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Methodology to compute missing weather variables when using the CORDEX database

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The objective of the technical report, is to obtain the full list of variables required in a BPS (Building Performance Simulation) weather file (Table 2), from the minimum list of CORDEX (Coordinated Regional Climate Downscaling Experiment) variables defined in the present paper (Table 1, symbols with a tilde and short name with “_cx” prefix).

The methodology employed is not new, but, to the authors' knowledge, it has never been fully described.

Table 1: output quantities of the CORDEX

Short name	Symbol	Unit	Long name
tas_cx	\tilde{T}_a^K	K	Near-Surface Air Temperature
huss_cx	\tilde{r}_s	kg_w/kg_da	Near-Surface Specific Humidity
ps_cx	\tilde{p}_{atm}	Pa	Surface Air Pressure
clt_cx	\tilde{clt}	%	Total cloud fraction
rsds_cx	$\tilde{S}_{GH}^\downarrow$	W/m2	Surface downwelling shortwave radiation
sfcWind_cx	\tilde{v}	m/s	Near-surface Wind Speed
pr_cx	$\tilde{p}\tilde{r}c$	Kg/m2/s	Precipitation
rlds_cx	\tilde{R}^\downarrow	W/m2	Surface Downwelling Longwave Radiation
uas_cx	\tilde{v}_{WE}	m/s	Eastward Near-Surface Wind
vas_cx	\tilde{v}_{SN}	m/s	Northward Near-Surface Wind

Table 2: Quantities contained in a weather file

Symb	Unit	Long name	Validity	Missing
$T_a = \tilde{T}_a^K - 273.15$	°C	Dry bulb temperature	[-70 ; 70]	99.9
T_{dp}	°C	Dew Point Temperature	[-70 ; 70]	99.9
rh	%	Relative Humidity	[0 ; 110]	999
$p = \tilde{p}_{atm}$	Pa	Atmospheric Station Pressure	[31000 ; 1200000]	999999
$K^\downarrow = \tilde{K}^\downarrow$	W/m2	Horizontal Infrared Radiation Intensity	[0 ; ∞]	9999
$S_{GH}^\downarrow = \tilde{S}_{GH}^\downarrow$	W/m2	Global Horizontal Radiation (not used)	[0 ; ∞]	9999
$S_{DIR,N}^\downarrow$	W/m2	Direct Normal Radiation	[0 ; ∞]	9999
$S_{DIFF,H}^\downarrow$	W/m2	Diffuse Horizontal Radiation	[0 ; ∞]	9999
wd	°	Wind Direction	[0 ; 360]	999
$ws = \tilde{v}$	m/s	Wind Speed	[0 ; 40]	999
$clt_{tot} = clt/10$	tenths	Total Sky Cover	[0 ; 10]	99
pr_d	mm	Liquid precipitation Depth		
$S_{DIR,H}^\downarrow$	W/m2	Direct Horizontal Radiation		
T_{sky}		Sky Temperature		

The data underlined in green in the Table 2 are additional BPS variables that facilitate the characterization of the thermal environment of the building. When the relationship between a BPS variable and a CORDEX variable is trivial, the relationship is formulated in the first column of Table 2.

1. Psychometrics

1.1. Saturation vapour pressure p_{sv} in [Pa] :

The saturation pressure p_{sv} in [Pa] is computed with the (ASHRAE, 2017) formula:

If $\tilde{T}_a^K < 273.15$ K :

$$p_{sv} = \exp \left[\frac{-5.6745359e^3}{\tilde{T}_a^K} + 6.3925247 - 9.6778430e^{-3} \cdot \tilde{T}_a^K + 6.2215701e^{-7} \cdot (\tilde{T}_a^K)^2 \right. \\ \left. + 2.0747825e^{-9} \cdot (\tilde{T}_a^K)^3 - 9.4840240e^{-13} \cdot (\tilde{T}_a^K)^4 + 4.1635019 \cdot \ln(\tilde{T}_a^K) \right]$$

