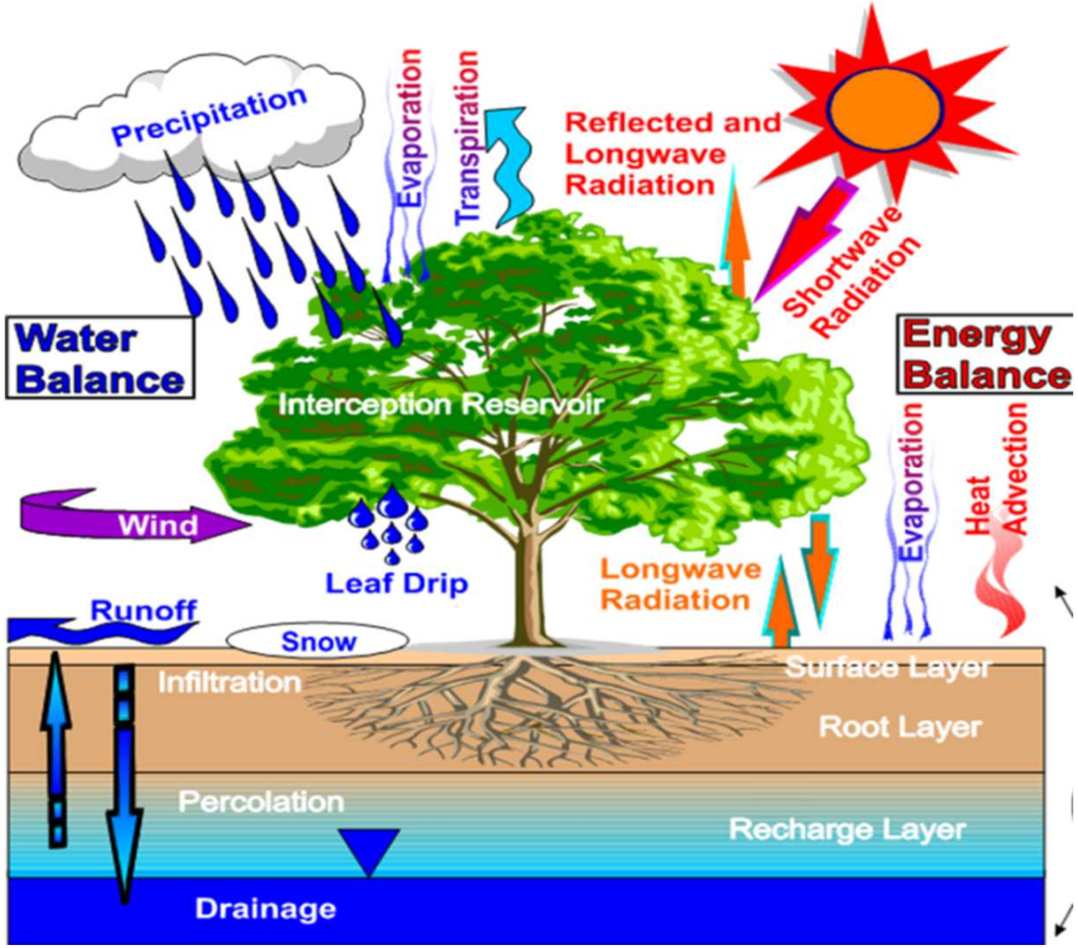
Spatial Tools in Water Resource Management

Wim Bastiaanssen

5. Basic physics of remote sensing and the surface energy balance

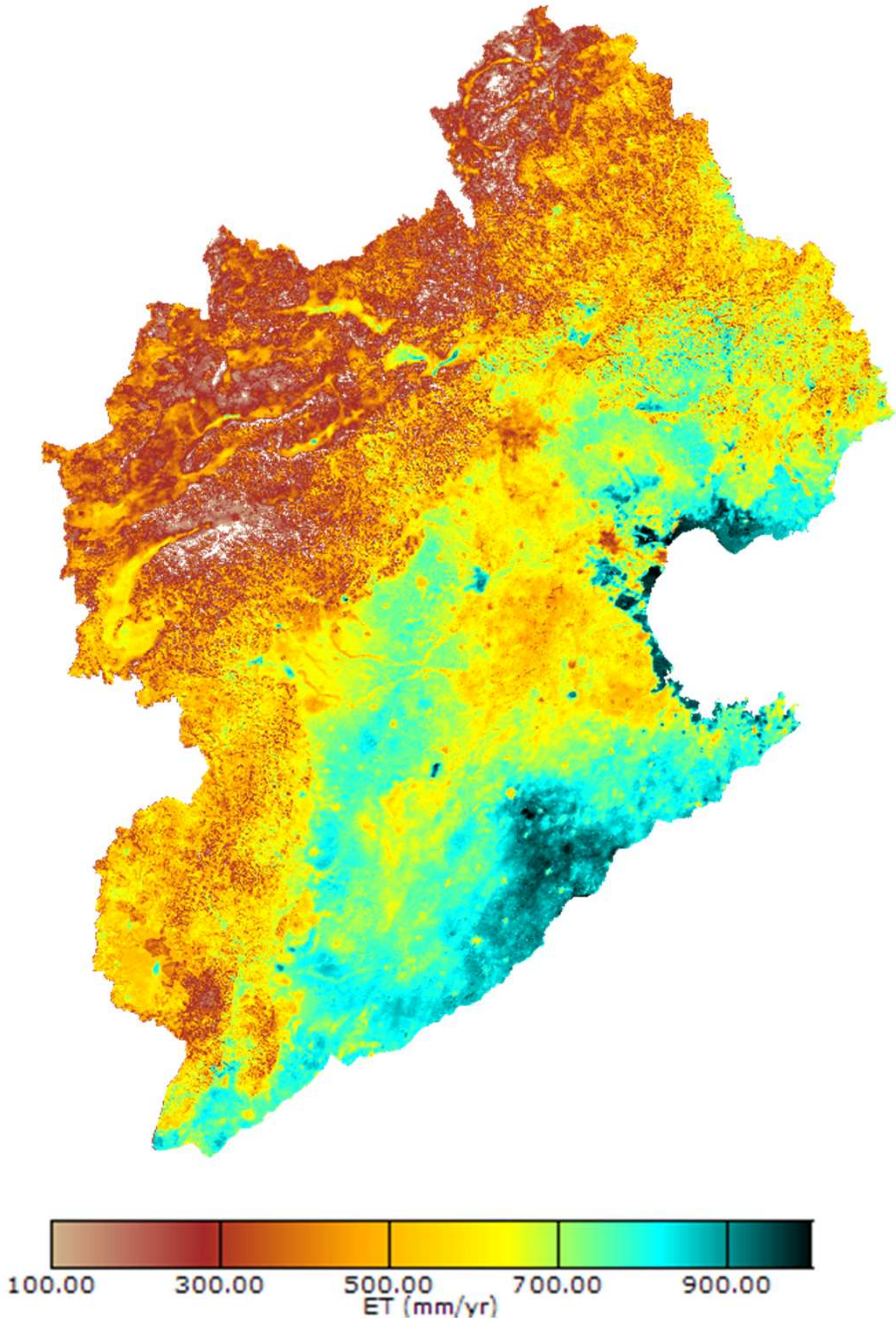
Pixel Intelligence (PI) – Mapping Technology



