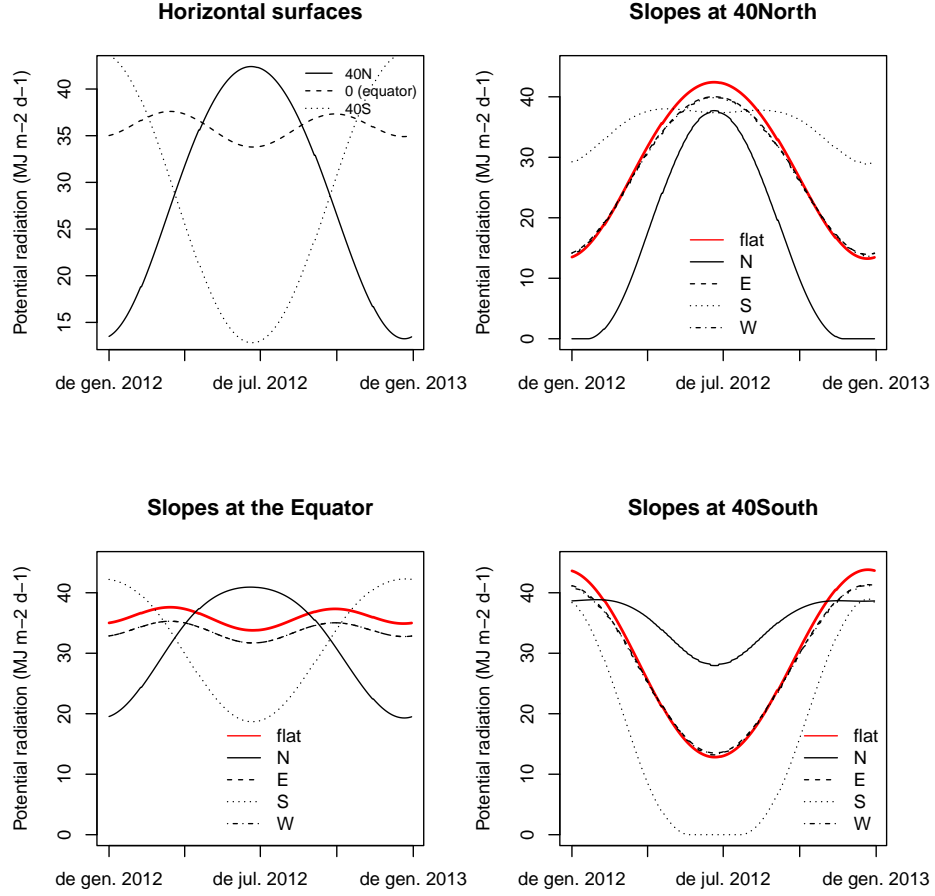
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## 'mbsToSbs': dot substituted for <80>

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## Warning in axis(side, at = z, labels = labels, ...): conversion failure on 'd'oct. 2012' in
## 'mbsToSbs': dot substituted for <99>
```



4.4 Incident solar radiation

Incident solar radiation is the amount of (direct) solar radiation reaching the surface after accounting for the atmosphere. Improving the method proposed in Peter E. Thornton, Running, and White (1997), P. E. Thornton and Running (1999) calculate incident daily total solar radiation R_g as:

$$R_g = R_{pot} \cdot T_{t,max} \cdot T_{f,max} \quad (4.14)$$

where $T_{t,max}$ is the maximum (cloud-free) daily total transmittance and $T_{f,max}$ is the proportion of $T_{t,max}$ realized on a given day (cloud correction). The maximum daily total transmittance $T_{t,max}$ is estimated as:

$$T_{t,max} = \left[\frac{\sum_{s=sr}^{ss} R_{pot,s} \cdot \tau^{(P_z/P_0) \cdot m_\theta}}{\sum_{s=sr}^{ss} R_{pot,s}} \right] + (\alpha_{e_p} \cdot e_p) \quad (4.15)$$

where $\tau = 0.87$ is the instantaneous transmittance at sea level, at nadir, for a dry atmosphere; e_p is the actual water vapor pressure (in kPa), estimated as explained before; $\alpha_{e_p} = -6.1 \cdot 10^{-2} \text{kPa}^{-1}$ is a parameter describing the effect of vapour pressure on $T_{t,max}$; $m_\theta = 1/\cos\theta$ is the optical air mass at solar zenith angle $\cos(\theta) = \sin\phi \cdot \sin\delta + \cos\phi \cdot \cos\delta \cdot \cos H$; and P_z/P_0 is the ratio between air pressure at elevation z_p and air pressure at the sea level, calculated as:

$$(P_z/P_0) = (1.0 - 2.2569 \cdot 10^{-5} \cdot z_p)^{5.2553} \quad (4.16)$$

In turn, $T_{f,max}$ was empirically related to $\Delta T = T_{\max} - T_{\min}$, the difference between maximum and minimum temperatures for the target point:

$$T_{f,max} = 1.0 - 0.9 \cdot e^{-B \cdot \Delta T^C} \quad (4.17)$$

being $C = 1.5$ and B calculated from:

$$B = b_0 + b_1 \cdot e^{-b_2 \cdot \hat{\Delta T}} \quad (4.18)$$

with $b_0 = 0.031$, $b_1 = 0.201$ and $b_2 = 0.185$. In this last equation, $\hat{\Delta T}$ is a 30-day moving average for the temperature range ΔT . For computational reasons, we do not estimate $\hat{\Delta T}$ from the 30-day moving window average of predicted ΔT values, but from the interpolation of pre-calculated $\hat{\Delta T}$ values in weather stations. On wet days (i.e. if $P_p > 0$) the estimation of $T_{f,max}$ is multiplied by a factor of 0.75 to account for clouds.

Although the calculation of incident solar radiation can be done independently of interpolation (see function `radiation_solarRadiation()`), it is automatically done in functions `interpolationpoints()` and `interpolationgrid()`.