If $\tilde{T}_a^K > 273.15$ K) :

$$p_{sv} = \exp \left[\frac{-5.8002206e^3}{\tilde{T}_a^K} + 1.3914993 - 4.8640239e^{-2} \cdot \tilde{T}_a^K + 4.1764768e^{-5} \cdot (\tilde{T}_a^K)^2 \right. \\ \left. - 1.4452093e^{-8} \cdot (\tilde{T}_a^K)^3 + 6.5459673 \cdot \ln(\tilde{T}_a^K) \right]$$

The specific humidity \tilde{r}_s ($[kg_v/kg]$) is a variable contained in the CORDEX projections. It is the ratio between the mass of water vapour in the air m_v and the total mass of the air $m_v + m_{da}$:

$$\tilde{r}_s = \frac{m_v}{m_v + m_{da}}$$

The moisture ratio W ($[kg_v/kg_{as}]$) is equal to the ratio between the mass of water vapour in the air and the mass of dry air:

$$W = \frac{m_v}{m_{da}} = \frac{\tilde{r}_s}{1 - \tilde{r}_s}$$

Water vapor and dry air are considered as perfect gaz. In a volume V of moist air at the temperature T , the mass m_v of water vapor is at the pressure p_v . The mass m_{da} of dry air is at the pressure ($p_{atm} - p_v$). Those variables are connected to each other through the following relationship, with M_v and M_{da} molecular masses, and R a constant:

$$p_v = \frac{m_v}{M_v} \cdot R \cdot T \\ p_{atm} - p_v = \frac{m_v}{M_v} \cdot R \cdot T$$

The moisture ratio is then: related to the partial vapor pressure:

$$W = \frac{m_v}{m_{da}} = \frac{M_v \cdot p_v V / RT}{M_{as} \cdot (\tilde{p}_{atm} - p_v) V / RT} = \frac{M_w}{M_{as}} \cdot \frac{p_v}{p_{atm} - p_v} = 0.6921945 \cdot \frac{p_v}{\tilde{p}_{atm} - p_v}$$

The vapor pressure is deduced from the previous relation:

$$p_v = \tilde{p}_{atm} \cdot \frac{W}{0.621945 + W}$$

The relative humidity rh ([%]) is obtained directly from the following formula:

$$rh = \frac{p_v}{p_{vs}} \cdot 100$$

1.2. Dew point temperature T_{dp} in [$^{\circ}C$]

The dew point temperature T_{dp} in [$^{\circ}C$] is obtained with the formula of (ASHRAE, 2017):

$$\alpha = \ln\left(\frac{p_v}{1000}\right)$$

$$T_{dp} = 6.54 + 14.526 \cdot \alpha + 0.7389 \cdot \alpha^2 + 0.09486 \cdot \alpha^3 + 0.4569 \cdot \alpha^{0.1984}$$

Note that this formula is only assumed to be valid for dew point temperatures between $0^{\circ}C$ and $93^{\circ}C$. Nevertheless, it will still be used for lower dew point temperatures.

Due to the interpolations of the dry temperature and the specific humidity, the calculated relative humidity might be outside the validity range [0% - 100%]. To keep a margin of error, and to avoid crashing calculation tools that do not accept a relative humidity equal to 0% (for which it is impossible to calculate the dew point temperature), the rh values are restricted to the interval [1% ; 99%].

Once the relative humidity has been corrected, the vapor pressure value is updated with the formula below, before calculating the dew point temperature.

$$p_v = p_{vs} \cdot \frac{rh}{100}$$

2. Wind direction

The wind direction is by definition the direction from which the wind comes (a north wind is a wind that comes from the north and goes to the south). In EnergyPlus, the convention used to define the wind direction is $wd = 0^{\circ}$ for a north wind, and then a clockwise rotation. Thus: North= 0.0° , East= 90.0° , South= 180.0° , West= 270.0° .

The wind direction wd is deduced from the two CORDEX wind velocity components ($\tilde{v}_{WE} = ua$ and $\tilde{v}_{SN} = va$). Four angular sectors are distinguished (North-East, South-East, South-West, North-West). The actual angular sector is determined from the signs of ua and va (first columns of Table 3). The equations to obtain wd for each angular sector are given in the remaining columns of Table 3. They are illustrated with Figure 1.

