Modelling incoming Potential Radiation on a land surface with PCRaster: POTRAD5.MOD manual

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http://www.geog.uu.nl/fg/ovandam/potrad/potrad.htm
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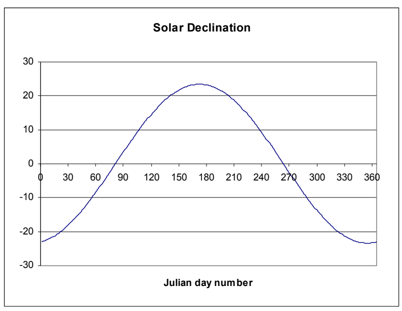
Introduction

Many processes on land surfaces are influenced by the amount of solar energy that is intercepted on the surface. In environmental modelling, like evapotranspiration models, incoming radiation is needed as input. Until recently it was not possible to calculate incoming radiation on a land surface, given by a Digital Elevation Model, in PCRaster (PCRaster, 1996). A new function HORIZONTAN was made, with which it is possible to calculate incoming radiation. This report describes the theoretical background for calculating the solar radiation on land surfaces and explains the PCRaster script POTRAD5.MOD in detail. The new function HORIZONTAN is explained. The model calculates incoming potential radiation as flux on a given time step (in $W.m^{-2}$) and daily, monthly or yearly total energy (in $MJ.m^{-2}.day^{-1}$) on any surface. Daily radiation is the integral of calculated fluxes per time step. Optional, a correction per time step for cloudiness can be used or a fixed value can be given (default is 1, no clouds). The model requires a Digital Elevation Model as input as well as and the latitude of the study area. Additional information on solar geometry and radiation terms is reported in Radiation Time Plots (·.tss files), of which a map with sample locations must be present (this option can be turned off by erasing these command lines).

Solar geometry

Movement of the sun

Solar declination is the annual fluctuation of the sun between the two tropics and varies between –23 and +23 degrees latitude. Solar declination *SolDec* [deg] is calculated according to (Supitt *et al.*, 1994):



$$SolDec = -23.4 \cdot \cos(360 \cdot (Day + 10) / 365)$$

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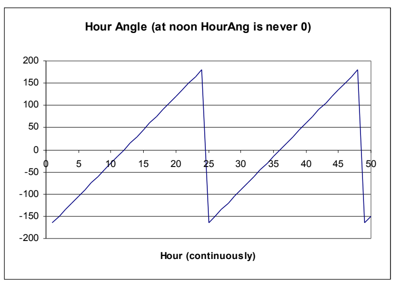
where *Day* [day] is the Julian day number.

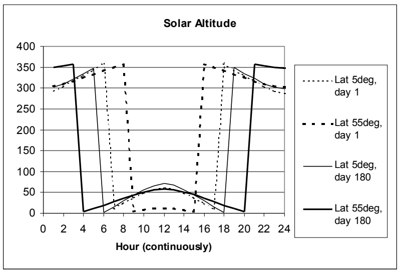


The hour angle describes the movement of the sun around the earth in 24 hours, which equals 15 degrees longitude per hour (360º/24h). The hour angle *HourAng* [deg] is given by:

$$HourAng = 15 \cdot (Hour-12) \qquad (2)$$

Hour [hour] is the actual hour during a day.

The position or height of the sun above the horizon is called the solar altitude or solar angle. Solar altitude *SolAlt* [deg] can be calculated for each location and moment during a year according to (Gates, 1980):



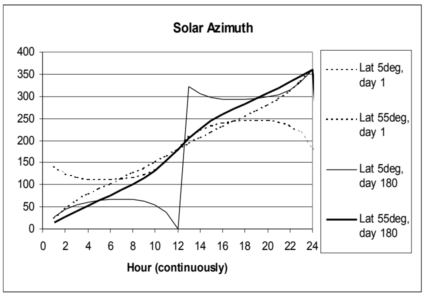
$$SolAlt = \mathrm{asin}\{\sin(Lat) \cdot \sin(SolDec) + \cos(Lat) \cdot \cos(SolDec) \cdot \cos(HourAng)\} \qquad (3)$$

(e

where *Lat* [deg] is the latitude of the area.