4.5 Outgoing longwave radiation and net radiation

Potential and actual evapotranspiration calculations require estimating the energy actually absorbed by evaporating surfaces. Daily net radiation R_n (in $\text{MJ} \cdot \text{m}^{-2} \cdot \text{day}^{-1}$) is calculated using:

$$R_n = R_s \cdot (1 - \alpha) - R_{nl} \quad (4.19)$$

where R_s is the input solar radiation (in $\text{MJ} \cdot \text{m}^{-2} \cdot \text{day}^{-1}$), $\alpha = 0.08$ accounts for surface albedo, and R_{nl} is the net longwave radiation. Outgoing longwave radiation is the radiation emitted by earth. Following McMahon et al. (2013) to obtain R_{nl} one first calculates clear sky radiation R_{so} using:

$$R_{so} = (0.75 + 0.00002 \cdot z) \cdot R_{pot} \quad (4.20)$$

where z is elevation and R_{pot} is potential radiation. R_{nl} is then calculated using:

$$R_{nl} = \sigma \cdot (0.34 - 0.14 \cdot \sqrt{e}) \cdot \frac{T_{\max}^4 + T_{\min}^4}{2} \cdot (1.35 \cdot \min(\frac{R_s}{R_{so}}, 1.0) - 0.35) \quad (4.21)$$

where e is the actual vapor pressure (kPa), T_{\max} and T_{\min} are the maximum and minimum temperatures (in Kelvin) and $\sigma = 4.903 \cdot 10^{-9} MJ \cdot K^{-4} \cdot m^{-2}$ is the Stephan-Boltzmann constant.

The following figure shows an example of radiation balance for a whole year for a single site (see functions `radiation_outgoingLongwaveRadiation()` and `radiation_netRadiation()`):

```
## Warning in axis(side, at = z, labels = labels, ...): conversion failure on 'd'abr. 2
## 'mbcsToSbcs': dot substituted for <e2>

## Warning in axis(side, at = z, labels = labels, ...): conversion failure on 'd'abr. 2
## 'mbcsToSbcs': dot substituted for <80>

## Warning in axis(side, at = z, labels = labels, ...): conversion failure on 'd'abr. 2
## 'mbcsToSbcs': dot substituted for <99>

## Warning in axis(side, at = z, labels = labels, ...): conversion failure on 'd'abr. 2
## 'mbcsToSbcs': dot substituted for <e2>

## Warning in axis(side, at = z, labels = labels, ...): conversion failure on 'd'abr. 2
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## 'mbcsToSbcs': dot substituted for <99>

## Warning in axis(side, at = z, labels = labels, ...): conversion failure on 'd'oct. 2
## 'mbcsToSbcs': dot substituted for <e2>

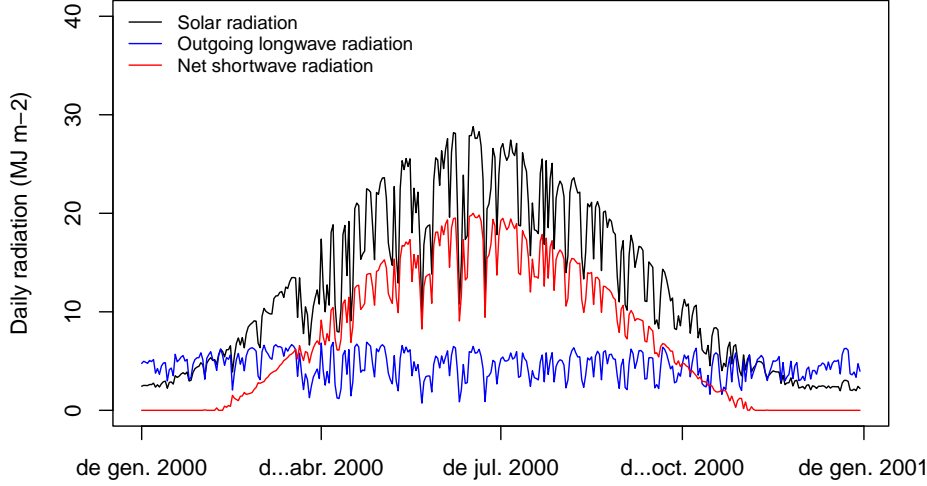
## Warning in axis(side, at = z, labels = labels, ...): conversion failure on 'd'oct. 2
## 'mbcsToSbcs': dot substituted for <80>

## Warning in axis(side, at = z, labels = labels, ...): conversion failure on 'd'oct. 2
## 'mbcsToSbcs': dot substituted for <99>

## Warning in axis(side, at = z, labels = labels, ...): conversion failure on 'd'oct. 2
## 'mbcsToSbcs': dot substituted for <e2>

## Warning in axis(side, at = z, labels = labels, ...): conversion failure on 'd'oct. 2
## 'mbcsToSbcs': dot substituted for <80>

## Warning in axis(side, at = z, labels = labels, ...): conversion failure on 'd'oct. 2
## 'mbcsToSbcs': dot substituted for <99>
```