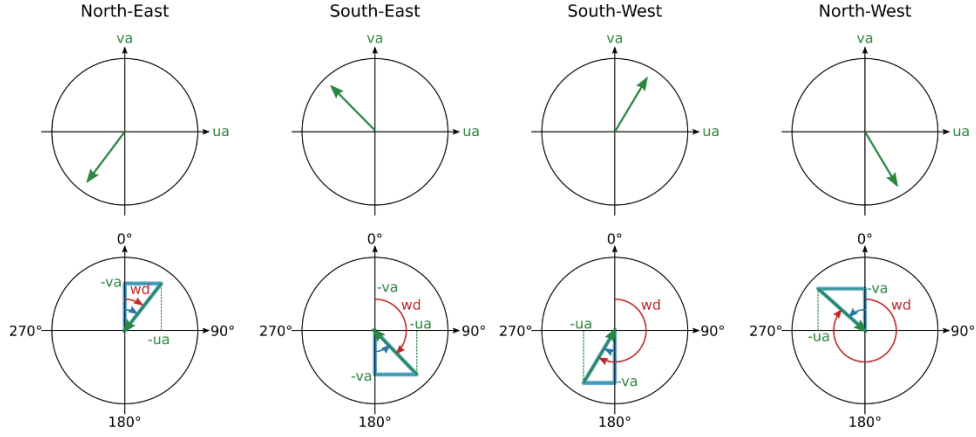


Figure 1: Wind direction calculation

Table 3: formulas to obtain wd for the 4 angular sectors

Dir	Signs	$\text{sign} \left[\frac{ua}{va} \right] = \text{sign} \left[\text{atan} \left(\frac{ua}{va} \right) \right]$	Formula with $\alpha = \frac{180}{\pi} \cdot \text{atan} \left(\frac{ua}{va} \right)$
NE	$ua < 0$ $va < 0$	pos	α
SE	$ua < 0$ $va > 0$	neg	$180 + \alpha$
SW	$ua > 0$ $va > 0$	pos	$180 + \alpha$
NW	$ua > 0$ $va < 0$	neg	$360 + \alpha$

3. Precipitation

The precipitation depth pr_d ([mm]) in BPS weather files corresponds to the height of liquid rain observed on an impermeable surface at the given time. This height is the result of the rainfall rate, and the evaporation rate of liquid rain on the ground surface. The data provided by the CORDEX database is the rainfall rate \widetilde{prc} ($[kg/m^2/s]$). A water evaporation model would have been needed to accurately express pr_d ([mm]) as a function of \widetilde{prc} ($[kg/m^2/s]$). Since the authors do not have this type of model, it was decided to approximate the precipitation height as the accumulated water height during the previous hour (3600s). Then:

$$pr_d = \frac{\widetilde{prc}}{\rho_{water}} \cdot 3600 \cdot 1000 = \widetilde{prc} \cdot 3600$$

4. Sky temperature

The sky temperature T_{sky} in [°C] is computed by assuming a black sky vault ($\varepsilon = 1$):

$$\begin{aligned}\tilde{K}^\downarrow &= \varepsilon \cdot \sigma \cdot (T_{sky} + 273.15)^4 \\ T_{sky} &= \left(\frac{\tilde{K}^\downarrow}{\varepsilon \cdot \sigma} \right)^{\frac{1}{4}} - 273.15\end{aligned}$$

5. Direct / Diffuse Solar radiation

The global solar radiation $\tilde{S}_{GH}^\downarrow$ must be decomposed into diffuse radiation on a horizontal surface $S_{DIFF,H}^\downarrow$, and normal direct radiation $S_{DIR,N}^\downarrow$ and on a horizontal surface $S_{DIR,H}^\downarrow$. To perform this decomposition, the method proposed by (Machard et al., 2020) will be followed.

5.1. Estimation of normal direct radiation

The calculation of the direct horizontal radiation $S_{DIR,H}^\downarrow$ only makes sense if the sun is visible, i.e. if the height of the sun h is strictly greater than 0. In practice, this calculation will only be performed if $h > 1^\circ$, otherwise $S_{DIR,N}^\downarrow = 0$.