Solar azimuth

Solar azimuth is the angle between the solar beams and the North-South axes of the earth. Solar azimuth *SolAzi* [deg] is calculated with (Oke, 1987):



$$SolAzi = \mathrm{acos}((\sin(SolDec) \cdot \cos(Lat) - \cos(SolDec) \cdot \sin(Lat) \cdot \cos(HourAng)) / \cos(SolAlt))$$

For *Hour* $\leq$ 12: SolAzi = SolAzi

For *Hour* > 12: SolAzi = 360 – SolAzi (4)

Solar azimuth is set to 90 if 89.994 < *SolAzi* < 90 and is set to 270 if 269.994 < *SolAzi* < 270. (pers. comm. R.Sluiter, Aug '99).

Surface azimuth or aspect and slope

Surface azimuth is the orientation of the surface of the area to the North-South axes of the sun. It is calculated with the PCRaster function ASPECT to give *AspMap* [deg]. The slope of the area is calculated with the PCRaster function SLOPE, of which the arctangent is calculated to give *SlopMap* [deg]. Both Slope and Aspect maps should not be exactly zero.

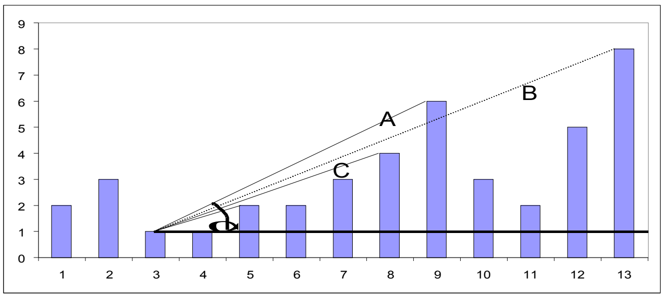
Critical angle of the sun

To determine whether a cell receives direct radiation, a critical angle for each cell is calculated. When the solar angle is larger then the critical angle, the cell receives direct solar radiation. A new PCRaster function called HORIZONTAN calculates the maximum tangent of the angles of neighbouring cells in the direction of the sun (the solar azimuth) *CritSun*. A map is created (*Shade*) in which the cells are assigned 1 when *SolAlt* [deg] is greater then *CritSun* [deg] and 0 when not. Negative tangents are set to 0. *Shade* also becomes 0 when *SolAlt* is greater then 90 deg, e.g. when then sun is below the horizon. The syntax of the function HORIZONTAN is:

NewMap = HORIZONTAN(DEM,Direction)

NewMap is of type scalar, DEM is of type scalar, Direction is of type directional.

Since the function can only be executed if there are neighbouring cells, no value can be given to cells at the edge of the DEM map. They



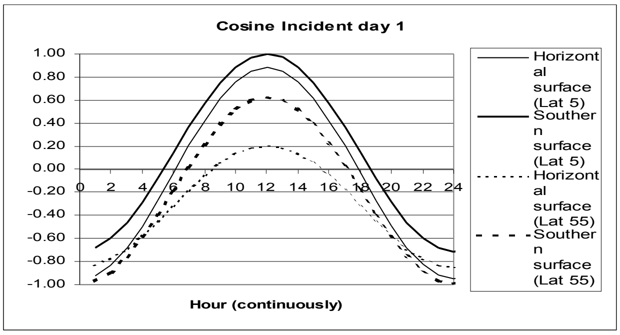
become missing values. Make sure that your DEM map is large enough and no crucial information is located in the edge cells. In the figure the tangent of angle α of cell 9 (A) is written down, although cell 13 (B) has a higher value.

