IRRIGATION WATER REQUIREMENTS

SW 711– IRRIGATION ENGINEERING

Carolyn Grace G. Somera

Professor

When to irrigate?
How much water to apply?

Three major considerations:

1. Water needs of the crop
2. Availability of water with which to irrigate
3. Capacity of the root-zone soil to store water

$$\boldsymbol{Irrigation\ frequency} = \frac{\boldsymbol{MAD}}{\boldsymbol{Crop\ ET\ rate}}$$

IRRIGATION FREQUENCY

$$Irrigation\ frequency = \frac{MAD}{ET}$$

MAD – management allowable deficit

ET – crop evapotranspiration rate

NET IRRIGATION REQUIREMENT

- The amount the soil can hold between field capacity and the moisture level selected when irrigation is needed (MAD).

$$\boldsymbol{Net\ irrigation, d_{net} = MAD \times AM}$$

NET IRRIGATION REQUIREMENT

Example 1

Determine the net depth of irrigation if the total available moisture in the root zone is 8 inches and the MAD is 40%.

$$d_{net} = MAD \times AM$$

$$d_{net} = 0.40 \times 8\ inches$$

$$\boldsymbol{d_{net} = 3.2\ inches}$$

GROSS IRRIGATION REQUIREMENT

- The amount that must be applied to assure enough water enters the soil and is stored within the plant root zone to meet crop needs.

$$Gross\ irrigation, d_{gross} = \frac{d_{net}}{E_a}$$

$$Gross\ irrigation, d_{gross} = \frac{MAD}{E_a}$$

GROSS IRRIGATION REQUIREMENT

Causes of Water Loss

1. Unequal distribution of water being applied over the field.
2. Deep percolation below the plant root zone in parts of the field.
3. Translocation or surface runoff in parts of the field.

GROSS IRRIGATION REQUIREMENT

Causes of Water Loss

4. Evaporation from the soil surface; flowing and ponded water.
5. Evaporation of water intercepted by the plant canopy under sprinkler systems.
6. Evaporation and wind drift from sprinklers or spray heads.
7. Non-uniform soils.

CROP EVAPOTRANSPIRATION (ET)

- It is the amount of water that plants use in transpiration and building cell tissue plus water evaporated from an adjacent soil surface.
- Also called "*consumptive use*".

CROP EVAPOTRANSPIRATION

1. **Transpiration**
   - water entering plant roots and used to build plant tissue or being passed through leaves of the plant into the atmosphere
2. **Evaporation**
   - water evaporating from adjacent soil, water surfaces, or from the surface of the leaves of the plant

FACTORS AFFECTING EVAPOTRANSPIRATION

1. **Climatological factors**
    - temperature
    - humidity
    - wind movement
    - length and duration of sunlight/sunshine
    - precipitation
2. **Irrigation practices**

FACTORS AFFECTING EVAPOTRANSPIRATION

3. **Length of growing season**
4. **Stage of crop growth / changes in crop physiology**
5. **Others:**
   - soil moisture condition
   - plant diseases and pests reduce consumptive use by inhibiting plant growth