5.1.1. Uncorrected normal direct solar radiation:

The calculation is based on a discretized spectrum of the direct solar radiation outside the atmosphere $i_0(\lambda_k)$ in [$W/m^2/nm$]. The spectrum is given in the Table 4.

The spectral radiation at the earth's surface $i(\lambda)$ is obtained with the following equation:

$$i(\lambda) = i_0(\lambda) \cdot \exp\{-[\alpha_r(\lambda) + \alpha_d(\lambda, \beta)] \cdot m(z_t)\}$$

$\alpha_r(\lambda)$ is the absorption coefficient due to molecular dispersion:

$$\alpha_r(\lambda) = 0.00816 \cdot \lambda^{-4}$$

$\alpha_d(\lambda)$ is the absorption coefficient due to particle dispersion which depends on the turbidity coefficient β , given in the Table 5:

$$\alpha_d(\lambda) = \beta \cdot \lambda^{-1.3}$$

m (without unit) is the optical mass of the air, which depends on the zenith angle z_t in [rad]. The zenith angle is deduced from the height of the sun h in [$^\circ$]:

$$z_t = (h - 90) \cdot \frac{\pi}{180}$$

$$czt = \cos(z_t)$$

$$m(z_t) = \frac{1.002432 \cdot czt^2 + 0.148386 \cdot czt + 0.0096467}{czt^3 + 0.149864 \cdot czt^2 + 0.0102963 \cdot czt + 0.000303978}$$

Table 4: Spectrum of solar radiation $i_0(\lambda_k)$ in $[W/m^2/nm]$, discretised over wavelength values λ_k , with $k \in [0; N - 1]$

λ_k [μm]	$i_0(\lambda_k)$ [$W/m^2/nm$]	λ_k [μm]	$i_0(\lambda_k)$ [$W/m^2/nm$]	λ_k [μm]	$i_0(\lambda_k)$ [$W/m^2/nm$]
0.115	0.000007	0.43	1.66	0.9	0.902
0.14	0.00003	0.44	1.833	1	0.757
0.16	0.00023	0.45	2.031	1.2	0.491
0.18	0.00127	0.46	2.092	1.4	0.341
0.2	0.0108	0.47	2.059	1.6	0.248
0.22	0.0582	0.48	2.1	1.8	0.161
0.23	0.0675	0.49	1.975	2	0.104
0.24	0.0638	0.5	1.966	2.2	0.08
0.25	0.0718	0.51	1.906	2.4	0.063
0.26	0.132	0.52	1.856	2.6	0.049
0.27	0.235	0.53	1.865	2.8	0.039
0.28	0.225	0.54	1.805	3	0.031
0.29	0.488	0.55	1.747	3.2	0.0229
0.3	0.52	0.56	1.716	3.4	0.0168
0.31	0.698	0.57	1.734	3.6	0.0137
0.32	0.84	0.58	1.737	3.8	0.0112
0.33	1.072	0.59	1.721	4	0.0096
0.34	1.087	0.6	1.687	4.5	0.006
0.35	1.107	0.62	1.622	5	0.0038
0.36	1.081	0.64	1.563	6	0.0018
0.37	1.19	0.66	1.505	7	0.001
0.38	1.134	0.68	1.445	8	0.006
0.39	1.112	0.7	1.386	10	0.00025
0.4	1.447	0.72	1.331	15	0.000049
0.41	1.773	0.75	1.251	20	0.000015
0.42	1.77	0.8	1.123	50	4E-07

Table 5: Turbidity coefficient β

Month	β
January	0.04
February	0.04
March	0.05
April	0.06
May	0.07
June	0.07
July	0.065
August	0.06
September	0.055
October	0.05
November	0.04
December	0.04

The uncorrected normal direct solar radiation at the earth's surface $S_{DIR,NO}^\downarrow$ in $[W/m^2]$ is obtained by calculating the integral of the irradiation spectrum at the earth's surface:

$$S_{DIR,NO}^\downarrow = \int_{\lambda} i(\lambda) d\lambda = \int_{\lambda} i_0(\lambda) \cdot \exp\{-[\alpha_r(\lambda) + \alpha_d(\lambda, \beta)] \cdot m(z_t)\} d\lambda$$