4.6 Diurnal trends in diffuse and direct radiation

Ecological studies sometimes require radiation information at a subdaily scale. This is particularly true for modeling studies that need to calculate canopy photosynthesis. Although *meteoland* has been designed to assist studies requiring meteorological data at daily scale, a function called `radiation_directDiffuseDay()` is provided to divide daily radiation into instantaneous direct and diffuse radiation. Values of instantaneous direct and diffuse radiation (shortwave and photosynthetic active radiation) are calculated following Spitters, Toussaint, and Goudriaan (1986). First, the ratio between daily diffuse and global radiation (R_d/R_g) is inferred from the ratio between daily potential and global radiation (R_g/R_{pot}):

$$R_d/R_g = 1 \quad R_g/R_{pot} < 0.07 \quad (4.22)$$

$$R_d/R_g = 1 - 2.3 \cdot (R_g/R_{pot} - 0.7)^2 \quad 0.07 \leq R_g/R_{pot} < 0.35 \quad (4.23)$$

$$R_d/R_g = 1.33 - 1.46 \cdot R_g/R_{pot} \quad 0.35 \leq R_g/R_{pot} < 0.75 \quad (4.24)$$

$$R_d/R_g = 0.23 \quad 0.75 \leq R_g/R_{pot} \quad (4.25)$$

In a clear day (e.g. not rainy) the ratio is modified to account for the circumsolar part of diffuse radiation:

$$R'_d/R_g = \frac{R_d/R_g}{1 + (1 - (R_d/R_g)^2) \cdot \cos^2(\pi/4 - \beta) \cdot \cos^3 \beta} \quad (4.26)$$

where β is the solar elevation angle. Otherwise $R'_d/R_g = R_d/R_g$. The daily diffuse shortwave radiation (R_d) is found by multiplying global radiation by the

(modified) ratio:

$$R_d = R_g \cdot (R'_d/R_g) \quad (4.27)$$

The diurnal trend of the irradiance is derived from the daily global radiation and the daily course of potential (i.e. extra-terrestrial) radiation. If we assume that the atmospheric transmission is constant during the daylight period:

$$R_{g,s}/R_{pot,s} = R_g/R_{pot} \quad (4.28)$$

this leads to an estimation of the instantaneous global radiation (assuming compatible units):

$$R_{g,s} = R_g \cdot (R_{pot,s}/R_{pot}) \quad (4.29)$$

and the instantaneous diffuse and direct beam fluxes are estimated using:

$$R_{d,s} = R_d \cdot (R_{pot,s}/R_{pot}) \quad (4.30)$$

$$R_{b,s} = R_{g,s} - R_{d,s} \quad (4.31)$$

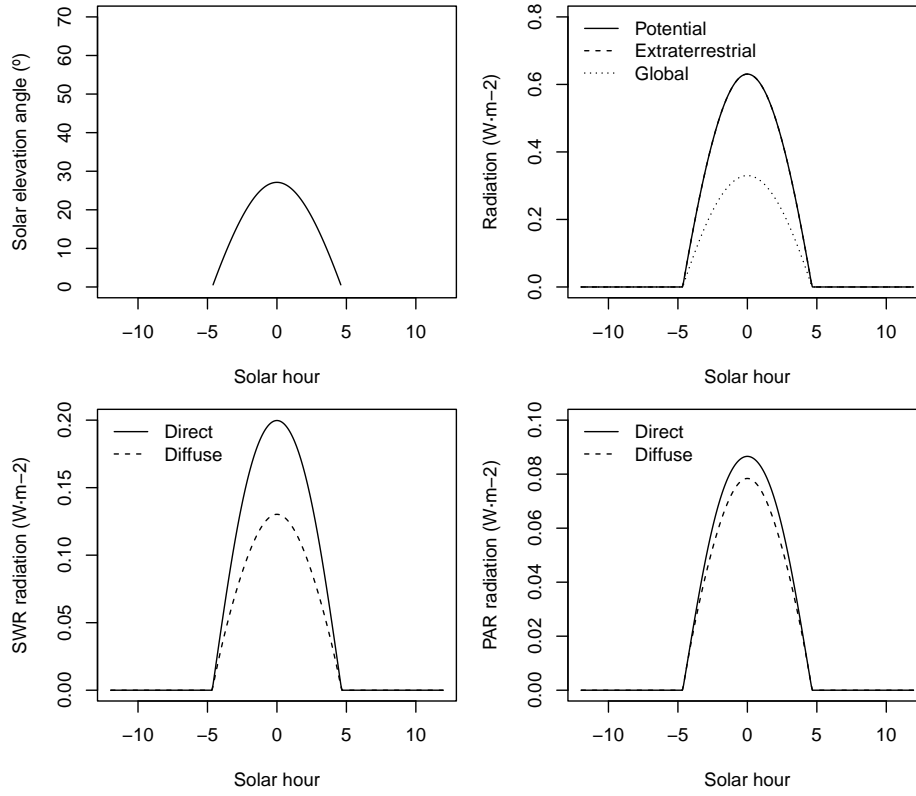
The whole procedure to calculate direct and diffuse radiation depends on the solar elevation angle, which changes through the day. Although R'_d/R_g is formulated as a ratio of daily values, the ratio needs to be calculated for every instant, as $R_{pot,s}$.