FACTORS AFFECTING EVAPOTRANSPIRATION

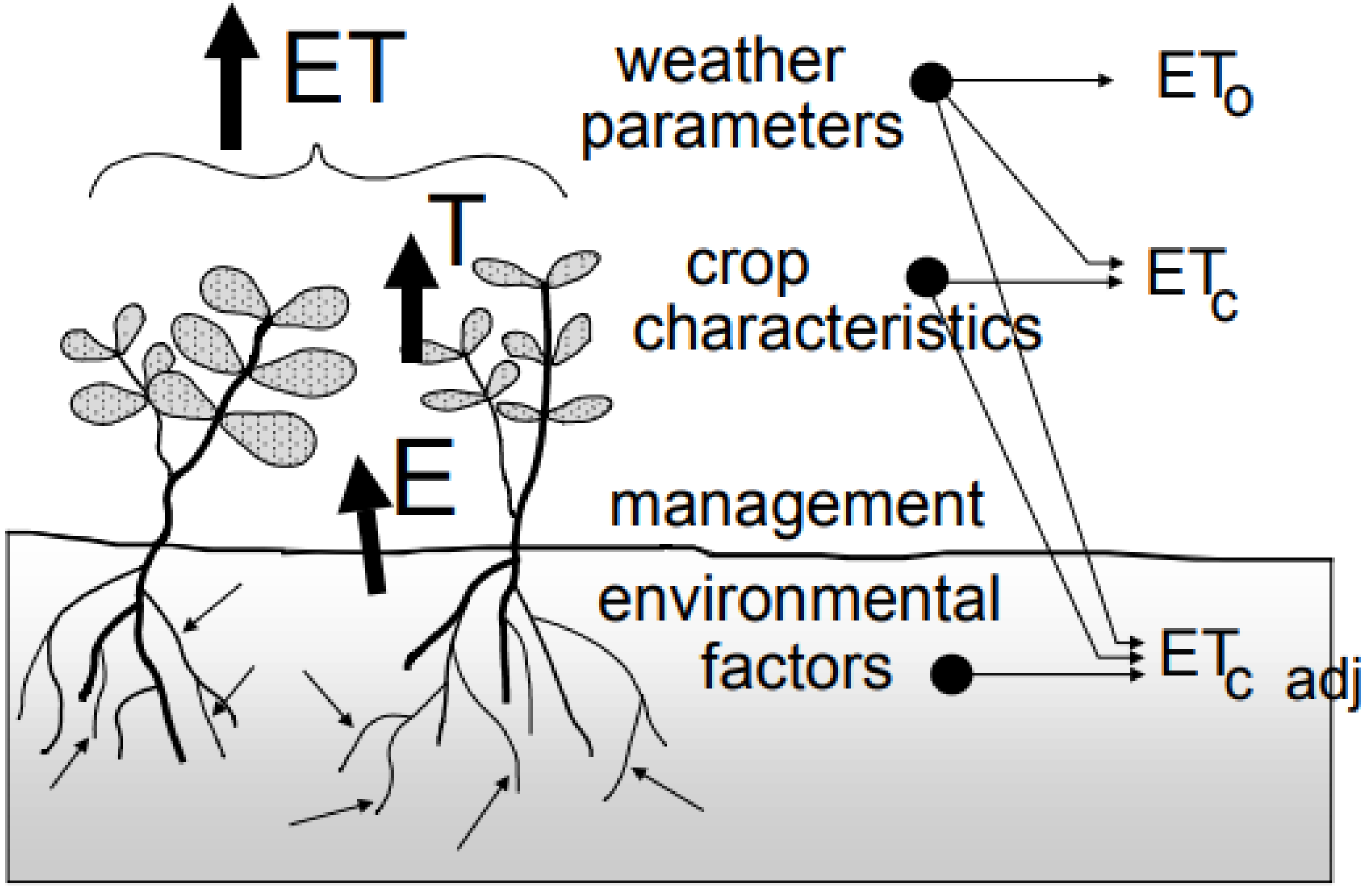


Figure 1. Factors affecting evapotranspiration

FACTORS AFFECTING EVAPOTRANSPIRATION

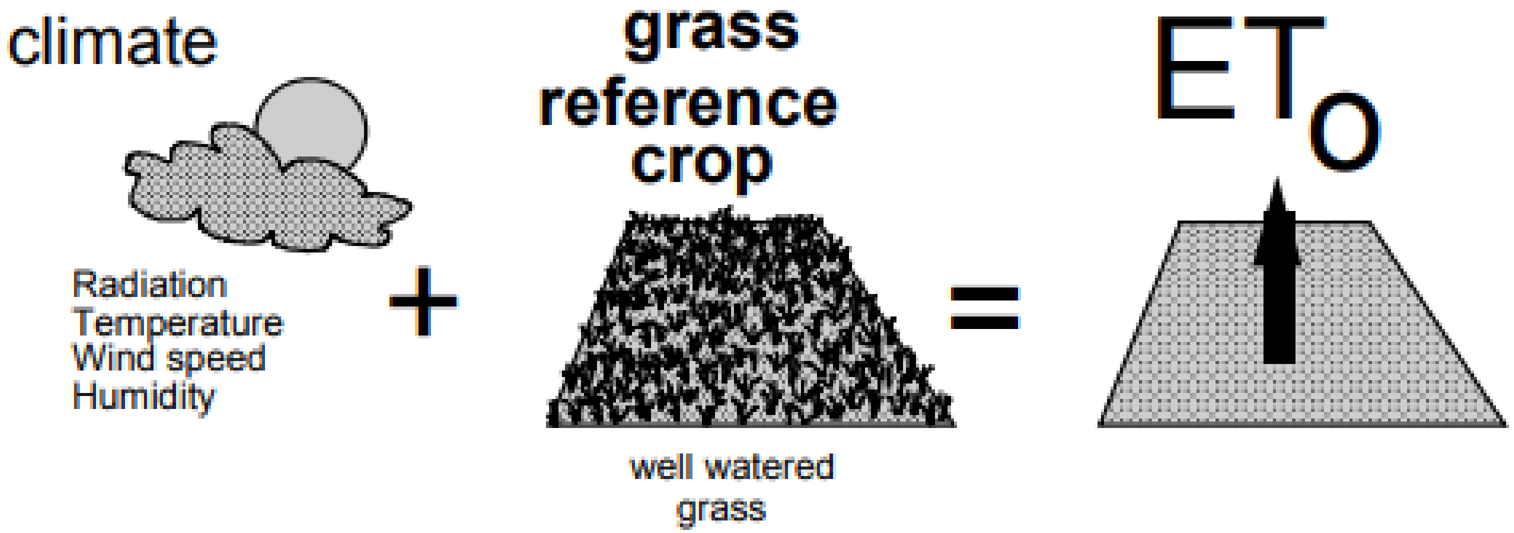


Figure 2. Reference evapotranspiration, ET_o

FACTORS AFFECTING EVAPOTRANSPIRATION

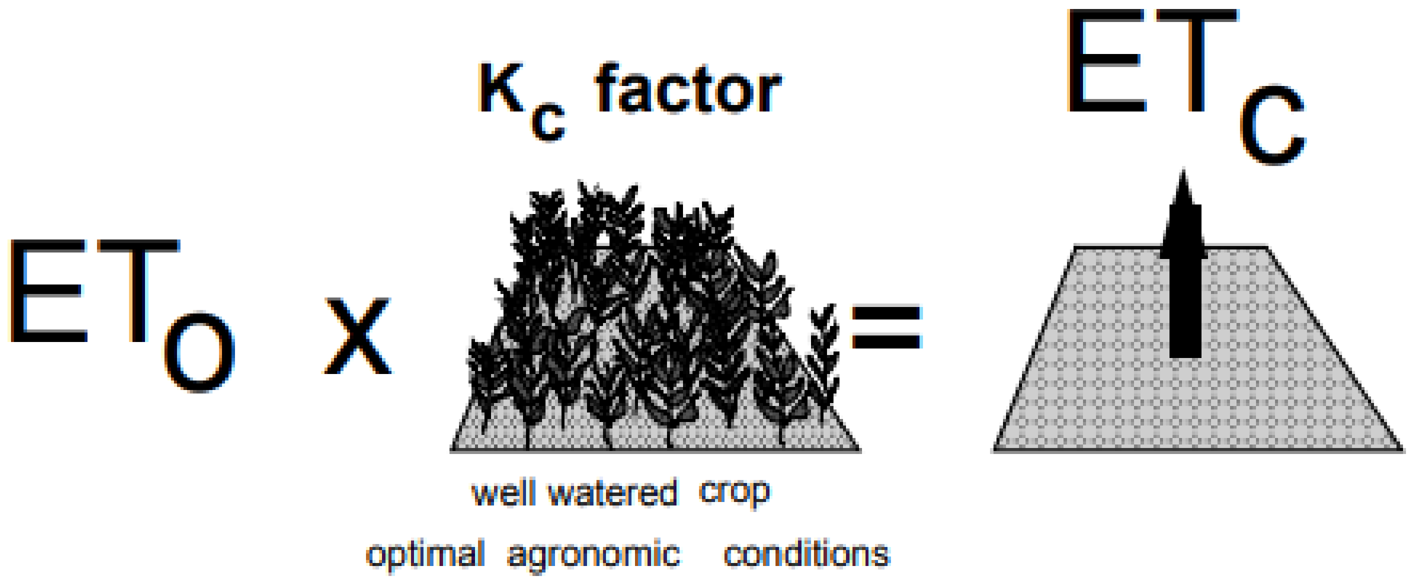


Figure 3. Crop evapotranspiration under standard condition, ET_C

FACTORS AFFECTING EVAPOTRANSPIRATION

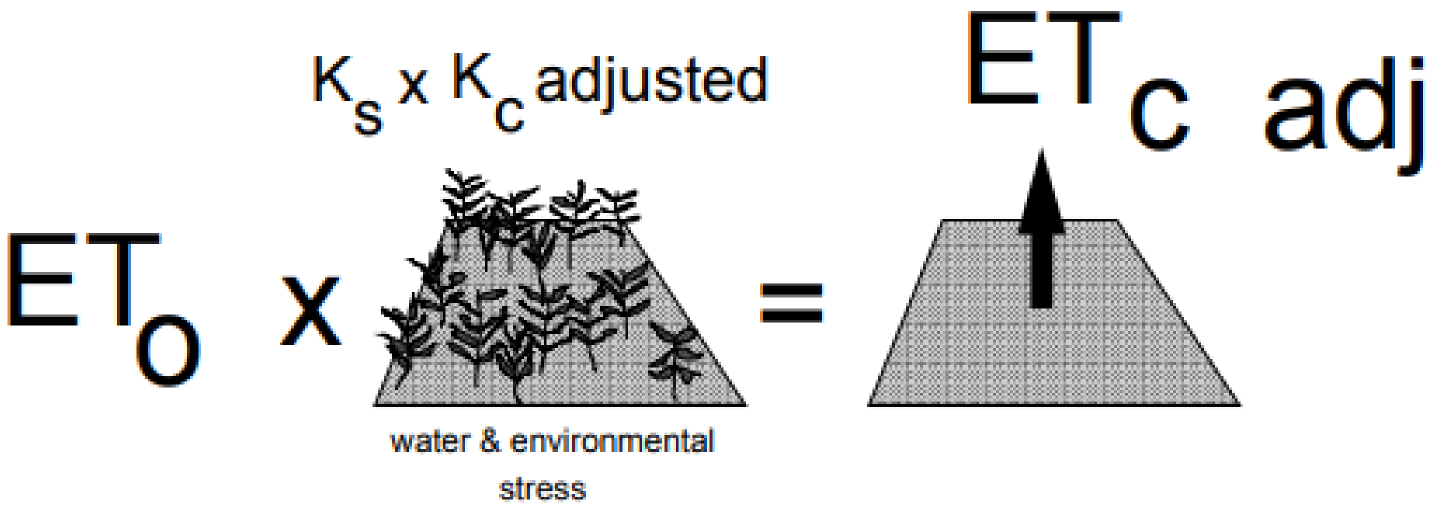


Figure 4. Non-standard conditions, $ET_{c\ adj}$

REFERENCE CROP EVAPOTRANSPIRATION, ET_o

- The evapotranspiration rate from a reference surface, not short of water, is called the reference crop evapotranspiration or reference evapotranspiration and is denoted as ET_o.
- The reference surface is a hypothetical grass reference crop with specific characteristics.

ESTIMATED CROP EVAPOTRANSPIRATION, ET_C

- More than 20 methods have been developed to estimate the rate of crop ET based on local climate factors.
- The simplest methods are equations that generally use only ***mean air temperature***.
- The more complex methods are described as ***energy equations***.
- These equations have been adjusted for reference crop ET with *lysimeter data*.

Selection of the method used for determining local crop ET depends on:

- Location, type, reliability, timeliness, and duration of climatic data
- Natural pattern of evapotranspiration during the year
- Intended use intensity of crop evapotranspiration estimates

Determination of Reference Evapotranspiration

1. **Temperature method**
   - FAO Modified Blaney-Criddle (FAO Paper 24)
   - Modified Blaney-Criddle (SCS Technical Release No. 21)
2. **Energy method**
   - Penman-Monteith method (FAO Paper 56)
3. **Radiation method**
   - FAO Radiation method (FAO Paper 24)
4. **Evaporation pan method**

Reference Evapotranspiration

Table 1. Application of the different ET_o methods

Application	Method
For irrigation scheduling on a daily basis	Penman-Monteith equation
For irrigation scheduling information on a 10+ day average basis	FAO Radiation method Evaporation pan method
For estimation of monthly and seasonal crop water needs	FAO Modified Blaney-Criddle equation

Reference Evapotranspiration

Table 2. Minimum length of record for each application

APPLICATION	DURATION OF DATA REQUIRED
Irrigation scheduling	daily
Irrigation system design	historical record of at least 10 years
Reservoir design, Water right determination	monthly water use estimates

1. PENMAN-MONTEITH METHOD

$$ET_o = \frac{0.408\,\Delta\,(R_n - G) + \gamma \frac{900}{T + 273} u_2 (e_s - e_a)}{\Delta + \gamma\,(1 + 0.34\,u_2)}$$

where: Et_o - reference evapotranspiration, mm day^{-1}
R_n - net radiation at the crop surface, MJ m^{-2} day^{-1}
G - soil heat flux density, MJ m^{-2} day^{-1}
T - air temperature at 2 m height, °C
U_2 - wind speed at 2 m height, m s^{-1}
e_s - saturation vapour pressure, kPa
e_a - actual vapour pressure, kPa
e_s-e_a - saturation vapour pressure deficit, kPa
Δ - slope vapour pressure curve, kPa $°C^{-1}$
γ - psychrometric constant, kPa $°C^{-1}$

Mean Temperature

- The sensible heat of the surrounding air transfers energy to the crop and exerts as such a controlling influence on the rate of evapotranspiration.

$$T_{mean} = \frac{T_{max} + T_{min}}{2}$$

where: T_{mean} – mean temperature, °C
T_{max} – maximum temperature, °C
T_{min} – minimum temperature, °C

Mean Saturation Vapor Pressure, e_s

- When air is enclosed above an evaporating water surface, an equilibrium is reached between the water molecules escaping and returning to the water reservoir.
- At that moment, the air is said to be saturated since it cannot store any extra water molecules.
- The corresponding pressure is called the *saturation vapor pressure*.

Mean Saturation Vapor Pressure, e_s

$$e^{0}(T) = 0.6108 exp\left[\frac{17.27\,T}{T + 237.3}\right]$$

$$e_s = \frac{e^{o}(T_{max}) + e^{o}(T_{min})}{2}$$

where: e°(T) – saturation vapor pressure at the air temperature T, kPa
T – air temperature, °C
exp[..] – 2.7183 (base of natural logarithm) raised to the power [..]

Mean Saturation Vapor Pressure, e_s

Example 2

The daily maximum and minimum air temperature are 33.4 and 22.6°C, respectively.

Determine the saturation vapor pressure for that day.

Given:

$T_{max} = 33.4\ ^oC$

$T_{min} = 22.6\ ^oC$

Mean Saturation Vapor Pressure, e_s

Solution:

$$e^0(T_{max}) = 0.6108exp\left[\frac{17.27\,T}{T + 237.3}\right]$$

$$e^0(T_{max}) = 0.6108exp\left[\frac{17.27\,(33.4)}{33.4 + 237.3}\right]$$

$$e^0(T_{max}) = 5.144\ kPa$$

$$e^0(T_{min}) = 0.6108exp\left[\frac{17.27\,T}{T + 237.3}\right]$$

$$e^0(T_{min}) = 0.6108exp\left[\frac{17.27\,(22.6)}{T + 237.3}\right]$$

$$e^0(T_{min}) = 2.742$$

Mean Saturation Vapor Pressure, e_s

Solution:

$$e_s = \frac{e^o(T_{max}) + e^o(T_{min})}{2}$$

$$e_s = \frac{5.144 + 2.742}{2}$$

$$\boldsymbol{e_s = 3.943\ kPa}$$

Mean Saturation Vapor Pressure, e_s

Using Table

At T_{max} = 33.4 °C

$e^o(T_{max})$= 5.144 kPa

At T_{min} = 22.6 °C

$e^o(T_{min})$= 2.743 kPa

e_s= 3.944 kPa

Table 3. Saturation vapor pressure at different temperatures

T °C	e_s kPa	T °C	e°(T) kPa	T °C	e°(T) kPa	T °C	e_s kPa
1.0	0.657	13.0	1.498	25.0	3.168	37.0	6.275
1.5	0.681	13.5	1.547	25.5	3.263	37.5	6.448
2.0	0.706	14.0	1.599	26.0	3.361	38.0	6.625
2.5	0.731	14.5	1.651	26.5	3.462	38.5	6.806
3.0	0.758	15.0	1.705	27.0	3.565	39.0	6.991
3.5	0.785	15.5	1.761	27.5	3.671	39.5	7.181
4.0	0.813	16.0	1.818	28.0	3.780	40.0	7.376
4.5	0.842	16.5	1.877	28.5	3.891	40.5	7.574
5.0	0.872	17.0	1.938	29.0	4.006	41.0	7.778
5.5	0.903	17.5	2.000	29.5	4.123	41.5	7.986
6.0	0.935	18.0	2.064	30.0	4.243	42.0	8.199
6.5	0.968	18.5	2.130	30.5	4.366	42.5	8.417
7.0	1.002	19.0	2.197	31.0	4.493	43.0	8.640
7.5	1.037	19.5	2.267	31.5	4.622	43.5	8.867
8.0	1.073	20.0	2.338	32.0	4.755	44.0	9.101
8.5	1.110	20.5	2.412	32.5	4.891	44.5	9.339
9.0	1.148	21.0	2.487	33.0	5.030	45.0	9.582
9.5	1.187	21.5	2.564	33.5	5.173	45.5	9.832
10.0	1.228	22.0	2.644	34.0	5.319	46.0	10.086
10.5	1.270	22.5	2.726	34.5	5.469	46.5	10.347
11.0	1.313	23.0	2.809	35.0	5.623	47.0	10.613
11.5	1.357	23.5	2.896	35.5	5.780	47.5	10.885
12.0	1.403	24.0	2.984	36.0	5.941	48.0	11.163
12.5	1.449	24.5	3.075	36.5	6.106	48.5	11.447

Slope of Saturation Vapor Curve, Δ

$$\Delta = \frac{4098\left[0.6108exp\left(\frac{17.27T}{T+237.3}\right)\right]}{(T+237.3)^2}$$

where: Δ – slope of saturation vapor pressure curve at air temperature T, kPa °C^{-1}
T – air temperature, °C
exp[..] – 2.7183 (base of natural logarithm) raised to the power [..].