[1]

PI Mapping computes the water, energy, radiation and heat balance of vegetated land surfaces

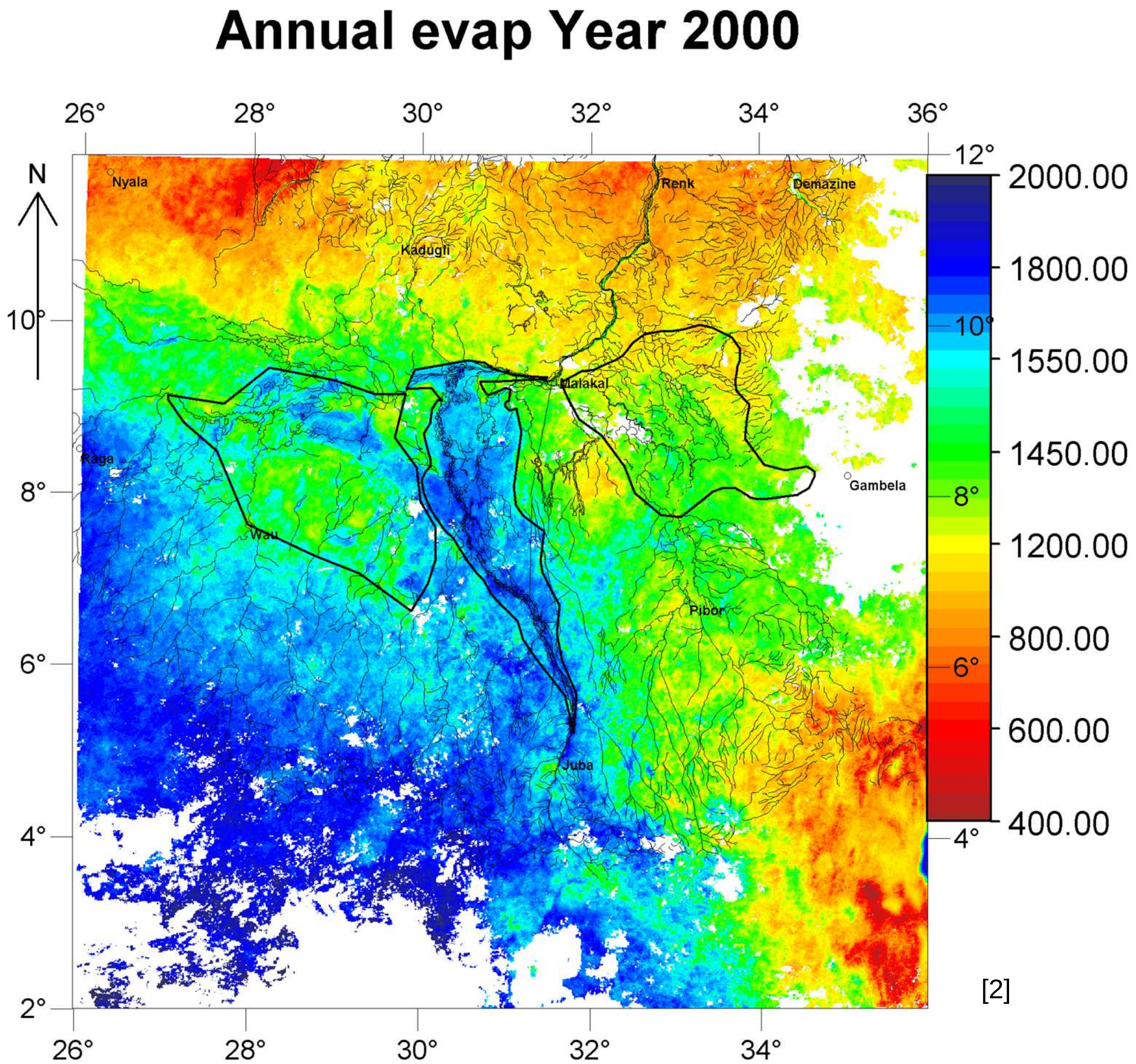
Annual ET Hai Basin 2003



Hai basin

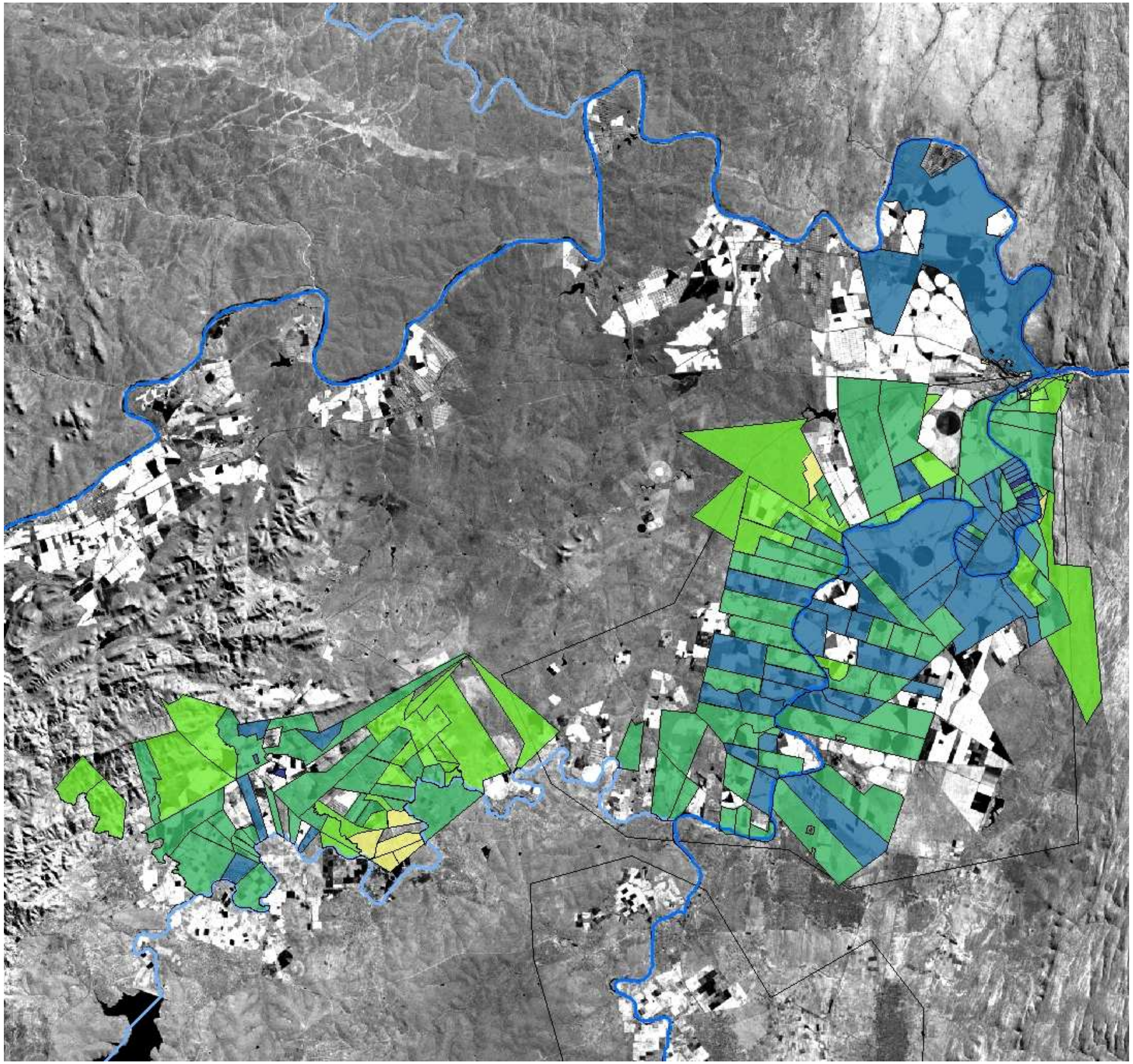
China

Wetland ET (Sudd and adjoining marshes)