The procedure for photosynthetic active radiation (PAR) is similar. Daily PAR is assumed to be half of daily global radiation (i.e. $R_{PAR} = 0.5 \cdot R_g$). The scattered diffuse component of PAR is bigger than that of global radiation, and the ratio of diffuse over total PAR radiation is:

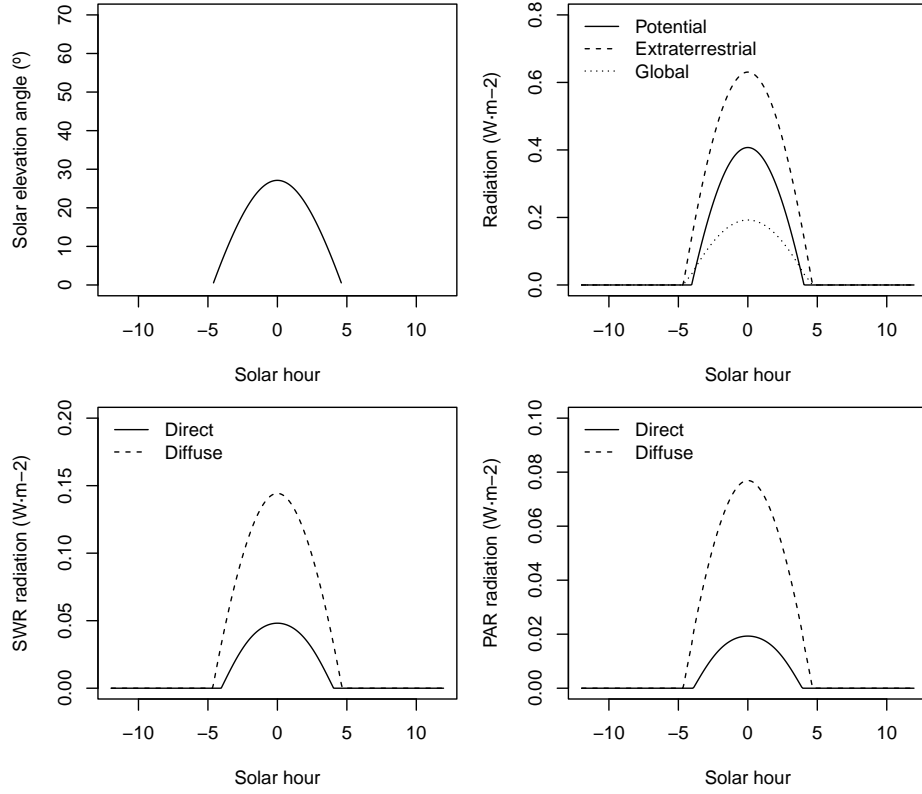
$$R_{PAR,d}/R_{PAR} = [1 + 0.3 \cdot (1 - (R_d/R_g)^2)] \cdot (R'_d/R_g) \quad (4.32)$$

The ratio $R_{PAR,d}/R_{PAR}$ is used to determine daily diffuse PAR and the calculation of instant rates are the same as for global radiation.

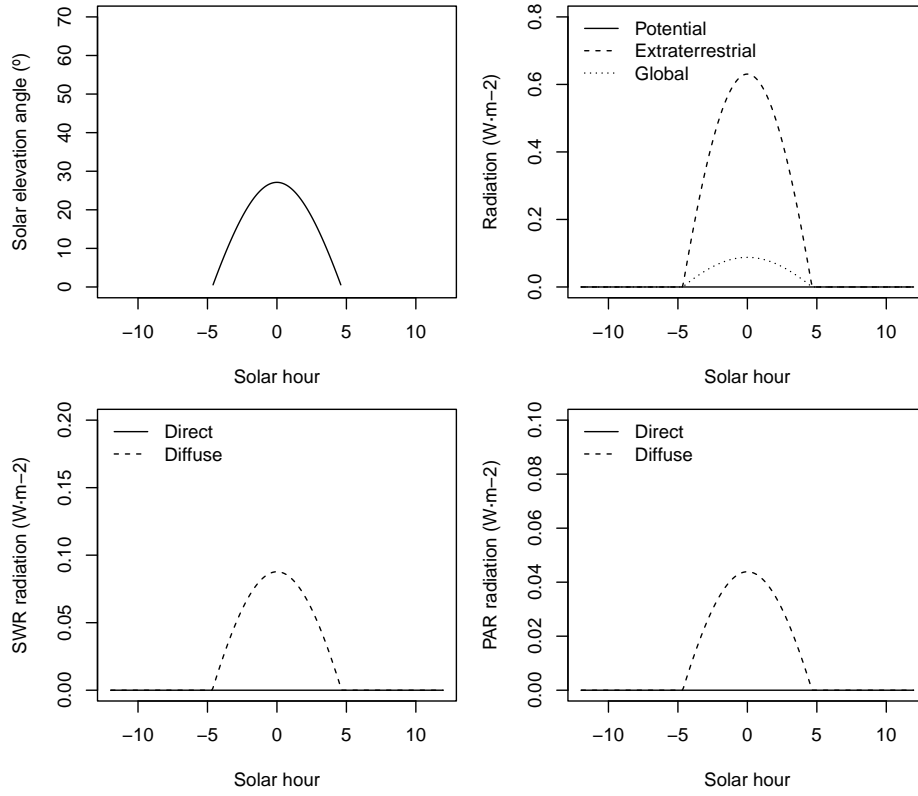
To illustrate the above calculations, we assume a target location in a flat terrain located at 42°N latitude and 100 m.a.s.l, having $7.2 \text{ MJ} \cdot \text{m}^{-2}$ of daily global radiation on the 2001/January/15 in a clear day, the hourly variation in solar elevation, potential/global radiation and diffuse/direct light for PAR and SWR would be:



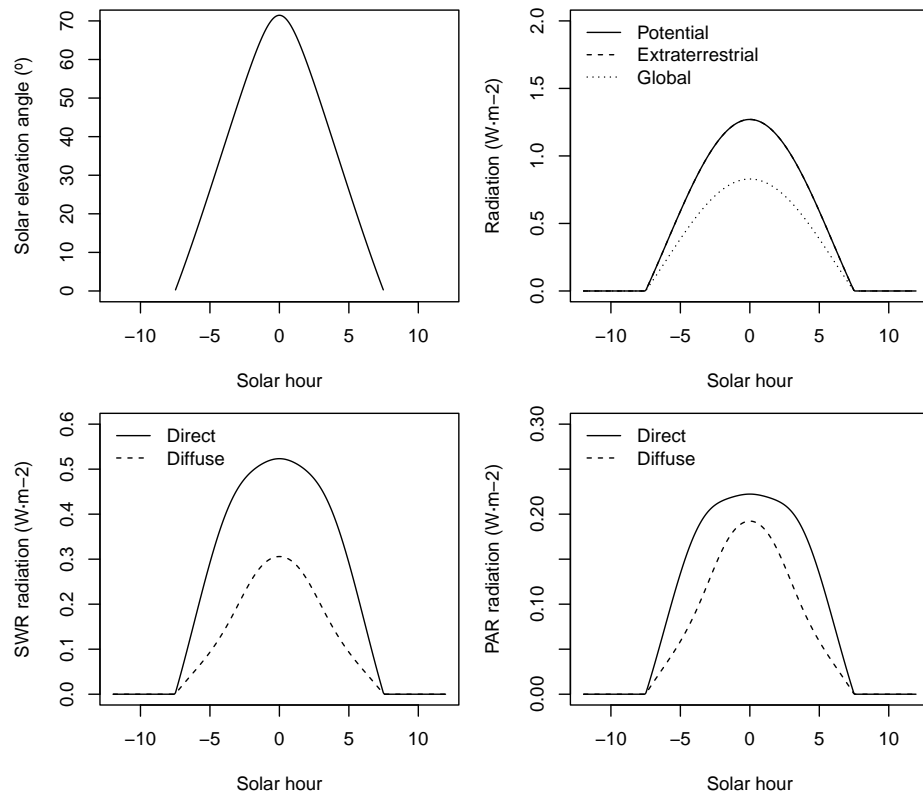
For a flat surface, the extraterrestrial radiation is the same that potential radiation, so that direct and diffuse light start and end at the same hours. If the same plot was on a north-facing slope of 10 degrees the daily global radiation would be $4.06 \text{ MJ} \cdot \text{m}^{-2}$ and the extraterrestrial radiation is larger than potential (i.e., accounting for topography) radiation, which has been reduced because of the orientation of the slope:



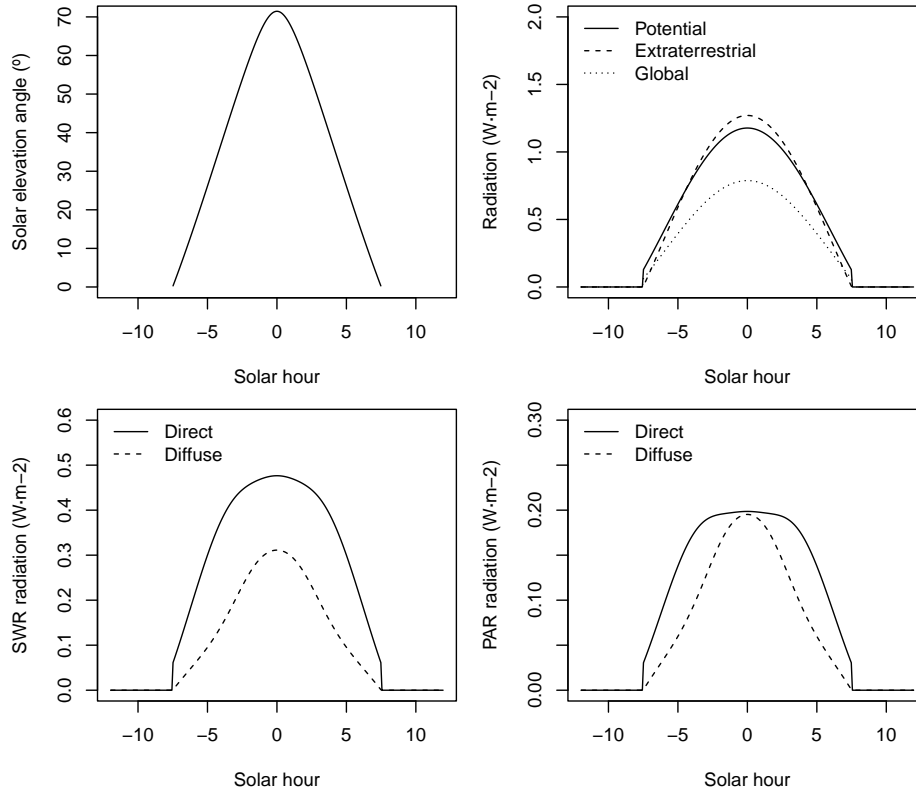
In this situation, diffuse light should follow extraterrestrial radiation hours whereas direct light should follow potential radiation hours. Finally, if the same plot was on a north-facing slope of 30 degrees the daily global radiation would be $1.96 \text{ MJ}\cdot\text{m}^{-2}$ and potential radiation would be 0. In this situation all radiation should correspond to diffuse radiation:



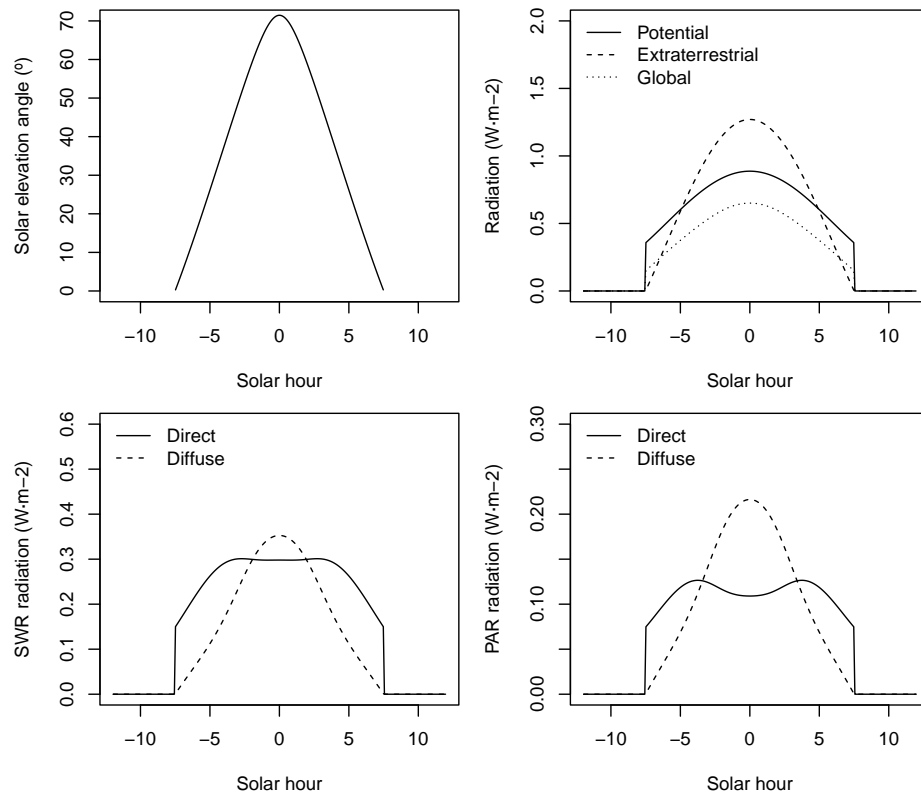
Let us now set the date to 15th of june, the flat surface would receive 27.7 MJm^{-2} divided into:



whereas the 10 degree north-facing slope would receive $27.3 \text{ MJ}\cdot\text{m}^{-2}$ divided into:



and the 30 degree slope would have $24.2 \text{ MJ}\hat{\text{m}}^{-2}$ and a repartition:



Chapter 5

Statistical correction of weather data

IMPORTANT NOTE: The functions to perform statistical correction of daily weather data have been *deprecated* since **ver. 2.0.0**. We still keep this theoretical explanation in case new functions are developed in the future.