Slope of Saturation Vapor Curve, Δ

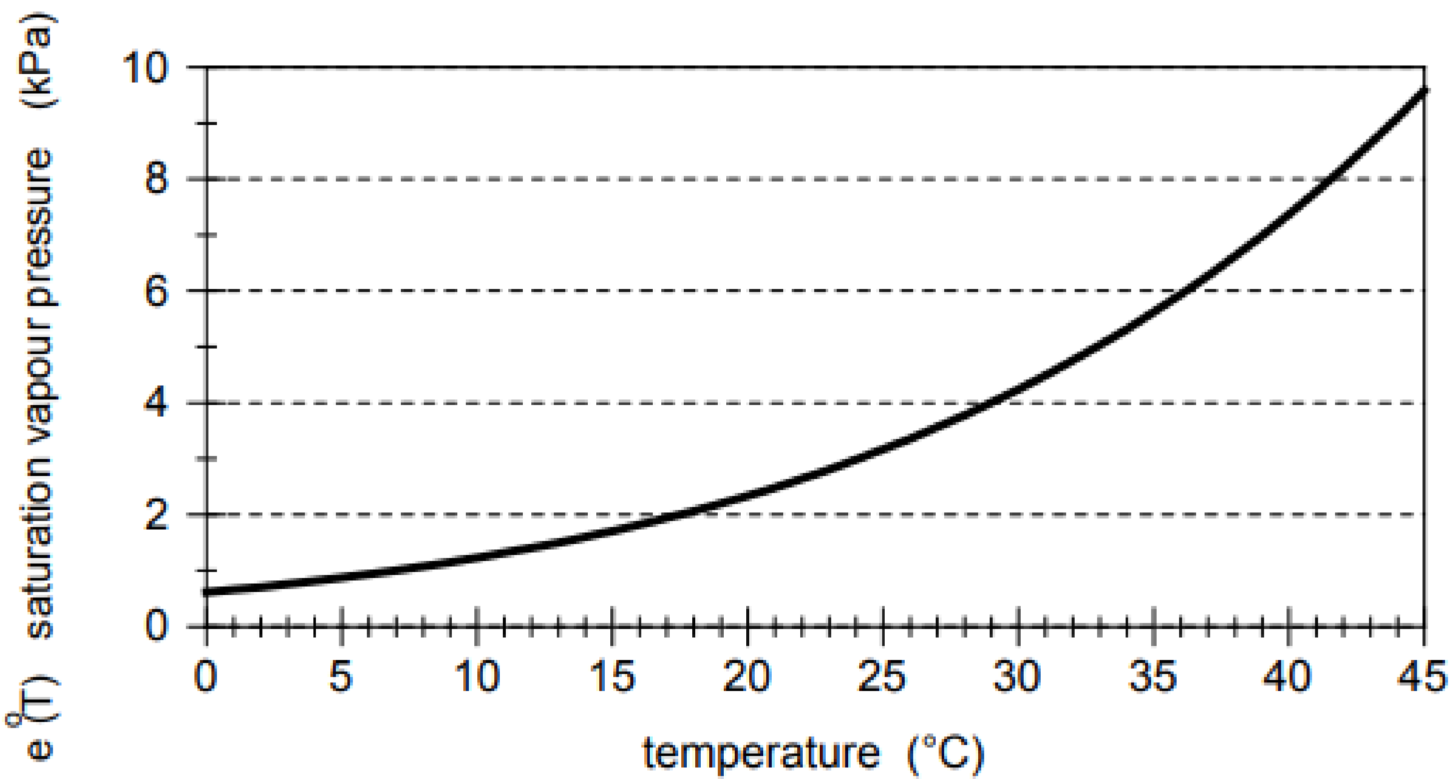


Figure 5. Saturation vapor pressure shown as a function of temperature: e°(T) curve

Slope of Saturation Vapor Curve, Δ

Δ can be determined using T_{mean} and the Table 4 (Table B.4-PAES 602:2016)

Table 4. Slope of vapor pressure curve

T °C	Δ kPa/°C	T °C	Δ kPa/°C	T °C	Δ kPa/°C	T °C	Δ kPa/°C
1.0	0.047	13.0	0.098	25.0	0.189	37.0	0.342
1.5	0.049	13.5	0.101	25.5	0.194	37.5	0.350
2.0	0.050	14.0	0.104	26.0	0.199	38.0	0.358
2.5	0.052	14.5	0.107	26.5	0.204	38.5	0.367
3.0	0.054	15.0	0.110	27.0	0.209	39.0	0.375
3.5	0.055	15.5	0.113	27.5	0.215	39.5	0.384
4.0	0.057	16.0	0.116	28.0	0.220	40.0	0.393
4.5	0.059	16.5	0.119	28.5	0.226	40.5	0.402
5.0	0.061	17.0	0.123	29.0	0.231	41.0	0.412
5.5	0.063	17.5	0.126	29.5	0.237	41.5	0.421
6.0	0.065	18.0	0.130	30.0	0.243	42.0	0.431
6.5	0.067	18.5	0.133	30.5	0.249	42.5	0.441
7.0	0.069	19.0	0.137	31.0	0.256	43.0	0.451
7.5	0.071	19.5	0.141	31.5	0.262	43.5	0.461
8.0	0.073	20.0	0.145	32.0	0.269	44.0	0.471
8.5	0.075	20.5	0.149	32.5	0.275	44.5	0.482
9.0	0.078	21.0	0.153	33.0	0.282	45.0	0.493
9.5	0.080	21.5	0.157	33.5	0.289	45.5	0.504
10.0	0.082	22.0	0.161	34.0	0.296	46.0	0.515
10.5	0.085	22.5	0.165	34.5	0.303	46.5	0.526
11.0	0.087	23.0	0.170	35.0	0.311	47.0	0.538
11.5	0.090	23.5	0.174	35.5	0.318	47.5	0.550
12.0	0.092	24.0	0.179	36.0	0.326	48.0	0.562
12.5	0.095	24.5	0.184	36.5	0.334	48.5	0.574

Slope of Saturation Vapor Pressure Curve, Δ

Example 3

Determine the saturation vapor pressure curve using the data on Example 2.

Given:

T_{max} = 33.4 °C
T_{min} = 22.6 °C

Solution:

$$T_{mean} = \frac{T_{max} + T_{min}}{2}$$

$$T_{mean} = \frac{33.4 + 22.6}{2}$$

$$\boldsymbol{T_{mean} = 28.0\ {}^{o}C}$$

Slope of Saturation Vapor Curve, Δ

Solution:

$$\Delta = \frac{4098\left[0.6108exp\left(\frac{17.27T}{T+237.3}\right)\right]}{(T+237.3)^2}$$

$$\Delta = \frac{4098\left[0.6108exp\left(\frac{17.27(28.0)}{28.0+237.3}\right)\right]}{(28.0+237.3)^2}$$

$$\mathbf{\Delta = 0.220\ kPa^{o}C^{-1}}$$

Slope of Saturation Vapor Curve, Δ

From Table 4 at T = 28°C

$$\Delta = \mathbf{0.220\ kPa^{o}}\boldsymbol{C^{-1}}$$

T °C	Δ kPa/°C	T °C	Δ kPa/°C
25.0	0.189	37.0	0.342
25.5	0.194	37.5	0.350
26.0	0.199	38.0	0.358
26.5	0.204	38.5	0.367
27.0	0.209	39.0	0.375
27.5	0.215	39.5	0.384
28.0	0.220	40.0	0.393
28.5	0.226	40.5	0.402
29.0	0.231	41.0	0.412
29.5	0.237	41.5	0.421
30.0	0.243	42.0	0.431
30.5	0.249	42.5	0.441
31.0	0.256	43.0	0.451
31.5	0.262	43.5	0.461
32.0	0.269	44.0	0.471
32.5	0.275	44.5	0.482
33.0	0.282	45.0	0.493
33.5	0.289	45.5	0.504
34.0	0.296	46.0	0.515
34.5	0.303	46.5	0.526
35.0	0.311	47.0	0.538
35.5	0.318	47.5	0.550
36.0	0.326	48.0	0.562
36.5	0.334	48.5	0.574

Actual Vapor Pressure, e_a

- It is the vapor pressure exerted by the water in the air.
- The actual vapor pressure of the air is the saturation vapor pressure at the dewpoint temperature.

$$e_a = e^0(T_{dew}) = 0.6108 exp\left[\frac{17.27\, T_{dew}}{T_{dew} + 237.3}\right]$$

where: Tdew – dewpoint temperature

Actual Vapor Pressure, e_a

- RH expresses the degree of saturation of the air as a ratio of the actual (e_a) to the saturation [$e^{o}(T)$] vapor pressure at the same temperature (T):
- It is the ratio between the amount of water the ambient air actually holds and the amount it could hold at the same temperature.

$$RH = 100\frac{e_a}{e^0(T)}$$

Actual Vapor Pressure, e_a

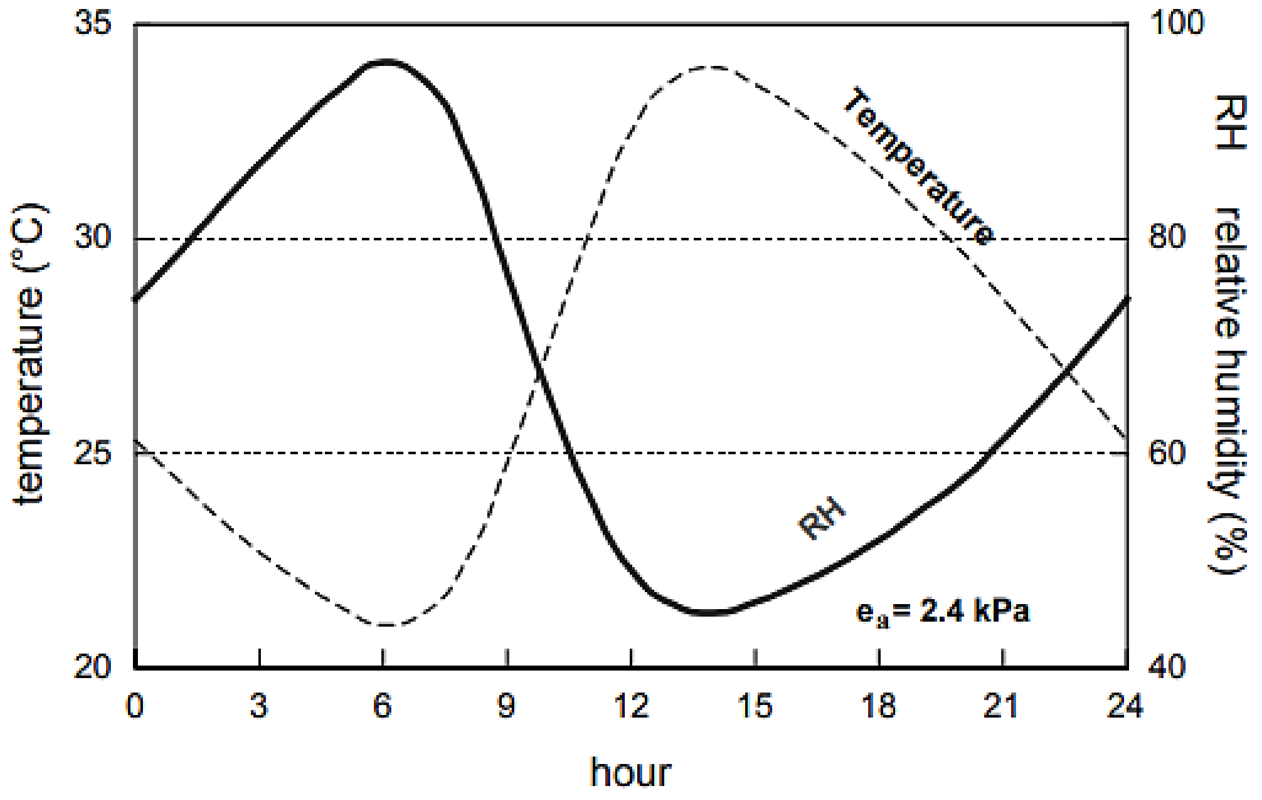


Figure 6. Variation of the relative humidity over 24 hours for a constant actual vapor pressure of 2.4 kPa

Actual Vapor Pressure, e_a

- **For RH_{max} and RH_{min}**

$$e_a = \frac{e^o(T_{min})\frac{RH_{max}}{100} + e^o(T_{max})\frac{RH_{min}}{100}}{2}$$

where: $e^o(T_{min})$ – saturation vapor pressure at daily minimum temperature T, kPa
$e^o(T_{max})$ – saturation vapor pressure at daily maximum temperature T, kPa
RH_{max} – maximum relative humidity, %
RH_{min} – minimum relative humidity, %

Actual Vapor Pressure, e_a

- **For RH_{max}**

When using equipment where errors in estimating RH_{min} can be large, or when RH data integrity are in doubt, then one should use only RH_{max}:

$$e_a = e^o(T_{min}) \frac{RH_{max}}{100}$$

Actual Vapor Pressure, e_a

- **For RH_{mean}**

In the absence of RH_{max} and RH_{min}, another equation can be used to estimate e_a:

$$e_a = \frac{RH_{mean}}{100}\left[\frac{e^o(T_{max}) + e^o(T_{min})}{2}\right]$$

Actual Vapor Pressure, e_a

Example 4

Determine the actual vapor pressure if the corresponding dewpoint temperature in Example 2 & 3 is 23.6°C.