[2]

Estimate water use per plot



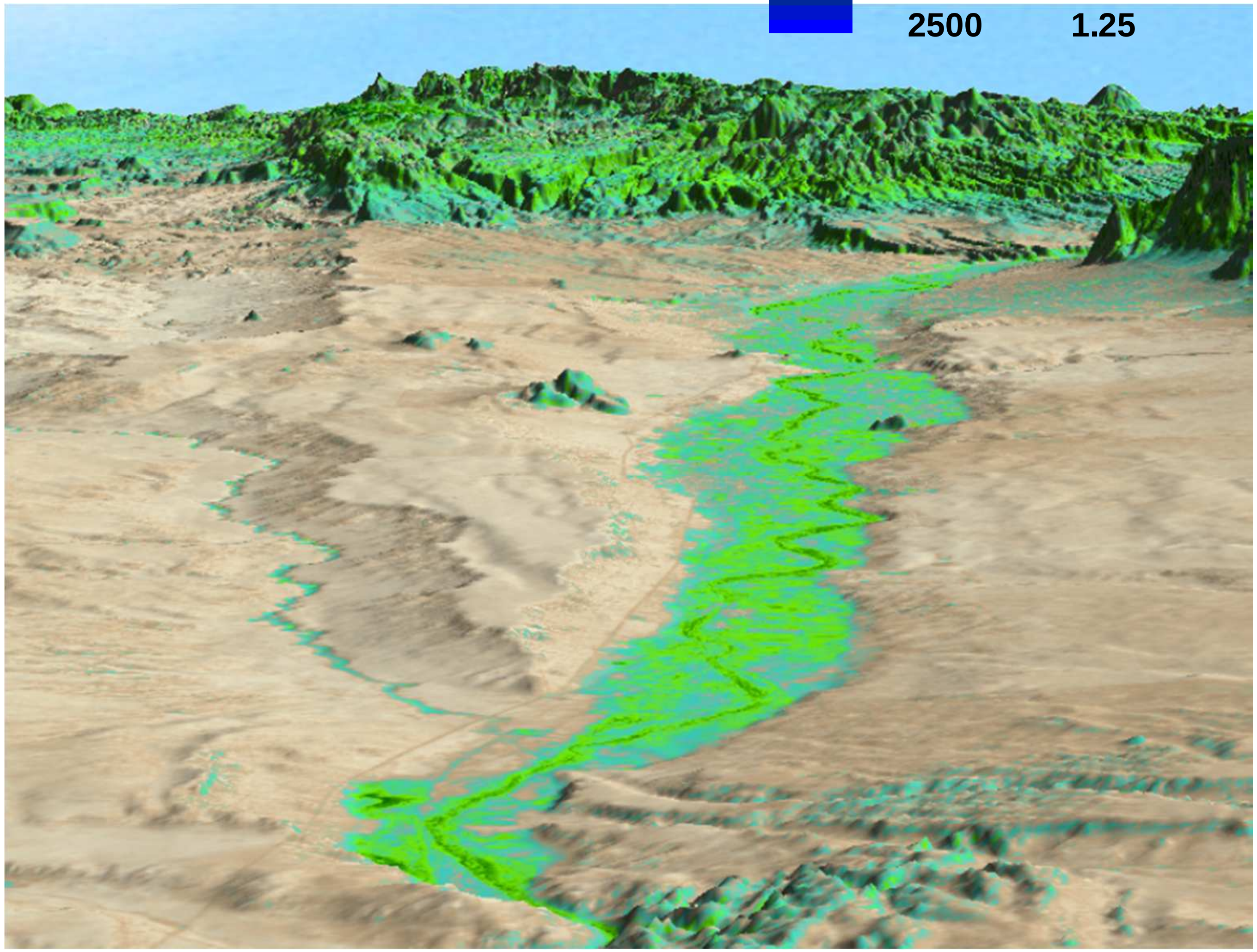
Avg ETa per plot

mm

- 501 - 750
- 751 - 900
- 901 - 1,050
- 1,051 - 1,200