Statistical correction is necessary when meteorological data is available at a spatial scale that is too coarse for landscape-level analysis. This is usually the case when taking predictions from global or regional climate models. The general idea of correction to the landscape level is that a fine-scale meteorological series is to be compared to coarse-scale series for the a historical (reference) period. The result of this comparison can be used to correct coarse-scale meteorological series for other periods (normally future projections).

5.1 Correction methods

Users of **meteoland** can choose between three different types of corrections:

- *Unbiasing*: consists in subtracting, from the series to be corrected, the average difference between the two series for the reference period (Déqué 2007). Let x_i be the value of the variable of the more accurate (e.g. local) series for a given day i and u_i the corresponding value for the less accurate series (e.g., climate model output). The bias, θ , is the average difference over all n days of the reference period:

$$\theta = \sum_i^n (u_i - x_i) / n \quad (5.1)$$

The bias calculated in the reference period is then subtracted from the value of u for any day of the period of interest.

- *Scaling*: A slope is calculated by regressing u on x through the origin (i.e. zero intercept) using data of the reference period. The slope can then be used as scaling factor to multiply the values of u for any day of the period of interest.
- *Empirical quantile mapping*: Due to its distributional properties, neither multiplicative or additive factors are appropriate for daily precipitation (Gudmundsson et al. 2012; Ruffault et al. 2014). In this case, it has been recommended to compare the empirical cumulative distribution function (CDF) of the two series for the reference period (Déqué 2007). The empirical CDFs of x and u for the reference period are approximated using tables of empirical percentiles, and this mapping is used to correct values of u for the period of interest:

$$c_d = ecdf_x^{-1}(ecdf_u(u_d)) \quad (5.2)$$

where $ecdf_x$ and $ecdf_u$ are the empirical CDFs of x and u respectively. Values between percentiles are approximated using linear interpolation. A difficulty arises for quantile mapping when the variables bounded by zero, such as precipitation. As the models tend to drizzle (or may have lower frequency of precipitation events), the probability of precipitation in the model may be greater or lower than that observed. To correct this, when model precipitation is zero an observed value is randomly chosen in the interval where the observed cumulative frequency is less than or equal to the probability of no precipitation in the model. This procedure ensures that the probability of precipitation after correction is equal to that observed (Boé et al. 2007).

For each target location to be processed, the correction routine first determines which is the nearest climate model cell and extracts its weather data series for the reference period and the period of interest. Then, the correction method chosen by the user for each variable is applied. Statistical corrections are done for each of the twelve months separately to account for seasonal variation of distributional differences (Ruffault et al. 2014).

5.2 Default approaches by variable

Although users can choose their preferred correction method for each variable, meteoland has default approaches.

Precipitation

By default, correction of precipitation is done using empirical quantile mapping.

Mean temperature

Unbiasing method is used by default to correct mean temperature. **Minimum and maximum temperatures**

To correct minimum (respectively maximum) temperature values, by default scaling is applied to the difference between minimum (resp. maximum) temperature and mean temperature.

Radiation

Radiation is by default corrected using the unbiasing procedure.

Relative humidity

Mean relative humidity is first transformed to specific humidity, the unbiasing method is applied by default to this variable and the result is back transformed to mean, minimum and maximum relative humidity using the previously corrected series of mean, maximum and minimum temperature, respectively.

Wind speed

By default, wind speed is corrected using the scaling method. Since historic wind data is often not available, however, if wind speed data is missing the coarse-scale wind estimate is taken directly without correction.

Chapter 6

Estimation of potential evapo-transpiration

Package **meteoland** allows calculating daily potential evapo-transpiration (PET) using Penman's formulation (Penman 1948, 1956) or Penman-Monteith formulation. PET is automatically calculated after meteorological data have been interpolated (i.e. within function `interpolate_data()`), but PET values can also be calculated for a single point using functions `penman()` or `penmanmonteith()`. For other formulations of PET, the reader is referred to the R package **Evapotranspiration**.