Solution:

$$e_a = 0.6108exp\left[\frac{17.27\,T_{dew}}{T_{dew} + 237.3}\right]$$

$$e_a = 0.6108exp\left[\frac{17.27\,(23.6)}{23.6 + 237.3}\right]$$

$$\boldsymbol{e_a = 2.913\,kPa}$$

Vapor Pressure Deficit, $e_s - e_a$

- It is the difference between the saturation and actual vapor pressure.
- It is an accurate indicator of the actual evaporative capacity of the air.

Vapor Pressure Deficit, $e_s - e_a$

Example 5

Determine the vapor pressure deficit with the data of the previous examples.

Solution:

$e_s - e_a = 3.943 - 2.913$

$\boldsymbol{e_s - e_a = 1.03\ kPA}$

Atmospheric Pressure, P

- The atmospheric pressure is the pressure exerted by the weight of the earth's atmosphere.

$$P = 101.3\left(\frac{293 - 0.0065\,z}{293}\right)^{5.26}$$

where: P – atmospheric pressure, kPa
z – elevation above sea level, m

Latent Heat of Vaporization, λ

- The latent heat of vaporization expresses the energy required to change a unit mass of water from liquid to water vapor in a constant pressure and constant temperature process.
- The value of the latent heat varies as a function of temperature.

Psychrometric Constant, γ

$$\gamma = \frac{c_p\, P}{\varepsilon\, \lambda}$$

$$\gamma = 0.665 \times 10^{-3} P$$

where: γ – psychrometric constant, kPa °C^{-1}
T – atmospheric pressure, kPa
λ – latent heat of vaporization, 2.45 MJ kg^{-1}
c_p – specific heat at constant pressure, 1.013 10^{-3} MJ kg^{-1} °C^{-1}
ε – ratio molecular weight of water vapour/dry air = 0.622.

Psychrometric Constant, γ

Example 6

Determine the atmospheric pressure and the psychrometric constant at an elevation of 80 m above sea level.

Solution:

$$P = 101.3\left(\frac{293 - 0.0065\,z}{293}\right)^{5.26}$$

$$\boldsymbol{P = 100.36\ kPa}$$

$$P = 101.3\left(\frac{293 - 0.0065\,(80)}{293}\right)^{5.26}$$

Psychrometric Constant, γ

Solution:

$$\gamma = 0.665 \times 10^{-3} P$$

$$\gamma = 0.665 \times 10^{-3} (100.36)$$

$$\boldsymbol{\gamma = 0.0667\ \mathbf{kPa}^{o}C^{-1}}$$

Psychrometric Constant, γ

Table 5. Psychrometric constant (γ) for different altitudes (z)

z (m)	γ kPa/°C	z (m)	γ kPa/°C	z (m)	γ kPa/°C	z (m)	γ kPa/°C
0	0.067	1000	0.060	2000	0.053	3000	0.047
100	0.067	1100	0.059	2100	0.052	3100	0.046
200	0.066	1200	0.058	2200	0.052	3200	0.046
300	0.065	1300	0.058	2300	0.051	3300	0.045
400	0.064	1400	0.057	2400	0.051	3400	0.045
500	0.064	1500	0.056	2500	0.050	3500	0.044
600	0.063	1600	0.056	2600	0.049	3600	0.043
700	0.062	1700	0.055	2700	0.049	3700	0.043
800	0.061	1800	0.054	2800	0.048	3800	0.042
900	0.061	1900	0.054	2900	0.047	3900	0.042
1000	0.060	2000	0.053	3000	0.047	4000	0.041

Based on λ= 2.45 MJ kg^{-1} at 20°C.

- *γ can be determined using z and Table B.5 (PAES 602:2016):*

Extraterrestrial Radiation, R_a

- The solar radiation received at the top of the earth's atmosphere on a horizontal surface.
- If the sun is directly overhead, the angle of incidence is zero and the extraterrestrial radiation is *0.0820 MJ m^{-2} min^{-1}*.

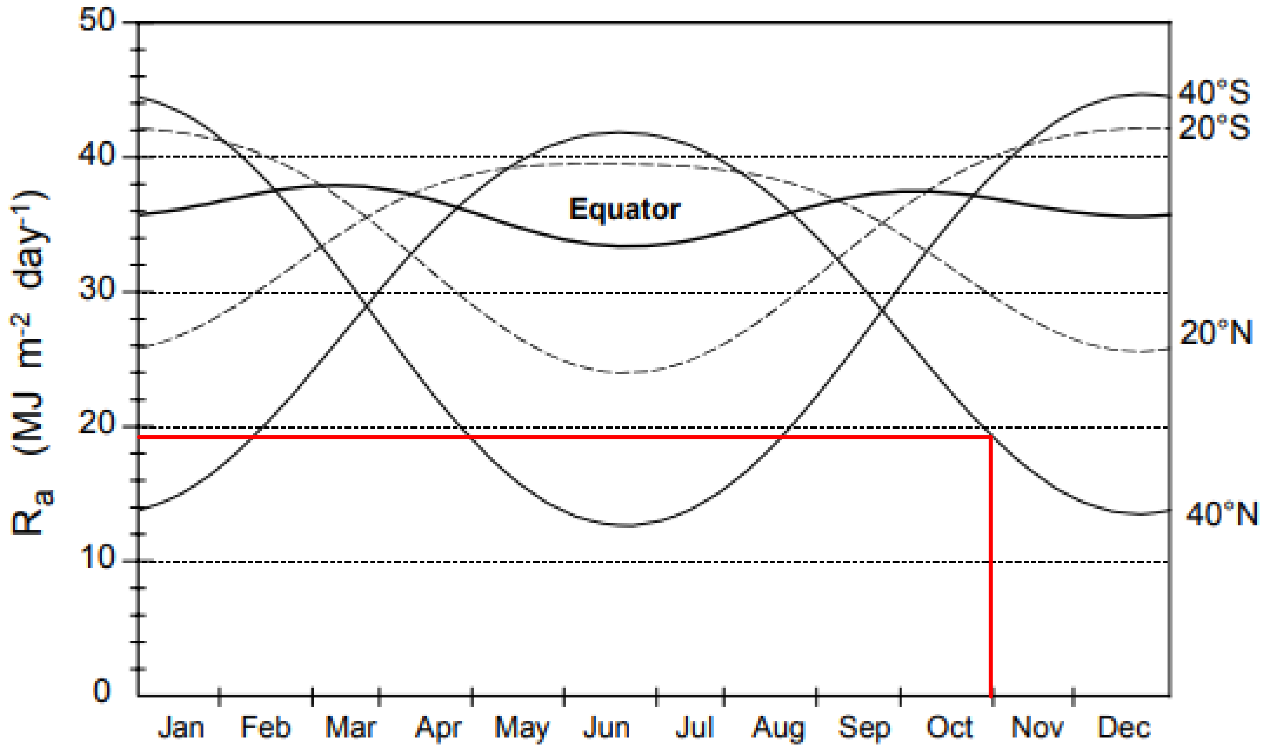


Figure 7. Annual variation in extraterrestrial radiation (R_a) at the equator, 20 and 40° north and south

Northern Hemisphere												Lat.
Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec	deg.
0	2.6	10.4	23	35.2	42.5	39.4	28	14.9	4.9	0.1	0	70
0.1	3.7	11.7	23.9	35.3	42	38.9	28.6	16.1	6	0.7	0	68
0.6	4.8	12.9	24.8	35.6	41.4	38.8	29.3	17.3	7.2	1.5	0.1	66
1.4	5.9	14.1	25.8	35.9	41.2	38.8	30	18.4	8.5	2.4	0.6	64
2.3	7.1	15.4	26.6	36.3	41.2	39	30.6	19.5	9.7	3.4	1.3	62
3.3	8.3	16.6	27.5	36.6	41.2	39.2	31.3	20.6	10.9	4.4	2.2	60
4.3	9.6	14.7	28.4	37	41.3	39.4	32	21.7	12.1	5.5	3.1	58
5.4	10.8	18.9	29.2	37.4	41.4	39.6	32.6	22.7	13.3	6.7	4.2	56
6.5	12	20	30	37.8	41.5	39.8	33.2	23.7	14.5	7.8	5.2	54
7.7	13.2	21.1	30.8	38.2	41.6	40.1	33.8	24.7	15.7	9	6.4	52
8.9	14.4	22.2	31.5	38.5	41.7	40.2	34.4	25.7	16.9	10.2	7.5	50
10.1	15.7	23.3	32.2	38.8	41.8	40.4	34.9	26.6	18.1	11.4	8.7	48
11.3	16.9	24.3	32.9	39.1	41.9	40.6	35.5	27.5	19.2	12.6	9.9	46
12.5	18	25.3	33.5	39.3	41.9	40.7	35.9	28.4	20.3	13.9	11.1	44
13.8	19.2	26.3	34.1	39.5	41.9	40.8	36.3	29.2	21.4	15.1	12.4	42
15	20.4	27.2	34.7	39.7	41.9	40.8	36.7	30	22.5	16.3	13.6	40
16.2	21.5	28.1	35.2	39.9	41.8	40.8	37	30.7	23.6	17.5	14.8	38
17.5	22.6	29	35.7	40	41.7	40.8	37.4	31.5	24.6	18.7	16.1	36
18.7	23.7	29.9	36.1	40	41.6	40.8	37.6	32.1	25.6	19.9	17.3	34
19.9	24.8	30.7	36.5	40	41.4	40.7	37.9	32.8	26.6	21.1	18.5	32
21.1	25.8	31.4	36.8	40	41.2	40.6	38	33.4	27.6	22.2	19.8	30
22.3	26.8	32.2	37.1	40	40.9	40.4	38.2	33.9	28.5	23.3	21	28
23.4	27.8	32.8	37.4	39.9	40.6	40.2	38.3	34.5	29.3	24.5	22.2	26
24.6	28.8	33.5	37.6	39.7	40.3	39.9	38.3	34.9	30.2	25.5	23.3	24
25.7	29.7	34.1	37.8	39.5	40	39.6	38.4	35.4	31	26.6	24.5	22
26.8	30.6	34.7	37.9	39.3	39.5	39.3	38.3	35.8	31.8	27.7	25.6	20
27.9	31.5	35.2	38	39	39.1	38.9	38.2	36.1	32.5	28.7	26.8	18
28.9	32.3	35.7	38.1	38.7	38.6	38.5	38.1	36.4	33.2	29.6	27.9	16
29.9	33.1	36.1	38.1	38.4	38.1	38.1	38	36.7	33.9	30.6	28.9	14
30.9	33.8	36.5	38	38	37.6	37.6	37.8	36.9	34.5	31.5	30	12
31.9	34.5	36.9	37.9	37.6	37	37.1	37.5	37.1	35.1	32.4	31	10
32.8	35.2	37.2	37.8	37.1	36.3	36.5	37.2	37.2	35.6	33.3	32	8
33.7	35.8	37.4	37.6	36.6	35.7	35.9	36.9	37.3	36.1	34.1	32.9	6
34.6	36.4	37.6	37.4	36	35	35.3	36.5	37.3	36.6	34.9	33.9	4
35.4	37	37.8	37.1	35.4	34.2	34.6	36.1	37.3	37	35.6	34.8	2
36.2	37.5	37.9	36.8	34.8	33.4	33.9	35.7	37.2	37.4	36.3	35.6	0

Table 6. Daily extraterrestrial radiation ($MJ/m^2/day$) for different latitudes for the 15th day of the month

Example 7

Determine the extraterrestrial radiation, R_a, for an area with a latitude of 15.72°N for the month of November.