- 1,201 - 1,350

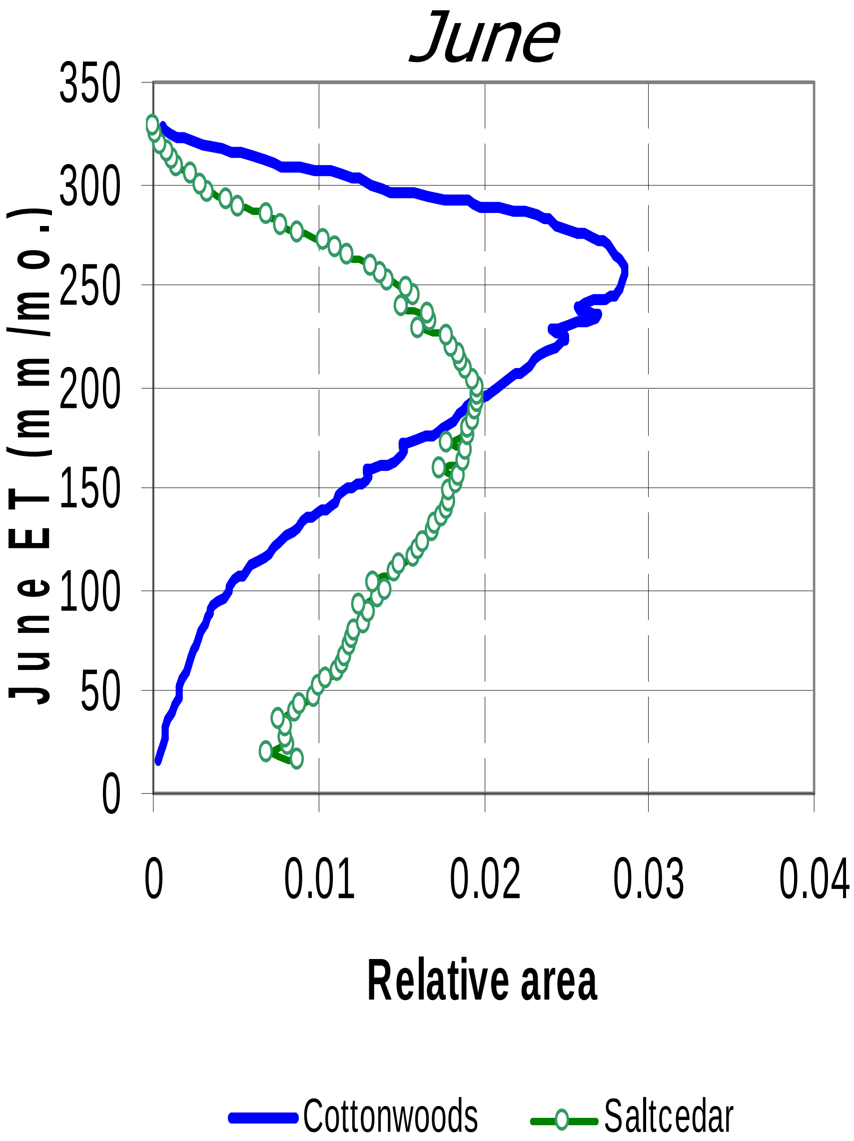
METRIC applications

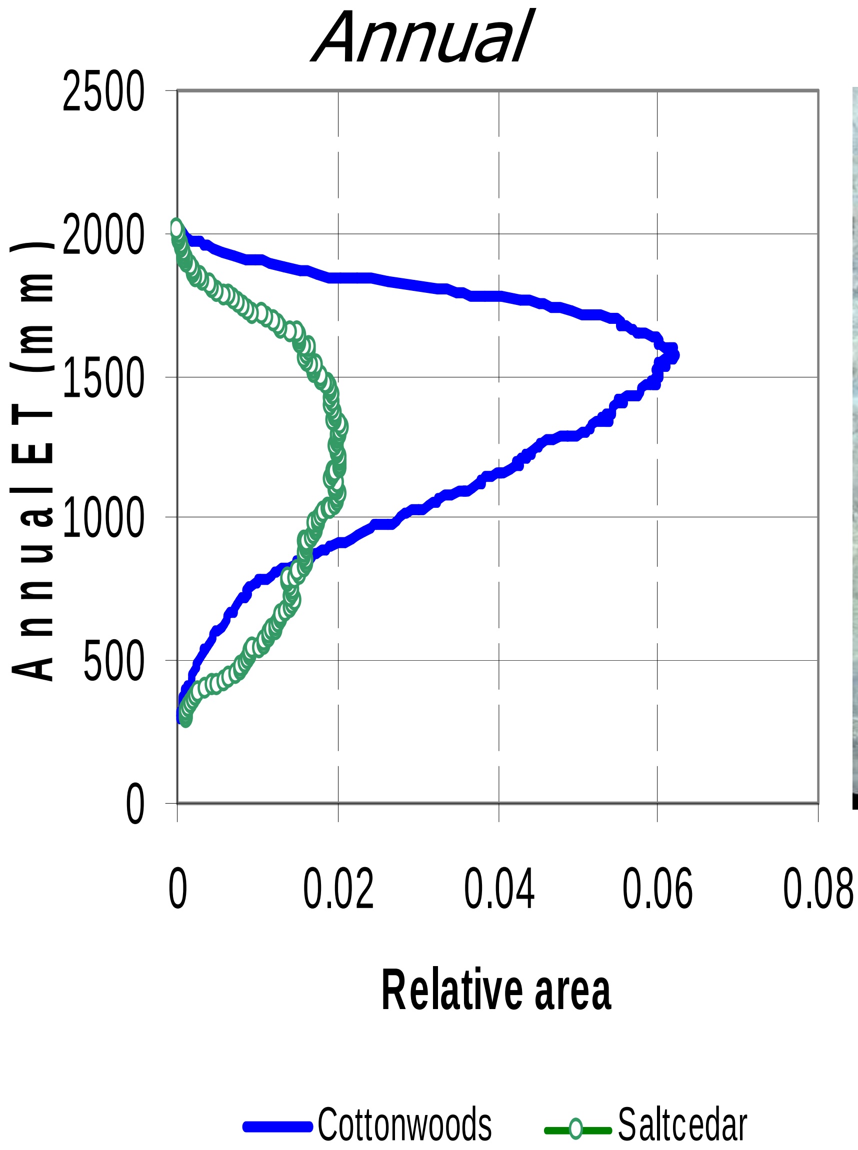
Middle Rio Grande of New Mexico