6.1 Penman formulation

Penman (1948) proposed an equation to calculate daily potential evaporation that combined an energy equation based on net incoming radiation with an aerodynamic approach. The Penman or Penman combination equation is:

$$E_{pot} = \frac{\Delta}{\Delta + \gamma} \cdot \frac{R_n}{\lambda} + \frac{\lambda}{\Delta + \lambda} \cdot E_a \quad (6.1)$$

where PET is the daily potential evaporation (in $mm \cdot day^{-1}$) from a saturated surface, R_n is the daily radiation to the evaporating surface (in $MJ \cdot m^{-2} \cdot day^{-1}$), Δ is the slope of the vapour pressure curve ($kPa \cdot ^\circ C^{-1}$) at air temperature, γ is the psychrometric constant ($kPa \cdot ^\circ C^{-1}$), and λ is the latent heat of vaporization (in $MJ \cdot kg^{-1}$). E_a (in $mm \cdot day^{-1}$) is a function of the average daily windspeed (u , in $m \cdot s^{-1}$), and vapour pressure deficit (D , in kPa):

$$E_a = f(u) \cdot D = f(u) \cdot (v_a^* - v_a) \quad (6.2)$$

where v_a^* is the saturation vapour pressure (kPa) and v_a the actual vapour pressure (kPa) and $f(u)$ is a function of wind speed, for which there are two alternatives (Penman 1948, 1956):

$$f(u) = 1.313 + 1.381 \cdot u \quad (6.3)$$

$$f(u) = 2.626 + 1.381 \cdot u \quad (6.4)$$

If wind speed is not available, an alternative formulation for E_{pot} is used as an approximation (Valiantzas 2006):

$$PET \simeq 0.047 \cdot R_s \cdot (T_a + 9.5)^{0.5} - 2.4 \cdot \left(\frac{R_s}{R_{pot}} \right)^2 + 0.09 \cdot (T_a - 20) \cdot \left(1 - \frac{RH_{mean}}{100} \right) \quad (6.5)$$

where R_s is the incoming solar radiation (in $MJ \cdot m^{-2} \cdot day^{-1}$), T_a is the mean daily temperature (in $^{\circ}C$), R_{pot} is the potential (i.e. extraterrestrial) solar radiation (in $MJ \cdot m^{-2} \cdot day^{-1}$) and RH_{mean} is the mean relative humidity (in percent).

6.2 Penman-Monteith formulation

The Penman-Monteith combination equation:

$$E_{pot} = \frac{1}{\lambda} \cdot \frac{\Delta \cdot R_n + D \cdot (\rho \cdot C_p / r_a)}{\Delta + \gamma \cdot (1 + r_c / r_a)} \quad (6.6)$$

where D is the vapour pressure deficit (in kPa), Δ is the slope of the saturated vapor pressure (in $Pa \cdot K^{-1}$), γ is the psychrometer constant (in $kPa \cdot K^{-1}$), λ is the latent heat vaporization of water (in $MJ \cdot kg^{-1}$) and C_p is the specific heat of air (in $MJ \cdot kg^{-1} \cdot K^{-1}$). r_c is the canopy resistance (in $s \cdot m^{-1}$). For simplicity, aerodynamic resistance (r_a) is currently set to $r_a = 208.0/u$ where u is the input wind speed.

Chapter 7

Weather generation

IMPORTANT NOTE: In version 0.8.6, **meteoland** incorporated the possibility of generating stochastic weather series. Note, however, that the corresponding functions have been *deprecated* since **ver. 2.0.0**. We still keep this theoretical explanation in case new functions are developed in the future.

Stochastic weather generators are algorithms that produce series of synthetic daily weather data. The parameters of the model are conditioned on existing meteorological records to ensure the characteristics of input weather series emerge in the daily stochastic process. The weather generation approaches available in **meteoland** are intended to be used to generate daily series of the same length as the input. It can be understood as a bootstrap resampling algorithm that tries to preserve some properties of the original weather series. The approach implemented in **meteoland** can be applied to any spatial structure and it preserves the spatial correlation and multivariate covariance structure of weather series (because it works on area-averaged weather and the chosen resampled days are applied to all points/pixels).

Two modes of weather generation are offered:

1. Unconditional weather generation is based on a first order Markov chain (MC) to simulate a series of precipitation states (dry/wet/extreme wet) and a K-nearest neighbor (k -NN) algorithm to select a pair of consecutive days with the same transition and similar weather for the first day.
2. Conditional weather generation couples the former generation algorithm with a second algorithm to generate multiyear variation.

7.1 Unconditional weather generation algorithm

The algorithm is based on Apipattanavis et al. (2007) and combines a Markov Chain (MC) to generate the sequence of precipitation states with a k -nearest neighbor (k -NN) bootstrap resampler to generate multivariate and multisite weather variables. The MC is used to better represent wet and dry spell statistics while the k -NN bootstrap resampler preserves the covariance structure between weather variables and across space.

The weather generation approach is based on the common practice of first simulating precipitation occurrence as a chain-dependent process. A three-state (dry / wet / extremely wet) Markov chain (MC) of order 1 is used to simulate an (area-averaged) precipitation state series. Nine transition probabilities are fit to the (area-averaged) input precipitation state series by month using maximum likelihood. A threshold of 0.3 mm (by default) is chosen to distinguish between dry and wet days, while the 80th percentile of precipitation (on wet days) is used as a threshold for extremely wet conditions. The fitted MC can be used to simulate (area-averaged) precipitation state series. A k -NN resampling algorithm of lag-1 is used to generate the values for all the weather variables, including disaggregation to L locations. The k -NN bootstrap resampler algorithm follows six steps (description adapted from Steinschneider et al. 2013):

1. Let $\bar{\mathbf{x}}_{t-1}$ be a vector of (area-averaged) weather variables already simulated for day $t - 1$. Also assume that the MC has simulated precipitation state series for days $t - 1$ and t .
2. Partition the historic record to find all pairs of consecutive days in a 7-day window (by default) centered on the day of the year of day t (i.e. if t is 15 January, then the window includes days from 12 to 18 January) that has the same sequence of (area-averaged) precipitation states simulated by the MC for days $t - 1$ and t . Assume there are Q such pairs.