28.9	32.3	35.7	38.1	38.7	38.6	38.5	38.1	36.4	33.2	29.6	27.9	16
29.9	33.1	36.1	38.1	38.4	38.1	38.1	38	36.7	33.9	30.6	28.9	14
30.9	33.8	36.5	38	38	37.6	37.6	37.8	36.9	34.5	31.5	30	12
31.9	34.5	36.9	37.9	37.6	37	37.1	37.5	37.1	35.1	32.4	31	10
32.8	35.2	37.2	37.8	37.1	36.3	36.5	37.2	37.2	35.6	33.3	32	8
33.7	35.8	37.4	37.6	36.6	35.7	35.9	36.9	37.3	36.1	34.1	32.9	6
34.6	36.4	37.6	37.4	36	35	35.3	36.5	37.3	36.6	34.9	33.9	4
35.4	37	37.8	37.1	35.4	34.2	34.6	36.1	37.3	37	35.6	34.8	2
36.2	37.5	37.9	36.8	34.8	33.4	33.9	35.7	37.2	37.4	36.3	35.6	0

Using Table 7, and by interpolation:

$$R_a = 29.72 \text{ MJ m}^{-2} \text{ day}^{-1}$$

Daylight hours, N

- Maximum possible duration of sunshine.
- It depends on the position of the sun and is hence a function of latitude and date.

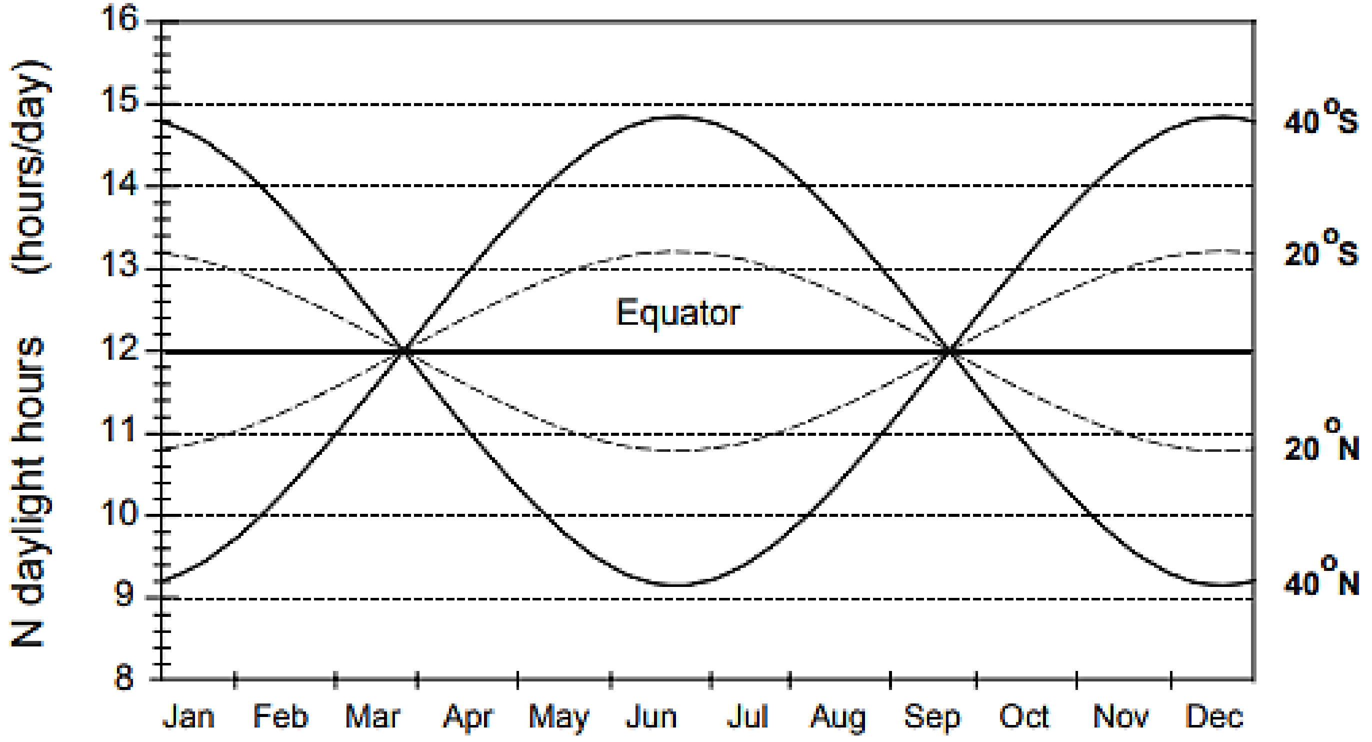


Figure 8. Annual variation of the daylight hours (N) at the equator, 20 and 40° north and south

Northern Hemisphere												Lat.
Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec	deg.
0	6.6	11	15.6	21.3	24	24	17.6	12.8	8.3	2.3	0	70
2.1	7.3	11.1	15.3	19.7	24	22.3	17	12.7	8.7	4.1	0	68
3.9	7.8	11.2	14.9	18.7	22	20.3	16.4	12.7	9	5.2	1.9	66
5	8.2	11.2	14.7	17.9	20.3	19.2	16	12.6	9.3	6	3.7	64
5.7	8.5	11.3	14.4	17.3	19.2	18.4	15.7	12.6	9.5	6.6	4.8	62
6.4	8.8	11.4	14.2	16.8	18.4	17.7	15.3	12.5	9.7	7.1	5.6	60
6.9	9.1	11.4	14.1	16.4	17.8	17.2	15.1	12.5	9.9	7.5	6.2	58
7.3	9.3	11.5	13.9	16	17.3	16.8	14.8	12.4	10.1	7.9	6.7	56
7.7	9.5	11.5	13.8	15.7	16.8	16.4	14.6	12.4	10.2	8.2	7.1	54
8	9.7	11.5	13.6	15.4	16.5	16	14.4	12.4	10.3	8.5	7.5	52
8.3	9.8	11.6	13.6	15.2	16.1	15.7	14.3	12.3	10.4	8.7	7.9	50
8.6	10	11.6	13.4	15	15.8	15.5	14.1	12.3	10.6	9	8.2	48
8.8	10.1	11.6	13.3	14.8	15.5	15.2	14	12.3	10.7	9.2	8.5	46
9.1	10.3	11.6	13.2	14.6	15.3	15	13.8	12.3	10.7	9.4	8.7	44
9.3	10.4	11.7	13.2	14.4	15	14.8	13.7	12.3	10.8	9.6	9	42
9.5	10.5	11.7	13.1	14.2	14.8	14.6	13.6	12.2	10.9	9.7	9.2	40
9.6	10.6	11.7	13	14.1	14.6	14.4	13.5	12.2	11	9.9	9.4	38
9.8	10.7	11.7	12.9	13.9	14.4	14.2	13.4	12.2	11.1	10.1	9.6	36
10	10.8	11.8	12.9	13.8	14.3	14.1	13.3	12.2	11.1	10.2	9.7	34
10.1	10.9	11.8	12.8	13.6	14.1	13.9	13.2	12.2	11.2	10.3	9.9	32
10.3	11	11.8	12.7	13.5	13.9	13.8	13.1	12.2	11.3	10.5	10.1	30
10.4	11	11.8	12.7	13.4	13.8	13.6	13	12.2	11.3	10.6	10.2	28
10.5	11.1	11.8	12.6	13.3	13.6	13.5	12.9	12.1	11.4	10.7	10.4	26
10.7	11.2	11.8	12.6	13.2	13.5	13.3	12.8	12.1	11.4	10.8	10.5	24
10.8	11.3	11.9	12.5	13.1	13.3	13.2	12.8	12.1	11.5	10.9	10.7	22
10.9	11.3	11.9	12.5	12.9	13.2	13.1	12.7	12.1	11.5	11	10.8	20
11	11.4	11.9	12.4	12.8	13.1	13	12.6	12.1	11.6	11.1	10.9	18
11.1	11.5	11.9	12.4	12.7	12.9	12.9	12.5	12.1	11.6	11.2	11.1	16
11.3	11.6	11.9	12.3	12.6	12.8	12.8	12.5	12.1	11.7	11.3	11.2	14
11.4	11.6	11.9	12.3	12.6	12.7	12.6	12.4	12.1	11.7	11.4	11.3	12
11.5	11.7	11.9	12.2	12.5	12.6	12.5	12.3	12.1	11.8	11.5	11.4	10
11.6	11.7	11.9	12.2	12.4	12.5	12.4	12.3	12	11.8	11.6	11.5	8
11.7	11.8	12	12.1	12.3	12.3	12.3	12.2	12	11.9	11.7	11.7	6
11.8	11.9	12	12.1	12.2	12.2	12.2	12.1	12	11.9	11.8	11.8	4
11.9	11.9	12	12	12.1	12.1	12.1	12.1	12	12	11.9	11.9	2
12	12	12	12	12	12	12	12	12	12	12	12	0

Table 8. Mean daylight hours for different latitudes for the 15th day of the month

Example 8

Using the data in Example 7, determine the mean daylight hours.

Using Table 8, and by interpolation:

N = 11.21 hours

11.1	11.5	11.9	12.4	12.7	12.9	12.9	12.5	12.1	11.6	11.2	11.1	16
11.3	11.6	11.9	12.3	12.6	12.8	12.8	12.5	12.1	11.7	11.3	11.2	14
11.4	11.6	11.9	12.3	12.6	12.7	12.6	12.4	12.1	11.7	11.4	11.3	12
11.5	11.7	11.9	12.2	12.5	12.6	12.5	12.3	12.1	11.8	11.5	11.4	10
11.6	11.7	11.9	12.2	12.4	12.5	12.4	12.3	12	11.8	11.6	11.5	8
11.7	11.8	12	12.1	12.3	12.3	12.3	12.2	12	11.9	11.7	11.7	6
11.8	11.9	12	12.1	12.2	12.2	12.2	12.1	12	11.9	11.8	11.8	4
11.9	11.9	12	12	12.1	12.1	12.1	12.1	12	12	11.9	11.9	2
12	12	12	12	12	12	12	12	12	12	12	12	0

Relative Sunshine Duration, n/N

- The relative sunshine duration is another ratio that expresses the cloudiness of the atmosphere.
- It is the ratio of the actual duration of sunshine, n, to the maximum possible duration of sunshine or daylight hours N.

Solar or Shortwave Radiation, R_s

- It is the amount of radiation reaching a horizontal plane.
- For a cloudless day, R_s is roughly 75% of extraterrestrial radiation.
- On a cloudy day, about 25% of the extraterrestrial radiation may still reach the earth's surface mainly as diffuse sky radiation.
- It is also known as *global radiation*, meaning that it is the sum of direct shortwave radiation from the sun and diffuse sky radiation from all upward angles.

Solar or Shortwave Radiation, R_s

$$R_s = \left(a_s + b_s \frac{n}{N}\right) R_a \qquad \boldsymbol{R_s = \left(0.25 + 0.50 \frac{n}{N}\right) R_a}$$

where: R_s – solar or shortwave radiation, MJ m^{-2} day^{-1}
n – actual duration of sunshine, hour
N – maximum possible duration of sunshine or daylight hours, hour
n/N relative sunshine duration
R_a – extraterrestrial radiation, MJ m^{-2} day^{-1}
a_s – regression constant, expressing the fraction of extraterrestrial radiation reaching the earth on overcast days (n = 0)
a_s+b_s – fraction of extraterrestrial radiation reaching the earth on clear days (n = N)

Example 9

If the actual duration of sunshine for Example 7&8 is 11 hours, what is the solar radiation?

$$R_s = \left(0.25 + 0.50\frac{n}{N}\right)R_a$$

$$R_s = \left(0.25 + 0.50\frac{11}{11.21}\right)(29.72)$$

$$\boldsymbol{R_s = 22.01\ MJ\ m^{-2}\, day^{-1}}$$

Clear-sky Solar Radiation, R_{so}

- R_s is the solar radiation that actually reaches the earth's surface in a given period, while R_{so} is the solar radiation that would reach the same surface during the same period but under cloudless conditions.

$$R_{so} = \left(0.75 + \frac{2\,z}{100{,}000}\right) R_a$$

where: z – station elevation above sea level, m

Example 10

Calculate the clear-sky radiation if the station elevation is 80 meters above sea level and extraterrestrial radiation is 29.72 MJ m^{-2} day^{-1}?

$$R_{so} = \left(0.75 + \frac{2\,z}{100{,}000}\right) R_a$$

$$\boldsymbol{R_{so} = 22.34\ MJ\ m^{-2}\, day^{-1}}$$

$$R_{so} = \left(0.75 + \frac{2\ \times 80}{100{,}000}\right) (29.72)$$

Relative Shortwave Radiation, R_s/R_{so}

- It is the ratio of the solar radiation (R_s) to the clear-sky solar radiation (R_{so}).
- It is a way to express the cloudiness of the atmosphere; the cloudier the sky the smaller the ratio.
- The ratio varies between about 0.33 (dense cloud cover) and 1 (clear sky).