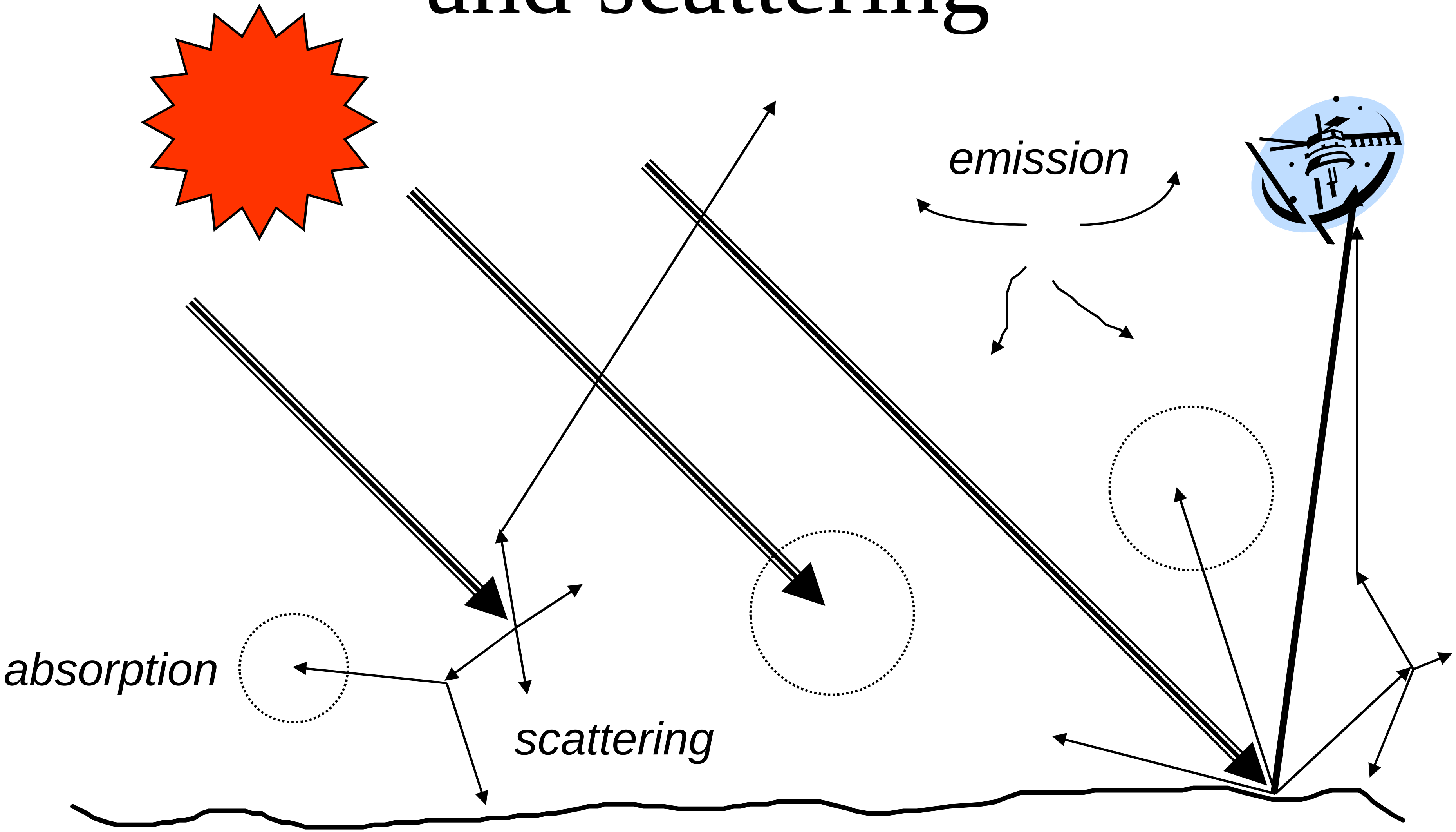
Frequency Distribution of ET

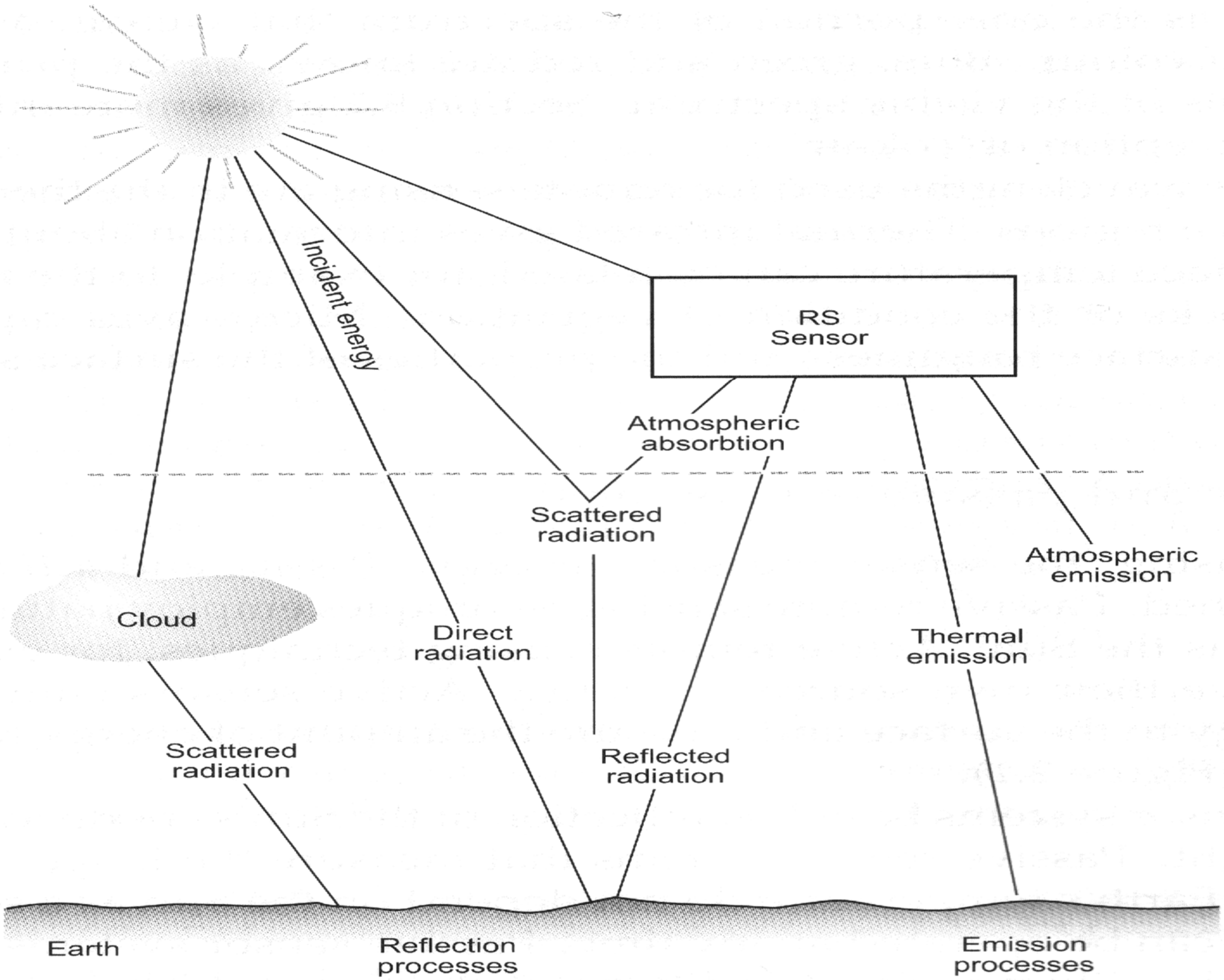
15,000 acres of cottonwood and salt cedar