3. Compute the distance between vector $\bar{\mathbf{x}}_{t-1}$ and the vectors $\bar{\mathbf{x}}_q^1$ corresponding to the first day of each q pair of consecutive days. The weighted Euclidean distance d_q between vector $\bar{\mathbf{x}}_{t-1}$ and $\bar{\mathbf{x}}_q^1$ is calculated as:

$$d_q = \sqrt{\sum_{i=1}^r w_i \cdot (\bar{x}_{i,t-1} - \bar{x}_{i,q}^1)^2} \quad (7.1)$$

where w_i is set to the inverse of the standard deviation of the i th weather variable. Here mean temperature and precipitation are used and we force a ten-fold weight for precipitation compared to temperature.

4. Order the distances d_q from smallest to largest and select the k smallest distances, where $k = \sqrt{Q}$. These corresponding k neighbors are assigned

resampling weights K using a discrete kernel function:

$$K[j] = \frac{1/j}{\sum_{j=1}^k 1/j} \quad (7.2)$$

where j indexes the k neighbors.

5. Sample one of the k neighbors and record the historic date associated with that selected neighbor. Then, use vectors of weather variables on the successive day to the recorded date for each of the L locations to simulate, multisite, weather for day t .
6. Repeat steps 1-5 for all days of the simulation.

To begin the resampling algorithm and generate initial (area-averaged) $\bar{\mathbf{x}}_1$ values for all weather variables, data from a random day from the simulation starting month is selected from the historic record that is consistent with the first precipitation state simulated by the MC.

7.2 Conditional weather generation

The algorithm described in the previous section allows generating intra-annual (i.e. seasonal) weather variation because of monthly calibration of the MC and k -NN selection of pairs of days on the basis of their day of the year. However, year-to-year variation in annual precipitation or mean temperature will arise due to stochasticity only. Multi-year variation (i.e. low-frequency periodic variations or long-term trends) cannot be simulated. Two alternative approaches are offered in **meteoland** to condition stochastic weather generation on multi-year variation.

1. Annual precipitation can be conditioned by using a stationary autoregressive (ARIMA) model annual precipitation and then using a k -nearest neighbor algorithm (similar to that of the previous section) to select years of the original weather series with annual precipitation similar to the simulated one and produce a bootstrap resample of weather data to train the MC-KNN algorithm (Steinschneider and Brown 2013). This option is recommended if low-frequency variation of annual precipitation is to be accounted for in long series.
2. Multi-year temperature or precipitation trends of the original series can be preserved by using a moving window. Each target year, a window around the target year is used to subset the original series. Annual precipitation to be simulated is then conditioned using a lognormal random trial of the precipitation corresponding to the selected years. Then, the same k -NN algorithm is used to produce a bootstrap resample of weather data from the years included in the moving window. This strategy is recommended to generate multiple stochastic series from (already corrected) climate change projections, as it preserves long-term trends.

Chapter 8

Miscellaneous functions

8.1 Downloading data from weather station networks

National meteorological agencies are increasingly adopting an open data philosophy. Previous versions of **meteoland** included functions for accessing daily weather data from different meteorological agencies in Spain. Since **ver. 2.0.0** these functions have been deprecated. Instead, the user is strongly recommended to use package **meteospain**.

8.2 Reshaping data obtained from other packages

meteoland provides functions to facilitate reshaping weather data acquired using other R packages into the **meteoland** format. At present, two packages are supported, **meteospain**, **worldmet**. The corresponding data reshape functions are called `meteospain2meteoland()` and `worldmet2meteoland()`.

8.3 Physical utility functions

Several utility functions are included in the package corresponding to physical calculations:

- `utils_atmosphericPressure()`: Atmospheric pressure P_{atm} in kPa from elevation z in m.

$$P_{atm}(z) = 101.32500 \cdot [1.0 - 2.2569 \cdot 10^{-5} \cdot z]^{5.2353} \quad (8.1)$$

- **utils_airDensity()**: Air density in $kg \cdot m^{-3}$ from temperature in Celsius and atmospheric pressure:

$$\rho_{air} = \frac{P_{atm}}{1.01 \cdot (T + 273.16) \cdot 0.287} \quad (8.2)$$

- **utils_saturationVP()**: Saturation water vapour pressure VP in kPa from temperature T in degrees Celsius:

$$VP(T) = 0.61078 \cdot e^{\left(\frac{17.269 \cdot T}{237.3 + T}\right)} \quad (8.3)$$

- **saturationVaporPressureCurveSlope()**: Saturation water vapour pressure curve slope s_{vp} in $kPa \cdot ^\circ C^{-1}$ from temperature T in degrees Celsius:

$$s_{vp}(T) = 4098.0 \cdot \frac{0.6108 \cdot e^{(17.27 \cdot T)/(T+237.3)}}{(T + 237.3)^2} \quad (8.4)$$

- **utils_averageDailyVP()**: Average daily water vapour pressure vp_{atm} in kPa calculated from minimum and maximum temperatures and relative humidities:

$$vp_{atm} = \frac{VP(T_{min}) \cdot (RH_{max}/100) + VP(T_{max}) \cdot (RH_{min}/100)}{2} \quad (8.5)$$

- **utils_latentHeatVaporisation()**: Latent heat of vaporisation λ_v in $MJ \cdot kg^{-1}$ from temperature in degrees Celsius:

$$\lambda_v(T) = (2.5023 - (0.00243054 \cdot T)) \quad (8.6)$$

- **utils_latentHeatVaporisationMol()**: Latent heat of vaporisation λ_v in $J \cdot mol^{-1}$ from temperature in degrees Celsius:

$$\lambda_v(T) = (2.5023 \cdot 10^6 - (2430.54 \cdot T)) \cdot 0.018 \quad (8.7)$$

- **utils_psychrometricConstant()**: Psychrometric constant in $kPa \cdot ^\circ C^{-1}$ from temperature in degrees Celsius and atmospheric pressure in kPa:

$$\gamma_v = \frac{0.00163 \cdot P_{atm}}{\lambda_v(T)} \quad (8.8)$$

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