Albedo (α) and Net Solar Radiation (R_{ns})

- The fraction of the solar radiation reflected by the surface is known as the albedo (α).
- The net solar radiation, R_{ns}, is the fraction of the solar radiation R_s that is not reflected from the surface. Its value is $(1-\alpha)Rs$.

Net Solar Radiation (R_{ns})

$$R_{ns} = (1 - \alpha)R_s \qquad R_{ns} = (1 - 0.23)R_s \qquad \boldsymbol{R_{ns} = 0.77R_s}$$

where: α – albedo or canopy reflection coefficient, which is 0.23 for the hypothetical grass reference crop.

Example 11

Calculate the net solar radiation if the shortwave radiation is 22.01 MJ m^{-2} day^{-1}?

$$R_{ns} = 0.77R_s$$

$$R_{ns} = 0.77 \times 22.01$$

$$\boldsymbol{R_{ns} = 16.95\ MJ\ m^{-2}\ day^{-1}}$$

Net Longwave Radiation, R_{nl}

- The earth, which is at a much lower temperature than the sun, emits radiative energy with wavelengths longer than those from the sun.
- The *terrestrial radiation* is referred to as *longwave radiation*.
- The rate of longwave energy emission is proportional to the absolute temperature of the surface raised to the fourth power.
- This relation is expressed quantitatively by the *Stefan-Boltzmann law*, that is net energy flux leaving the earth's surface is less than that emitted.

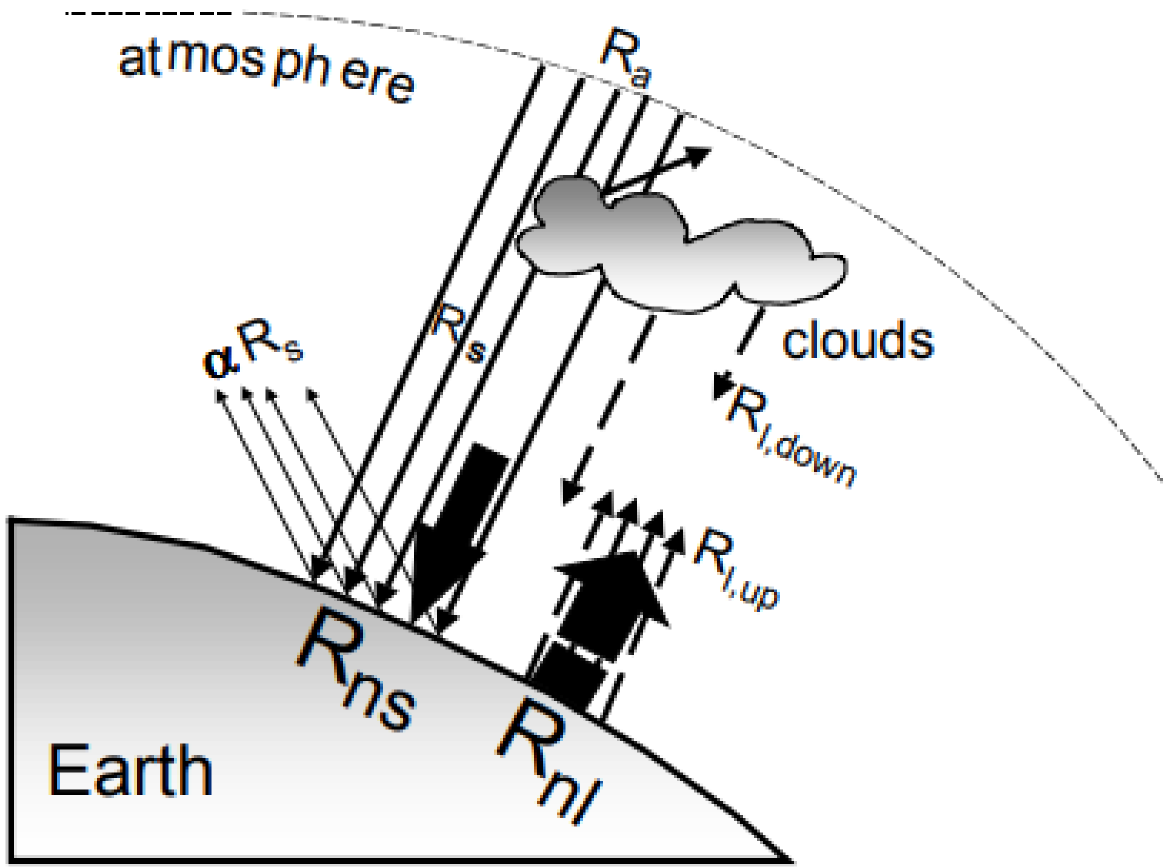


Figure 9. Various components of radiation

- The difference between outgoing and incoming longwave radiation is called the *net longwave radiation*.
- R_{nl} represents the *energy loss*

Net Longwave Radiation, R_{nl}

$$R_{nl} = \frac{\left(\sigma T_{max,K^4} + \sigma T_{min,K^4}\right)}{2}(0.34 - 0.14\sqrt{e_a})\left(1.35\frac{R_s}{R_{so}} - 0.35\right)$$

where: σ – Stefan-Boltzmann constant, 4.093 10^{-9}, MJ K^{-4} m^{-2} day^{-1}

$T_{max, K}$ – maximum absolute temperature during the 24-hour period (K = °C + 273.16)

$T_{min, K}$ – minimum absolute temperature during the 24-hour period (K = °C + 273.16)

T (°C)	σTK⁴ (MJ m⁻² d⁻¹)	T (°C)	σTK⁴ (MJ m⁻² d⁻¹)	T (°C)	σTK⁴ (MJ m⁻² d⁻¹)
1.0	27.70	17.0	34.75	33.0	43.08
1.5	27.90	17.5	34.99	33.5	43.36
2.0	28.11	18.0	35.24	34.0	43.64
2.5	28.31	18.5	35.48	34.5	43.93
3.0	28.52	19.0	35.72	35.0	44.21
3.5	28.72	19.5	35.97	35.5	44.50
4.0	28.93	20.0	36.21	36.0	44.79
4.5	29.14	20.5	36.46	36.5	45.08
5.0	29.35	21.0	36.71	37.0	45.37
5.5	29.56	21.5	36.96	37.5	45.67
6.0	29.78	22.0	37.21	38.0	45.96
6.5	29.99	22.5	37.47	38.5	46.26
7.0	30.21	23.0	37.72	39.0	46.56
7.5	30.42	23.5	37.98	39.5	46.85
8.0	30.64	24.0	38.23	40.0	47.15
8.5	30.86	24.5	38.49	40.5	47.46
9.0	31.08	25.0	38.75	41.0	47.76
9.5	31.30	25.5	39.01	41.5	48.06
10.0	31.52	26.0	39.27	42.0	48.37
10.5	31.74	26.5	39.53	42.5	48.68
11.0	31.97	27.0	39.80	43.0	48.99
11.5	32.19	27.5	40.06	43.5	49.30
12.0	32.42	28.0	40.33	44.0	49.61
12.5	32.65	28.5	40.60	44.5	49.92
13.0	32.88	29.0	40.87	45.0	50.24
13.5	33.11	29.5	41.14	45.5	50.56
14.0	33.34	30.0	41.41	46.0	50.87
14.5	33.57	30.5	41.69	46.5	51.19
15.0	33.81	31.0	41.96	47.0	51.51
15.5	34.04	31.5	42.24	47.5	51.84
16.0	34.28	32.0	42.52	48.0	52.16
16.5	34.52	32.5	42.80	48.5	52.49

Table 9. σTK^4 (Stefan-Boltzmann law) at different temperatures (T)

Net Radiation, R_n

- It is the difference between incoming and outgoing radiation of both short and long wavelengths.
- It is the balance between the energy absorbed, reflected and emitted by the earth's surface or the difference between the incoming net shortwave (R_{ns}) and the net outgoing longwave (R_{nl}) radiation
- It is normally positive during the daytime and negative during the nighttime.

$$R_n = R_{ns} - R_{nl}$$

Example 12

Determine the net longwave radiation and net radiation if the maximum temperature is 33.4 °C, minimum temperature is 22.6 °C, actual vapor pressure is 2.913 kPa, relative shortwave radiation is 0.99 and net shortwave radiation is 16.95 MJ m^{-2} day^{-1}.

T (°C)	σT_K^4 (MJ m^{-2} d^{-1})	T (°C)	σT_K^4 (MJ m^{-2} d^{-1})	T (°C)	σT_K^4 (MJ m^{-2} d^{-1})
1.0	27.70	17.0	34.75	33.0	43.08
1.5	27.90	17.5	34.99	33.5	43.36
2.0	28.11	18.0	35.24	34.0	43.64
2.5	28.31	18.5	35.48	34.5	43.93
3.0	28.52	19.0	35.72	35.0	44.21
3.5	28.72	19.5	35.97	35.5	44.50
4.0	28.93	20.0	36.21	36.0	44.79
4.5	29.14	20.5	36.46	36.5	45.08
5.0	29.35	21.0	36.71	37.0	45.37
5.5	29.56	21.5	36.96	37.5	45.67
6.0	29.78	22.0	37.21	38.0	45.96
6.5	29.99	22.5	37.47	38.5	46.26
7.0	30.21	23.0	37.72	39.0	46.56

Using Table 9, and by interpolation:

$$\sigma T_{max,K^4} = 43.30 \text{ MJ m}^{-2} \text{ day}^{-1}. \qquad \sigma T_{min,K^4} = 37.52 \text{ MJ m}^{-2} \text{ day}^{-1}.$$

$$R_{nl} = \frac{\left(\sigma T_{max,K^4} + \sigma T_{min,K^4}\right)}{2}(0.34 - 0.14\sqrt{e_a})\left(1.35\frac{R_s}{R_{so}} - 0.35\right)$$

$$R_{nl} = \frac{(43.30 + 37.52)}{2}\left(0.34 - 0.14\sqrt{2.913}\right)(1.35 \times 0.99 - 0.35)$$

$$\boldsymbol{R_{nl} = 4.03\ \mathbf{MJ\ m^{-2}\ day^{-1}}}$$

$$R_n = R_{ns} - R_{nl}$$

$$R_n = 16.95 - 4.03$$

$$\boldsymbol{R_n = 12.92\ \mathbf{MJ\ m^{-2}\ day^{-1}}}$$

Soil Heat Flux, G

- It is the energy that is utilized in heating the soil.
- It is positive when the soil is warming and negative when the soil is cooling.

For day and ten-day periods:

$$G_{day} \approx 0$$

Soil Heat Flux, G

For monthly periods:

- When assuming a constant soil heat capacity of 2.1 MJ m^{-3} °C^{-1} and an appropriate soil depth, the following equation can be used to derive G for monthly periods:

$$G_{month,i} = 0.07(T_{month,i+1} - T_{month,i-1})$$

where: $T_{month,i+1}$ = mean air temperature of next month, °C
$T_{month,i-1}$ = mean air temperature of previous month, °C

Soil Heat Flux, G

For monthly periods:

- or if $T_{month,i+1}$ is unknown

$$G_{month,i} = 0.07(T_{month,i} - T_{month,i-1})$$

where: $T_{month,i}$ = mean air temperature of month i, °C

Soil Heat Flux, G

For hourly or shorter periods:

- during daylight periods

$$G_{hr} = 0.1R_n$$

- during nighttime periods

$$G_{hr} = 0.5R_n$$

Wind Speed, u_2

- As wind speed at a given location varies with time, it is necessary to express it as an average over a given time interval.
- Wind speed is given in meters per second ($m\ s^{-1}$) or kilometres per day ($km\ day^{-1}$).
- Surface friction tends to slow down wind passing over it.
- Wind speed is slowest at the surface and increases with height.