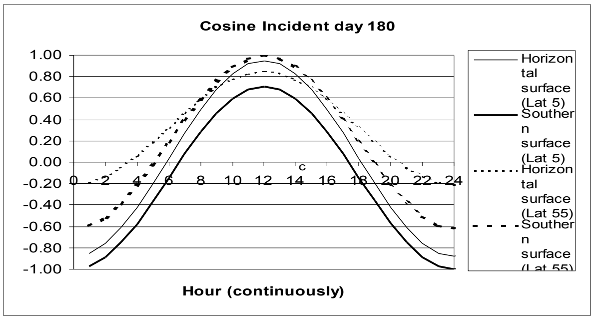
There are two methods of using horizontan in POTRAD5.MOD. They can be used on either a static DEM or a dynamic DEM: a DEM which changes in time. The static DEM has the horizontan statements in the initial section of the script. This will slow down the initial calculations but speeds up the calculation of the remaining time steps. Horizontan is calculated for 5° (vs. 51) or 10° (vs. 52) intervals, which decreases the accuracy somewhat. For a dynamic DEM, the horizontan calculations have to be made in the dynamic section (vs. 50). Horizontan is calculated for the exact angle, which increases the accuracy. More details in the last part of this document.

Incidence of the solar beams on the surface

The angle of incident is the angle between of the incoming solar beams and the aspect and slope of the surface. It is used to correct the incoming solar flux for the surface area on which these solar beams are projected. The angle itself is not calculated, but only the cosine of the angle of incident *cosIncidence* [-], which is used directly to correct the solar flux normal to the beam. The cosine of the angle of incidence is calculated according to (Campbell, 1981):

$$\text{cosIncident} = \cos(\text{SolAlt}) \cdot \sin(\text{SlopMap}) \cdot \cos(\text{SolAzi}-\text{AspMap}) + \sin(\text{SolAlt}) \cdot \cos(\text{SlopMap})$$ (





Solar radiation

Radiation outer atmosphere

Solar radiation *Sout* [W.m^{-2}] that reach the outer layer of the atmosphere is calculated with (Kreider & Kreith, 1975):

$$\text{Sout} = \text{Sc} \cdot (1 + 0.034 \cdot \cos(360 \cdot \text{Day}/365))$$ (

Where *Sc* [W.m^{-2}] is the solar constant of 1367 W.m^{-2} (Duffie and Beckman, 1991). The radiation, which reaches the earth surface normal to the beam, is decreased due to the amount of air it has to pass through and the transmissivity *Trans* [-] of the air at the location of the study area. The radiation normal to the beam *Snor* [W.m^{-2}] is given by (Gates, 1980):

$$\text{Snor} = \text{Sout} \cdot \text{Trans}^{\text{Mh}}$$ (

In which *Mh* [-] is the relative path length of the optical air mass at altitude h [m]. Transmissivity is usually between 0.5 and 0.8, but can be as low as 0.4 in the tropics (Whitmore *et al.*, 1993). A value of 0.6 is commonly used (Jetten, 1994; Whitmore *et al.*, 1993). To calculate the relative path length of an optical air mass at altitude *h*, the relative path length of optical air mass at sea level *M0* [-] is corrected for the atmospheric pressure at altitude h. Thus *Mh* is calculated with (Kreider & Kreith, 1975):

$$Mh = M0 \cdot AtmPcor \qquad ($$

The relative path length of the optical air mass at sea level *M0* [-] is calculated according to (Kreider & Kreith, 1975):

$$M0 = \sqrt{\{1229 + (614 \cdot \sin(SolAlt))^2\}} - 614 \cdot \sin(SolAlt) \qquad ($$

And the atmospheric pressure correction *AtmPcor* [-] is given by (List, 1984):

$$AtmPcor = ((288 - 0.0065 \cdot Map)/288)^{5.256} \qquad ($$

Radiation at earth surface

To calculate direct radiation on the earth's surface, the incoming radiation normal to the beam *Snor* must be corrected by the orientation and slope of the surface *cosIncident*. To calculate the actual radiation energy a correction for cloud cover *Cloud* [-] can be taken into account (default 1, no clouds). Only those cells, which are not in the shade of neighbouring cells, receive direct sunlight *Sdir* [$W.m^{-2}$], which was given by *Shade* (1: no shade, 0 shade). Direct radiation is now given by :