This integral is calculated numerically.

$$S_{DIR,N0}^{\downarrow} = \sum_{k=0}^{N-2} \frac{i(\lambda_k) + i(\lambda_{k+1})}{2} \cdot (\lambda_{k+1} - \lambda_k) = \sum_{k=0}^{N-1} a_k \cdot i(\lambda_k)$$

With :

- $a_0 = \frac{\lambda_1 - \lambda_0}{2}$
- $a_k = \frac{\lambda_{k+1} - \lambda_{k-1}}{2}$ for $k \in [1; N - 2]$
- $a_{N-1} = \frac{\lambda_{N-1} - \lambda_{N-2}}{2}$

So :

$$S_{DIR,N0}^{\downarrow} = \sum_{k=0}^{N-1} a_k \cdot i_0(\lambda_k) \cdot \exp\{-[\alpha_r(\lambda_k) + \alpha_d(\lambda_k, \beta)] \cdot m(z_t)\}$$

5.1.2. Correction due to cloud cover

Normal direct radiation is corrected for the effects of cloud cover by the following formula:

$$S_{DIR,N1}^{\downarrow} = \left(1 - \frac{\overline{cIt}}{100}\right) \cdot S_{DIR,N0}^{\downarrow}$$

5.1.3. Correction due to the variation of the sun/earth distance

The incident normal direct radiation is corrected for the sun-earth distance with the following formula:

$$S_{DIR,N2}^{\downarrow} = k \cdot S_{DIR,N1}^{\downarrow}$$

The coefficient k is calculated only once in the year. It depends on the number of the day in the year N_d , as well as the pulsation ratio $w_n = \frac{2\pi}{366}$:

$$k = \frac{1}{1353} \cdot [1353 + 45.326 \cdot \cos(w_n \cdot N_d) + 0.88018 \cdot \cos(2 \cdot w_n \cdot N_d) - 0.00461 \cdot \cos(3 \cdot w_n \cdot N_d) + 1.8037 \cdot \sin(w_n \cdot N_d) + 0.097462 \cdot \sin(2 \cdot w_n \cdot N_d) + 0.18412 \cdot \sin(3 \cdot w_n \cdot N_d)]$$

5.1.4. Correction for humidity in the air

The correction due to the presence of vapor in the atmosphere is done by subtracting a quantity F from the previously calculated radiation:

$$S_{DIR,N}^{\downarrow} = S_{DIR,N2}^{\downarrow} - F$$

With:

$$F = 70 + 2.8 \cdot m \cdot \frac{p_v}{100}$$

In the previous equation, the vapor pressure p_v is converted from [Pa] to [$mbar$] with a factor 100. The optical depth m has been computed previously.

5.2. Solar radiation decomposition

If the calculated normal direct radiation is less than 0 ($S_{DIR,N}^{\downarrow} \leq 0$), the direct radiation is null, and all solar radiation is diffuse: $S_{DIR,N}^{\downarrow} = 0$, $S_{DIR,H}^{\downarrow} = 0$, $S_{DIFF,H}^{\downarrow} = \tilde{S}_{GH}^{\downarrow}$

Otherwise, the solar radiation is projected onto the horizontal plane:

$$S_{DIR,H}^{\downarrow} = S_{DIR,N}^{\downarrow} \cdot \sin\left(\frac{\pi}{180} \cdot h\right)$$

If the direct horizontal radiation exceeds the global horizontal radiation ($S_{DIR,H}^{\downarrow} > \tilde{S}_{GH}^{\downarrow}$), direct radiation is corrected: $S_{DIR,H}^{\downarrow} = \tilde{S}_{GH}^{\downarrow}$, $S_{DIR,N}^{\downarrow} = \frac{S_{DIR,H}^{\downarrow}}{\sin\left(\frac{\pi}{180} \cdot h\right)}$

Then the horizontal diffuse flow is calculated:

$$S_{DIFF,H}^{\downarrow} = \tilde{S}_{GH}^{\downarrow} - S_{DIR,H}^{\downarrow}$$

6. References

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