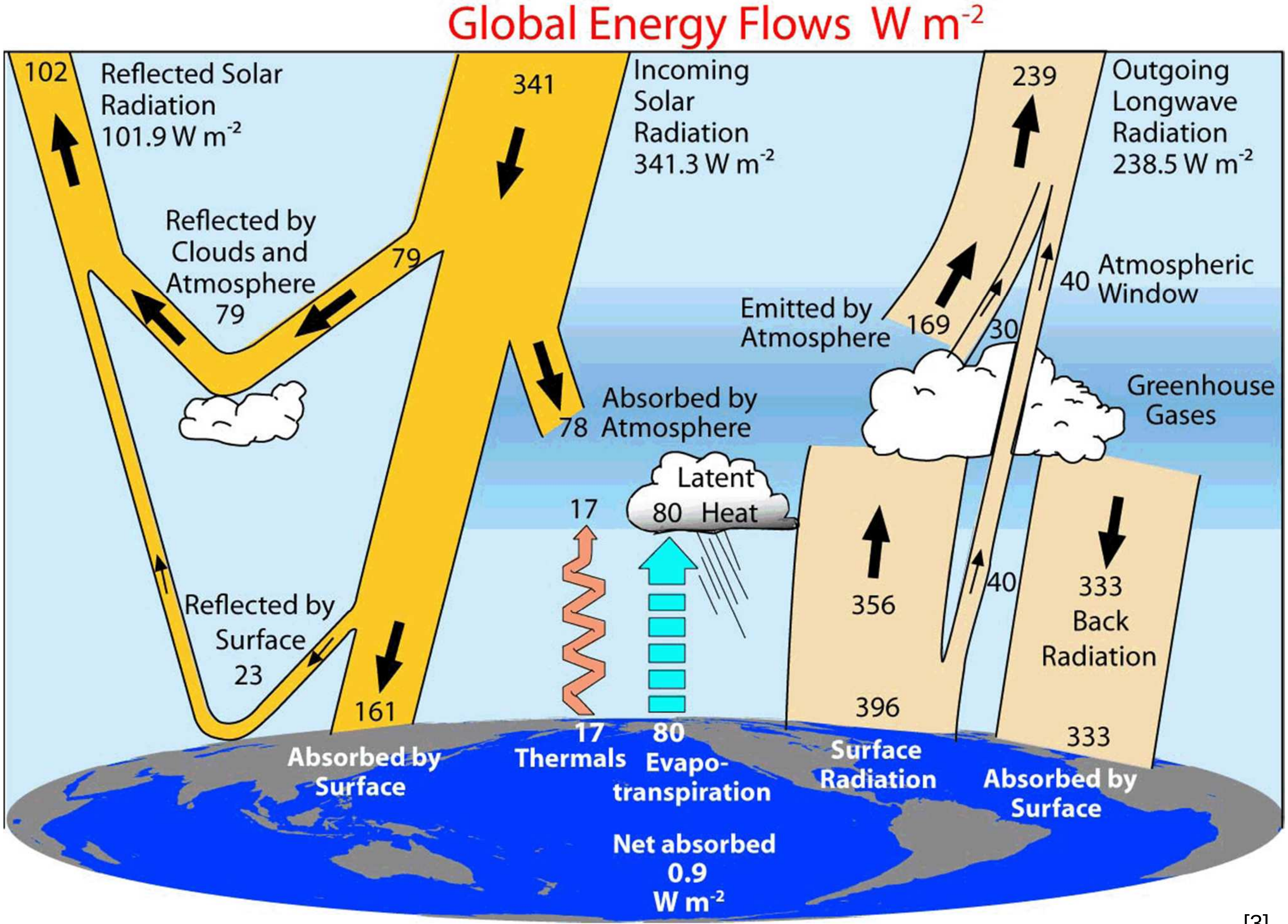




Atmospheric absorption and scattering

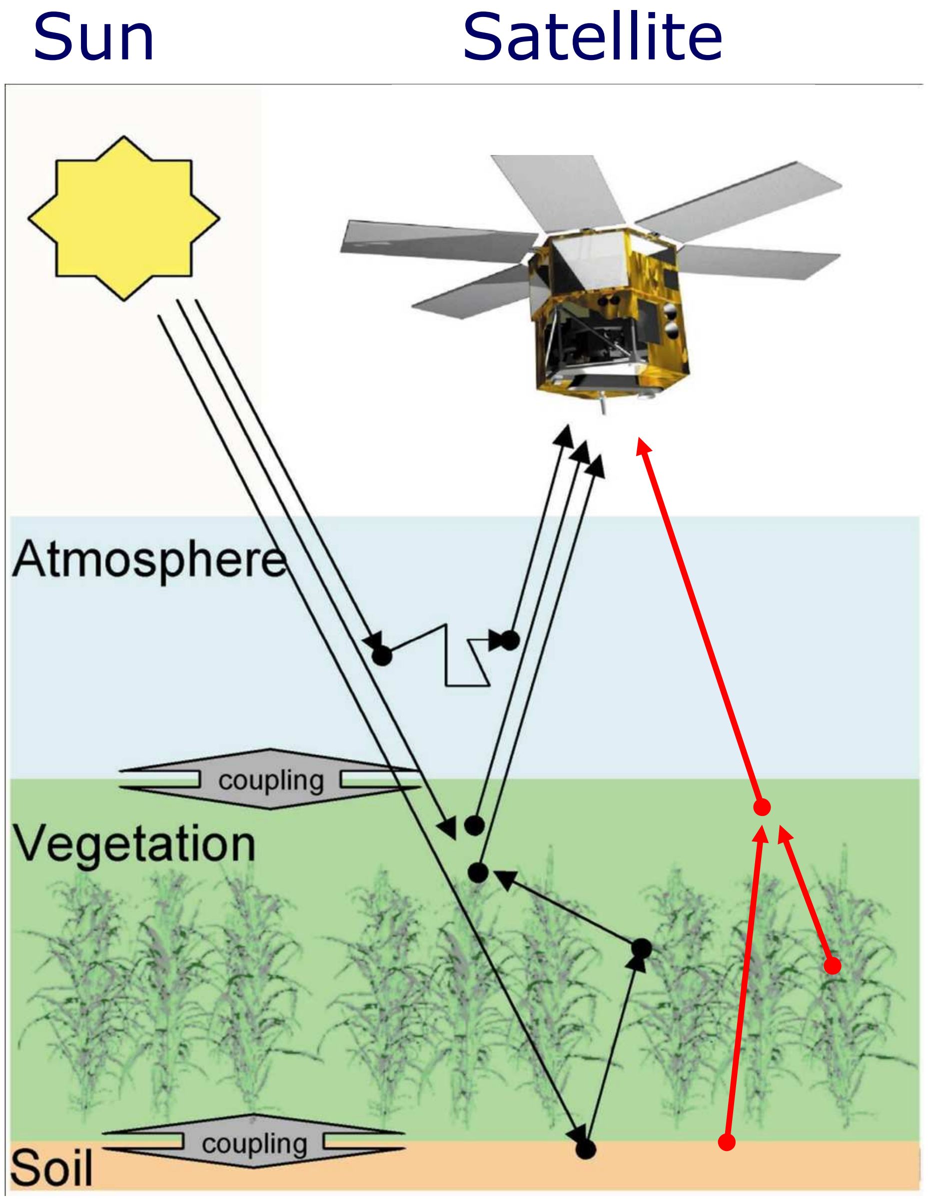



Incident energy
RS
Sensor
Atmospheric
absorbtion
Scattered
radiation
Atmospheric
emission
Cloud
Direct
radiation
Thermal
emission
Scattered
radiation
Reflected
radiation
Earth
Reflection
processes
Emission
processes


Global Energy Flows W m-2
102
Reflected Solar Radiation 101.9 W m-2
341
Incoming Solar Radiation 341.3 W m-2
239
Outgoing Longwave Radiation 238.5 W m-2
Reflected by Clouds and Atmosphere 79
79
40 Atmospheric Window
Emitted by Atmosphere
169
30
Greenhouse Gases
78 Absorbed by Atmosphere
Latent 80 Heat
17
Reflected by Surface 23
356
40
333 Back Radiation
396
333
161
17 Thermals
80 Evapo-transpiration
Absorbed by Surface
Surface Radiation
Absorbed by Surface
Net absorbed 0.9 W m-2

[3]

Remote Sensing



Two sources of radiation:

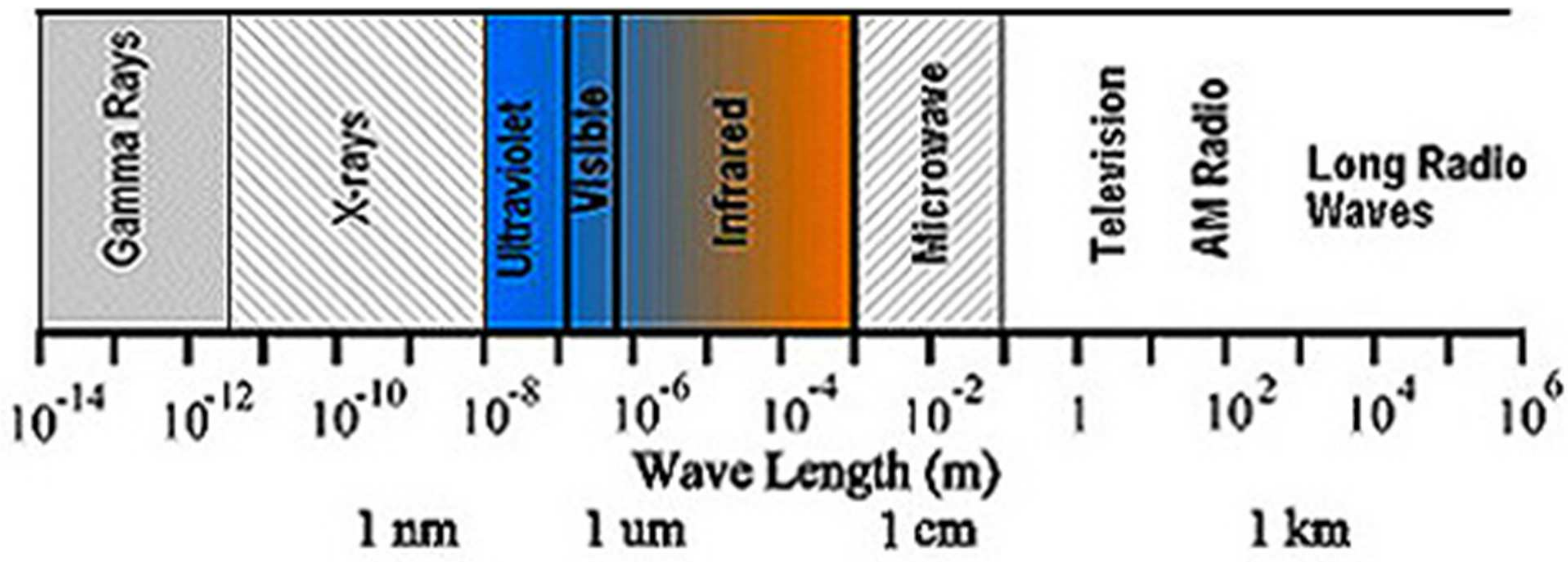
Solar radiation

- visible
- near infrared
- short-wave infrared

Earth Surface

- thermal infrared
- microwave

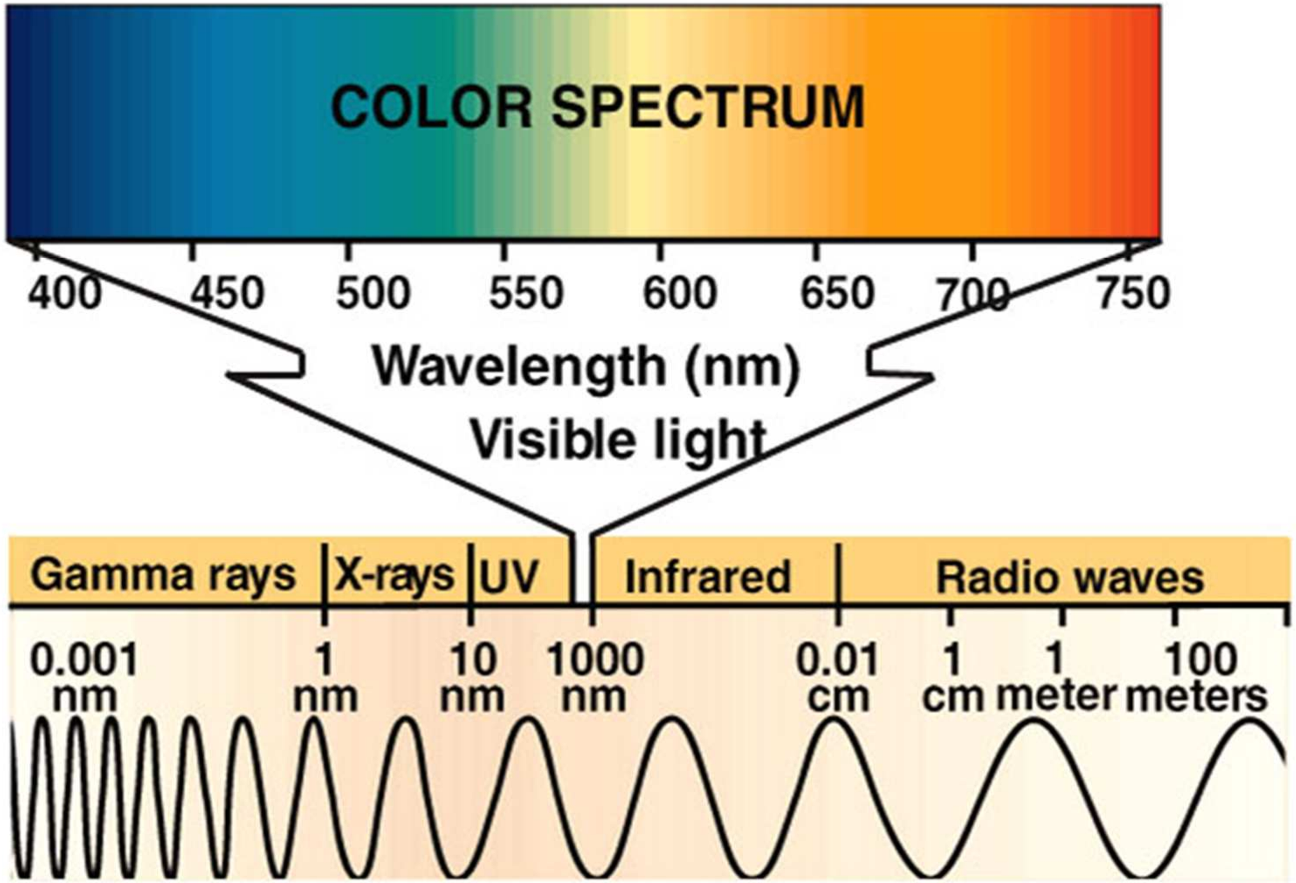
What can remote sensing measure?