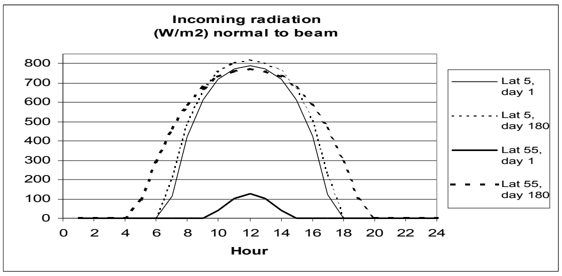
$$Sdir = Snor \cdot cosIncident \cdot Shade \cdot Cloud \qquad ($$

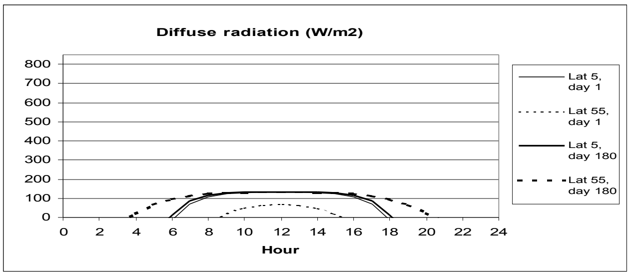
Indirect or diffuse sunlight is calculated for each solar altitude. When the sun is above the horizon it is assumed that all cells receive the same amount of diffuse radiation, corrected for their altitude. Diffuse radiation *Sdiff* [$W.m^{-2}$] is calculated according to:

$$Sdiff = Sout \cdot (0.271 - 0.294 \cdot Trans^{Mh}) \cdot \sin(SolAlt) \qquad ($$

Total incoming radiation *Stot* [$W.m^{-2}$] is calculated with:

$$Stot = Sdir + Sdiff \qquad ($$





Day, month and year radiation

Total hourly radiation energy is the integral of total incoming radiation of one hour. Total hourly radiation energy per interval *RadInterval* [$MJ.m^{-2}$.interval] is calculated with:

$$PotRad = ((Sold + Stot)/2 \cdot 3600) / 1000000 \qquad ($$

Where *Sold* [$W.m^{-2}$] is the previous calculation of total incoming radiation *Stot* and *Stot* is the current one. It is multiplied by 60 seconds and 60 minutes and divided by 1000000 to give smaller values (MJoules). Total daily radiance *PRadD* [$MJ.m^{-2}$.d] is the sum of the hourly radiation intervals:

$$PRadD = \Sigma(PotRad) \qquad ($$

Month and Year sums are the equivalent sum of the day sums. Two Month sums are incorporated: Actual monthly sums: PradM*.* and 30 days total PradMD*.*. The actual monthly sums give the month sums at exactly the last time step in a month and this can only be used when HourStep and DayStep is 1 and likewise the total number of time steps in one year is 8760. When using another combination of DayStep and/or HourStep, PradMD must be used, which gives the radiation sum of 30 days. The total number of time steps in one year for a number of HourStep/DayStep combinations is given in the left hand side of Table 1. The middle section of Table 1 gives the total number of time steps per 30 days interval that must be filled in the timer section. The right hand side of Table 1 gives an overview of the year sum of radiation, as calculated with the DayStep/HourStep combination for an unobstructed grid-cell at latitude 52° N, which gives an indication for the accuracy of the combination.

The combination of HourStep and DayStep that gives the smallest amount of time steps in one year, 4 hours and 30 days = 73 ts, is 96.9% of the radiation as calculated with one hour and one day. It is better to skip days than to skip hours. With a DayStep of 10 days, radiation is still 100%.

Table 1 : No. of time steps in one year for a number of DayStep – HourStep combinations, the corresponding 30 days time step and the result of the YearSum.

	Total no. of Time Steps				**No. of time steps for 30 days report**				**Year radiation sum (MJ.m^{-2})**			
	Hour step				**Hour step**				**Hour step**			
Day Step	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**
1	8760	4380	2920	2190	720	360	240	180	4774	4718	4677	4645
2	4380	2190	1460	1095	360	180	120	90	4774			
3	2920	1460		730	240	120		60	4776			
4	2190	1095	730		180	90	60		4772			
5	1752	876	584	438	144	72	48	36	4774			
6	1460	730		365	120	60		30				
8	1095		365		90		30					
10	876	438	292	219	72	36	24	18	4774		4680	
12	730	365			60	30						
15	584	292		146	48	24		12				
20	438	219	146		36	18	12		4764			
24	365				30							
30	292	146		73	24	12		6	4765			4627