Wind Speed, u_2

- For elevation other than 2 meters

$$\boldsymbol{u_2 = u_z \frac{4.87}{ln(67.8\,z - 5.42)}}$$

where: u_2 = wind speed at 2m above ground surface, m s^{-1}
u_z = measured wind speed at z m above ground surface, m s^{-1}
z = height of measurement above ground surface, m

Example 13

Determine the reference evapotranspiration for a day given the following data:

Mean temperature = 28.0 °C

Slope of saturation vapor pressure curve = 0.220 kPa $°C^{-1}$

Vapor pressure deficit = 1.03 kPa

Psychrometric constant = 0.067 kPa $°C^{-1}$

Net radiation = 12.92 MJ m^{-2} day^{-1}

Wind speed = 7.4 km day^{-1}

$$ET_o = \frac{0.408\,\Delta\,(R_n - G) + \gamma\,\frac{900}{T + 273}\,u_2(e_s - e_a)}{\Delta + \gamma\,(1 + 0.34\,u_2)}$$

$$ET_o = \frac{0.408\,(0.220)\,(12.92 - 0) + (0.067)\,\frac{900}{28 + 273}\,(0.086)\,(1.03)}{0.220 + 0.067\,(1 + 0.34 \times 0.086)}$$

$$\boldsymbol{ET_o = 4.07\ mmday^{-1}}$$

RADIATION METHOD

- It is essentially an adaptation of the Makkink formula (1957).
- It suggested for areas where available climatic data include measured air temperature and sunshine, cloudiness or radiation, but not measured wind speed and air humidity.
- It is more reliable than the Blaney-Criddle method

RADIATION METHOD

$$ET_O = W \times R_s$$

$$R_s = \left(0.25 + 0.50\frac{n}{N}\right)R_a$$

where: W = weighting factor
R_s = solar radiation, mm/day
R_a = extraterrestrial radiation, mm/day
n/N = ratio between actual measured bright sunshine hours and maximum possible sunshine hours

For Extraterrestrial radiation, R_a

Use the $T_{dailymean}$

$$T_{max} = \frac{\sum T_{max}\ daily\ values}{number\ of\ days\ in\ the\ month\ considered}$$

$$T_{min} = \frac{\sum T_{min}\ daily\ values}{number\ of\ days\ in\ the\ month\ considered}$$

$$T_{dailymean} = \frac{T_{max} + T_{min}}{2}$$

Example 14

Determine the reference evapotranspiration for the month of July using radiation method given the following data:

Latitude = 30 °N

Altitude = 95 m

Sunshine (n) mean = 11.5 h/day

Temperature = 28.5 °C

Table 10. Extraterrestrial radiation expressed in equivalent evaporation (mm/day) for different latitudes

At 30 °N latitude,

R_a = 16.8 mm/day

Northern Hemisphere												Lat.
Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec	deg.
3.8	6.1	9.4	12.7	15.8	17.1	16.4	14.1	10.9	7.4	4.5	3.2	50
4.3	6.6	9.8	13.0	15.9	17.2	16.5	14.3	11.2	7.8	5.0	3.7	48
4.9	7.1	10.2	13.3	16	17.2	16.6	14.5	11.5	8.3	5.5	4.3	46
5.3	7.6	10.6	13.7	16.1	17.2	16.6	14.7	11.9	8.7	6.0	4.7	44
5.9	8.1	11.0	14.0	16.2	17.3	16.7	15.0	12.2	9.1	6.5	5.2	42
6.4	8.6	11.4	14.3	16.4	17.3	16.7	15.2	12.5	9.6	7.0	5.7	40
6.9	9.0	11.8	14.5	16.4	17.2	16.7	15.3	12.8	10.0	7.5	3.1	38
7.4	9.4	12.1	14.7	16.4	17.2	16.7	15.4	13.1	10.6	8.0	6.6	36
7.9	9.8	12.4	14.8	16.5	17.1	16.8	15.5	13.4	10.8	8.5	7.2	34
8.3	10.2	12.8	15.0	16.5	17.0	16.8	15.6	13.6	11.2	9.0	7.8	32
8.8	10.7	13.1	15.2	16.5	17.0	16.8	15.7	13.9	11.6	9.5	8.3	30
9.3	11.1	13.4	15.3	16.5	16.8	16.7	15.7	14.1	12.0	9.9	8.8	28
9.8	11.5	13.7	15.3	16.4	16.7	16.6	15.7	14.3	12.3	10.3	9.3	26
10.2	11.9	13.9	15.4	16.4	16.6	16.5	15.8	14.5	12.6	10.7	9.7	24
10.7	12.3	14.2	15.5	16.3	16.4	16.4	15.8	14.6	13.0	11.1	10.2	22
11.2	12.7	14.4	15.6	16.3	16.4	16.3	15.9	14.8	13.3	11.6	10.7	20
11.6	13.0	14.6	15.6	16.1	16.1	16.1	15.8	14.9	13.6	12.0	11.1	18
12.0	13.3	14.7	15.6	16.0	15.9	15.9	15.7	15.0	13.9	12.4	11.6	16
12.4	13.6	14.9	15.7	15.8	15.7	15.7	15.7	15.1	14.1	12.8	12.0	14
12.8	13.9	15.1	15.7	15.7	15.5	15.5	15.6	15.2	14.4	13.3	12.5	12
13.2	14.2	15.3	15.7	15.5	15.3	15.3	15.5	15.3	14.7	13.6	12.9	10
13.6	14.5	15.3	15.6	15.3	15.0	15.1	15.4	15.3	14.8	13.9	13.3	8
13.9	14.8	15.4	15.4	15.1	14.7	14.9	15.2	15.3	15.0	14.2	13.7	6
14.3	15.0	15.5	15.5	14.9	14.4	14.6	15.1	15.3	15.1	14.5	14.1	4
14.7	15.3	15.6	15.3	14.6	14.2	14.3	14.9	15.3	15.3	14.8	14.4	2
15.0	15.5	15.7	15.3	14.4	13.9	14.1	14.8	15.3	15.4	15.1	14.8	0

Table 11. Values of Weighting Factor (W) for the Effect of Radiation ET_o at Different Temperatures and Altitudes

Temperature (°C)	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36	38	40
Altitude (z)	**Weighting Factor (W)**																			
0	0.43	0.46	0.49	0.52	0.55	0.58	0.61	0.64	0.66	0.68	0.71	0.73	0.75	0.77	0.78	0.8	0.82	0.83	0.84	0.85
500	0.45	0.48	0.51	0.54	0.57	0.602	0.62	0.65	0.67	0.7	0.72	0.74	0.76	0.78	0.79	0.81	0.82	0.84	0.85	0.86
1000	0.46	0.49	0.52	0.55	0.58	0.61	0.64	0.66	0.69	0.71	0.73	0.75	0.77	0.79	0.8	0.82	0.83	0.85	0.86	0.87
2000	0.49	0.52	0.55	0.58	0.61	0.64	0.66	0.69	0.71	0.73	0.75	0.77	0.79	0.81	0.82	0.84	0.85	0.86	0.87	0.88
3000	0.52	0.55	0.58	0.61	0.64	0.66	0.69	0.71	0.73	0.75	0.77	0.79	0.81	0.82	0.84	0.85	0.86	0.88	0.88	0.89
4000	0.55	0.58	0.61	0.64	0.66	0.69	0.71	0.73	0.76	0.78	0.79	0.81	0.83	0.84	0.85	0.86	0.88	0.89	0.9	0.9

At z = 95 m and T_{mean} = 28 °C, **W_{28} = 0.7719 = 0.77**

At z = 95 m and T_{mean} = 30 °C, **W_{30} = 0.7819 = 0.78**

At T = 28.5 °C, W_{28} = 0.77, and W_{30} = 0.78, **$W_{28.5}$ = 0.7733 = 0.77**

Table 12. Mean Daily Duration of Maximum Possible Sunshine Hours (N) for Different Months and Latitudes

Northern Lats	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Southern Lats	July	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June
50	8.5	10.1	11.8	13.8	15.4	16.3	15.9	14.5	12.7	10.8	9.1	8.1
48	8.8	10.2	11.8	13.6	15.2	16.0	15.6	14.3	12.6	10.9	9.3	8.3
46	9.1	10.4	11.9	13.5	14.9	15.7	15.4	14.2	12.6	10.9	9.5	8.7
44	9.3	10.5	11.9	13.4	14.7	15.4	15.2	14.0	12.6	11.0	9.7	8.9
42	9.4	10.6	11.9	13.4	14.6	15.2	14.9	13.9	12.6	11.1	9.8	9.1
40	9.6	10.7	11.9	13.3	14.4	15.0	14.7	13.7	12.5	11.2	10.0	9.3
35	10.1	11.0	11.9	13.1	14.0	14.5	14.3	13.5	12.4	11.3	10.3	9.8
30	10.4	11.1	12.0	12.9	13.6	14.0	13.9*	13.2	12.4	11.5	10.6	10.2
25	10.7	11.3	12.0	12.7	13.3	13.7	13.5	13.0	12.3	11.6	10.9	10.6
20	11.0	11.5	12.0	12.6	13.1	13.3	13.2	12.8	12.3	11.7	11.2	10.9
15	11.3	11.6	12.0	12.5	12.8	13.0	12.9	12.6	12.2	11.8	11.4	11.2
10	11.6	11.8	12.0	12.3	12.6	12.7	12.6	12.4	12.1	11.8	11.6	11.5
5	11.8	11.9	12.0	12.2	12.3	12.4	12.3	12.3	12.1	12.0	11.9	11.8
0	12.1	12.1	12.1	12.1	12.1	12.1	12.1	12.1	12.1	12.1	12.1	12.1

At 30 ^{o}N latitude, **N = 13.9 hours/day**

$$R_s = \left(0.25 + 0.50\,\frac{n}{N}\right) R_a$$

$$R_s = \left(0.25 + 0.50\,\frac{11.5}{13.9}\right)(16.8)$$

$$\boldsymbol{R_s = 11.2\ mm/day}$$

$$ET_O = W \times R_s$$

$$ET_O = 0.77 \times 11.2\ mm/day$$

$$\boldsymbol{ET_O = 8.62\ mm/day}$$

BLANEY-CRIDDLE METHOD

- This method is suggested for areas where available climatic data cover air temperature data only.
- This method is inaccurate under “extreme” climatic conditions.
- In windy, dry, sunny areas, the ET_o is underestimated (up to some 60%), while in calm, humid, clouded areas, the ET_o is overestimated (up to some 40 %).