POTRAD5 VERSIONS

There are 7 versions of POTRAD5. The versions are different for the latitude of the study area and the number of HORIZONTAN calculation that have to be made. These versions should be used for very large maps (over 200 by 200 cells). POTRAD v51 and v52 calculate HORIZONTAN in the initial part of the script, either for 5° azimuth intervals (vs. 51) or 10° intervals (vs. 52), whereby vs. 52 is faster than vs. 51, but also less accurate. The initialisation of the program can take several minutes, depending on the total number of cells in the map. Version 5 has to be used in studies where the DEM changes over time, since this version calculates HORIZONTAN for each new time step. The other version can only be used in a static topography. Table 2 gives an overview the differences between the versions. A total year of 860 time steps on a test map of 200*200 cells lasted almost 22 hours for vs5, less than 3 hours for vs51 and less than 2 hours for vs52 on a Pentium-II 330MHZ with 64MB RAM. Although vs51 and vs52 are considerably faster, their output of the year sum of radiation is considerably different for vs50, for unknown reasons. This will be studied in the near future.

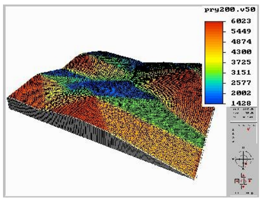
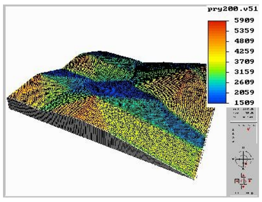
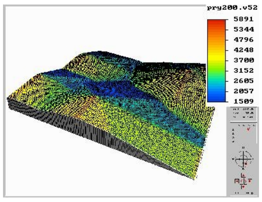
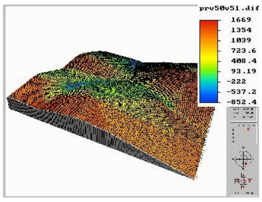
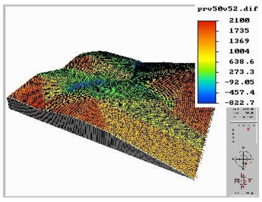
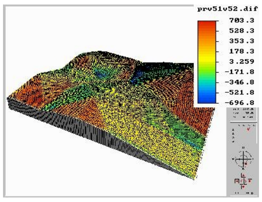
Table 2: POTRAD5 versions

Name	**LAT**	**HORIZONTAN**
POTRAD5	all: 90 <-> -90 deg	every possible one: 0-360 deg
POTRAD51	all: 90 <-> -90 deg	5 deg interval: calc. of #3 (#8) valid for #0-#5 (#5-#0)
POTRAD52	all: 90 <-> -90 deg	10 deg interval: calc. of #5 valid for #0-#10 deg
RADN51	North > 23 deg	5 deg interval: calc. of #3 (#8) valid for #0-#5 (#5-#0)
RADN52	North > 23 deg	10 deg interval: calc. of #5 valid for #0-#10 deg
RADS51	South < -23 deg	5 deg interval: calc. of #3 (#8) valid for #0-#5 (#5-#0)
RADS52	South < -23 deg	10 deg interval: calc. of #5 valid for #0-#10 deg

Output examples of the different versions are given in the "Examples" section. At the moment (July 2000) the difference between vs 5 and vs 51/vs 52 are unacceptable large for unknown reasons. Updates can be expected in the near future.

Output examples

Differences between v50, v51 and v52

<table>
<tr><td>v50: 200 by 200 cells, lat 52 deg, year sum radiation</td><td>v51: 200 by 200 cells, lat 52 deg, year sum radiation</td><td>v52: 200 by 200 cells, lat 52 deg, year sum radiation</td></tr>
<tr><td></td><td></td><td></td></tr>
<tr><td>Difference v50 & v51</td><td>Difference v50 & v52</td><td>Difference v51 & v52</td></tr>
<tr><td></td><td></td><td></td></tr>
</table>

PCRaster can be found at: http://www.geog.uu.nl/pcraster.htm

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