BLANEY-CRIDDLE METHOD

- This method is suggested for areas where available climatic data cover air temperature data only.

$$ET_O = p(0.46T + 8)$$

where: ETo = reference crop evapotranspiration for the month considered, mm day^{-1}
T = mean daily temperature over the month considered, °C
p = mean daily percentage of total annual daytime, hours

BLANEY-CRIDDLE METHOD

$$T_{max} = \frac{Sum\ of\ all\ T_{max}\ values\ during\ the\ month}{number\ of\ days\ of\ the\ month}$$

$$T_{min} = \frac{Sum\ of\ all\ T_{min}\ values\ during\ the\ month}{number\ of\ days\ of\ the\ month}$$

$$T_{mean} = \frac{T_{max} + T_{min}}{2}$$

Table 13. Mean daily percentage (p) of annual daytime hours for different latitudes

Latitude	North	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
	South	July	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June
60		0.15	0.2	0.26	0.32	0.38	0.41	0.4	0.34	0.28	0.22	0.17	0.13
55		0.17	0.21	0.26	0.32	0.36	0.39	0.38	0.33	0.28	0.23	0.18	0.16
50		0.19	0.23	0.27	0.31	0.34	0.39	0.35	0.32	0.28	0.24	0.2	0.18
45		0.2	0.23	0.27	0.3	0.34	0.35	0.34	0.32	0.28	0.24	0.21	0.2
40		0.22	0.24	0.27	0.3	0.32	0.34	0.33	0.31	0.28	0.25	0.22	0.21
35		0.23	0.25	0.27	0.29	0.31	0.32	0.32	0.3	0.28	0.25	0.23	0.22
30		0.24	0.25	0.27	0.29	0.31	0.32	0.31	0.3	0.28	0.26	0.24	0.23
25		0.24	0.26	0.27	0.29	0.3	0.31	0.31	0.29	0.28	0.26	0.25	0.24
20		0.25	0.26	0.27	0.28	0.29	0.3	0.3	0.29	0.28	0.26	0.25	0.25
15		0.26	0.26	0.27	0.28	0.29	0.29	0.29	0.28	0.28	0.27	0.26	0.25
10		0.27	0.27	0.27	0.28	0.28	0.29	0.29	0.28	0.28	0.27	0.26	0.26
5		0.27	0.27	0.27	0.28	0.28	0.28	0.28	0.28	0.28	0.27	0.27	0.27
0		0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27

Example 15

Calculate ET_o using Blaney-Criddle method if the T_{mean} is 28.0 °C for the month of November and latitude of 15.72 °N.

Latitude	North	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
	South	July	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June
60		0.15	0.2	0.26	0.32	0.38	0.41	0.4	0.34	0.28	0.22	0.17	0.13
55		0.17	0.21	0.26	0.32	0.36	0.39	0.38	0.33	0.28	0.23	0.18	0.16
50		0.19	0.23	0.27	0.31	0.34	0.39	0.35	0.32	0.28	0.24	0.2	0.18
45		0.2	0.23	0.27	0.3	0.34	0.35	0.34	0.32	0.28	0.24	0.21	0.2
40		0.22	0.24	0.27	0.3	0.32	0.34	0.33	0.31	0.28	0.25	0.22	0.21
35		0.23	0.25	0.27	0.29	0.31	0.32	0.32	0.3	0.28	0.25	0.23	0.22
30		0.24	0.25	0.27	0.29	0.31	0.32	0.31	0.3	0.28	0.26	0.24	0.23
25		0.24	0.26	0.27	0.29	0.3	0.31	0.31	0.29	0.28	0.26	0.25	0.24
20		0.25	0.26	0.27	0.28	0.29	0.3	0.3	0.29	0.28	0.26	0.25	0.25
15		0.26	0.26	0.27	0.28	0.29	0.29	0.29	0.28	0.28	0.27	0.26	0.25

For 15.72 °N latitude, **p = 0.26**

$$ET_O = p(0.46T + 8)$$

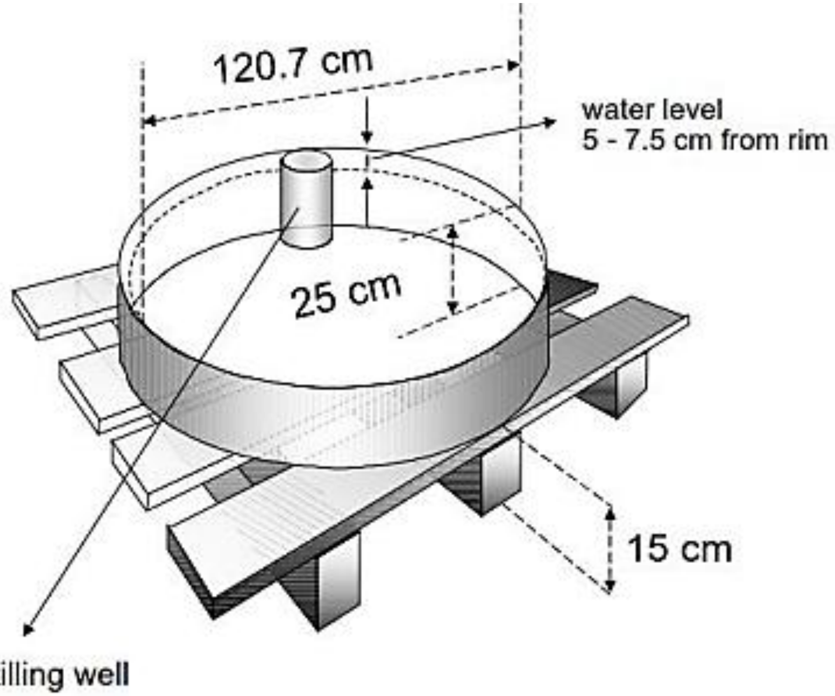
$$ET_O = 0.26(0.46 \times 28.0 + 8)$$

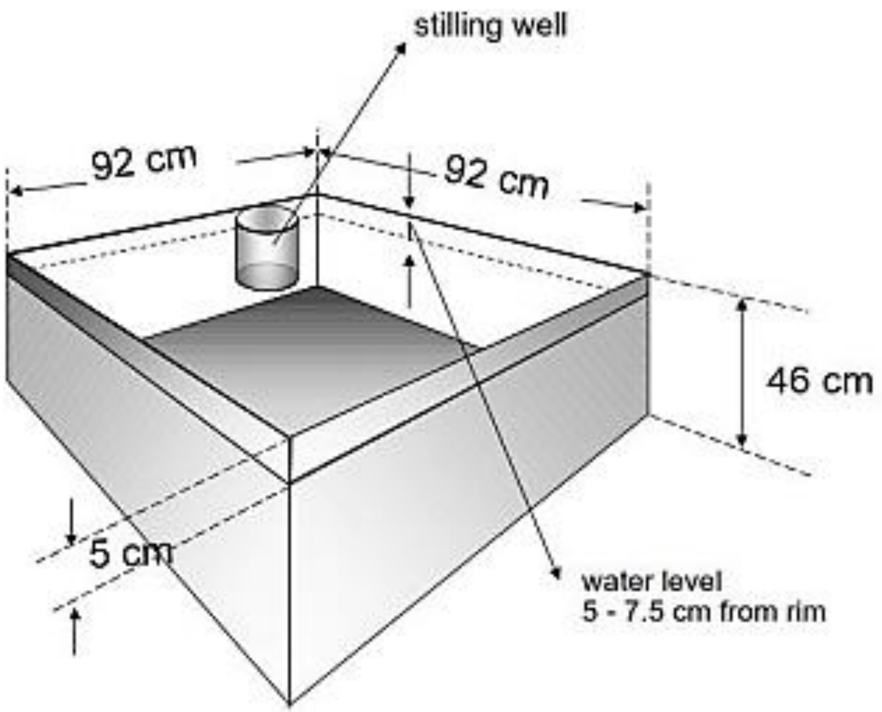
$$\boldsymbol{ET_O = 5.43\ mm\ day^{-1}}$$

Thus the mean reference crop evapotranspiration ET_o = 5.43 mm/day during the whole month of November.

PAN EVAPORATION METHOD

- Evaporation pans provide a measurement of the combined effect of temperature, humidity, windspeed and sunshine on the reference crop evapotranspiration Et_o.





Principle of Evaporation Pan

1. The pan is installed in the field
2. The pan is filled with a known quantity of water
3. The water is allowed to evaporate during a certain period of time (usually 24 hours)
4. After 24 hours, the remaining quantity of water (i.e. water depth) is measured
5. The amount of evaporation per time unit is calculated; this is the pan evaporation: E_{pan} (in mm/24 hours)
6. The E_{pan} is multiplied by a pan coefficient, K_{pan}, to obtain the ET_o

$$ET_O = K_{pan} \times E_{pan}$$

Where: E_{pan} = pan evaporation, represents the mean daily value of the period considered, mm day^{-1}

K_p = pan coefficient

For the Class A evaporation pan, the K_{pan} varies between 0.35 and 0.85. Average K_{pan} = 0.70

For the Sunken Colorado pan, the K_{pan} varies between 0.45 and 1.10. Average K_{pan} = 0.80

The K_{pan} is high if

- the pan is placed in a fallow area
- the humidity is high (i.e. humid)
- the windspeed is low

The K_{pan} is high if

- the pan is placed in a cropped area
- the humidity is low (i.e. dry)
- the windspeed is high

Class A pan	Case A: Pan placed in short green cropped area				Case B: Pan placed in dry fallow area			
RH mean (%) →		low < 40	medium 40-70	high > 70		low < 40	medium 40-70	high > 70
Wind speed (m/s)	Windward side distance of green crop (m)				Windward side distance of dry fallow (m)			
Light < 2	1	0.55	0.65	0.75	1	0.7	0.8	0.85
	10	0.65	0.75	0.85	10	0.6	0.7	0.8
	100	0.7	0.8	0.85	100	0.55	0.65	0.75
	1000	0.75	0.85	0.85	1000	0.5	0.6	0.7
Moderate 2 to 5	1	0.5	0.6	0.65	1	0.65	0.75	0.8
	10	0.6	0.7	0.75	10	0.55	0.65	0.7
	100	0.65	0.75	0.8	100	0.5	0.6	0.65
	1000	0.7	0.8	0.8	1000	0.45	0.55	0.6
Strong 5 to 8	1	0.45	0.5	0.6	1	0.6	0.65	0.7
	10	0.55	0.6	0.65	10	0.5	0.55	0.65
	100	0.6	0.65	0.7	100	0.45	0.5	0.6
	1000	0.65	0.7	0.75	1000	0.4	0.45	0.55
Very Strong > 8	1	0.4	0.45	0.5	1	0.5	0.6	0.65
	10	0.45	0.55	0.6	10	0.45	0.5	0.55
	100	0.5	0.6	0.65	100	0.4	0.45	0.5
	1000	0.55	0.6	0.65	1000	0.35	0.4	0.45

Table 14. Pan coefficients (K_p) for Class A pan for different pan siting and environment and different levels of mean relative humidity and wind speed

Sunken Colorado	Case A: Pan placed in short green cropped area				Case B: Pan placed in dry fallow area			
RH mean (%) →		low < 40	medium 40-70	high > 70		low < 40	medium 40-70	high > 70
Wind speed (m/s)	Windward side distance of green crop (m)				Windward side distance of dry fallow (m)			
Light < 2	1	0.75	0.75	0.8	1	1.1	1.1	1.1
	10	1	1	1	10	0.85	0.85	0.85
	≥ 100	1.1	1.1	1.1	100	0.75	0.75	0.8
					1000	0.7	0.7	0.75
Moderate 2 to 5	1	0.65	0.7	0.7	1	0.95	0.95	0.95
	10	0.85	0.85	0.9	10	0.75	0.75	0.75
	≥ 100	0.95	0.95	0.95	100	0.65	0.65	0.7
					1000	0.6	0.6	0.65
Strong 5 to 8	1	0.55	0.6	0.65	1	0.8	0.8	0.8
	10	0.75	0.75	0.75	10	0.65	0.65	0.65
	≥ 100	0.8	0.8	0.8	100	0.55	0.6	0.65
					1000	0.5	0.55	0.6
Very Strong > 8	1	0.5	0.55	0.6	1	0.7	0.75	0.75
	10	0.65	0.7	0.7	10	0.55	0.6	0.65
	≥ 100	0.7	0.75	0.75	100	0.5	0.55	0.6
					1000	0.45	0.5	0.55

Table 15. Pan coefficients (K_p) for Colorado sunken panfor different pan siting and environment and different levels of mean relative humidity and wind speed

Example 16

Determine the reference evapotranspiration using pan evaporation method given the following data:

Type of pan: Class A evaporation pan

Water depth in pan on day 1 = 150 mm

Water depth in pan on day 2 = 144 mm

Rainfall (during 24 hours) = 0 mm

K_{pan} = 0.75

$$E_{pan} = 150\ mm - 144\ mm$$

$$E_{pan} = 6\ mm/day$$

$$ET_O = K_{pan} \times E_{pan}$$

$$ET_O = 0.75 \times 6\ mm/day$$

$$\boldsymbol{ET_O = 4.5\ mm/day}$$