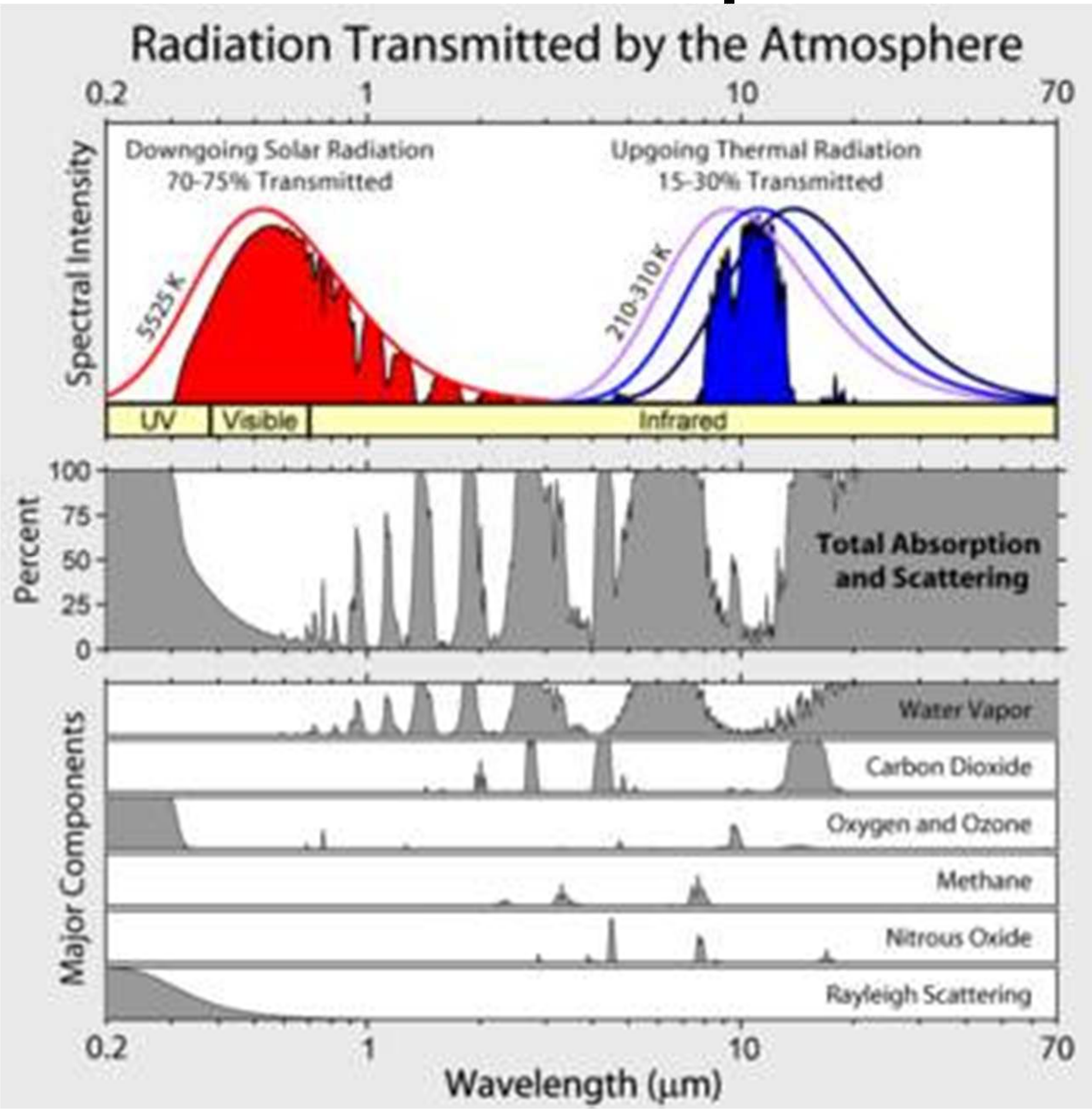
[4]

- Optical wavelength region:
- Reflective: visible [0.38 – 0.72 μm]
- near infrared [0.72-1.30 μm]
- middle infrared [1.30-3.00 μm]
- Thermal, Emissive: far infrared [7.00-15.0 μm]

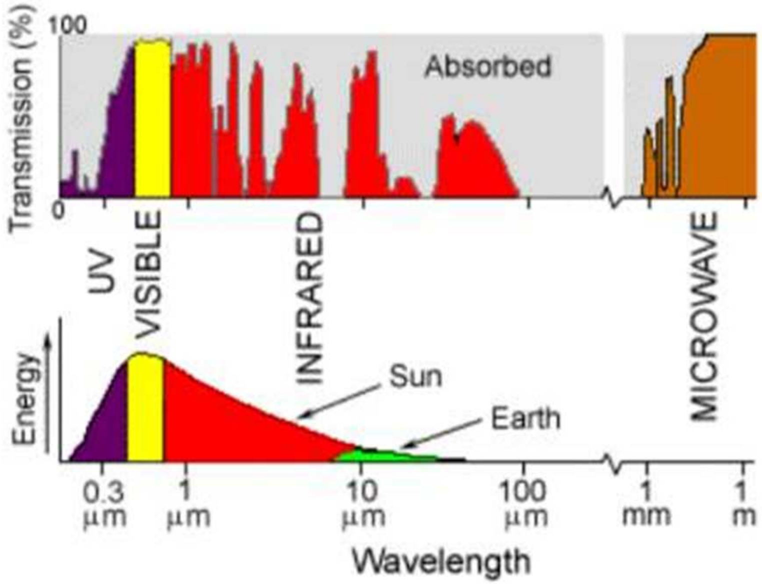
Visible spectrum



Atmospheric windows



[5]



[6]

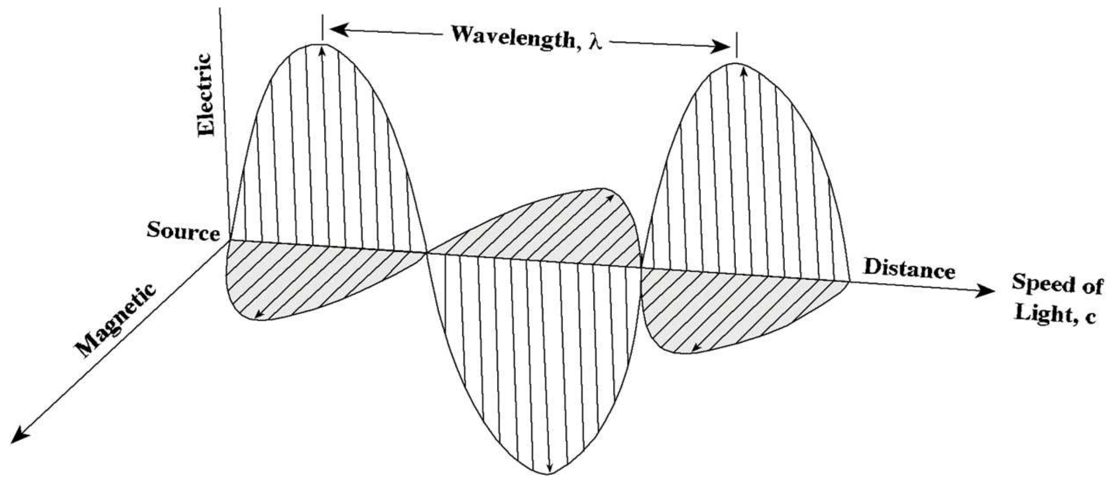
Relation between frequency and wavelength

$$c = \lambda \upsilon, \text{ so } \upsilon = \frac{c}{\lambda} \text{ and } \lambda = \frac{c}{\upsilon}$$

c speed of light, m/s

λ wavelength, m (but we often use μm or nm)

υ frequency, Hz (s^{-1})



Frequency-wavelength relation

- Generally in the microwave part of the spectrum we use frequency instead of wavelength
- Typically measured in s^{-1}, called *Hertz* (Hz)
  - Most often Gigahertz (GHz) = 10^9Hz

$$\text{Frequency } \nu = \frac{c}{\lambda}$$

$$\text{where } c = \text{speed of light}$$

$$= 3.00 \times 10^8 \text{ m s}^{-1}$$

Planck equation, details

Planck's equation (the spectral curves shown)

$$L_\lambda = \frac{2hc^2}{\lambda^5\left(e^x - 1\right)}, \text{ where } x = \frac{hc}{k\lambda T}$$

Stefan-Boltzmann equation

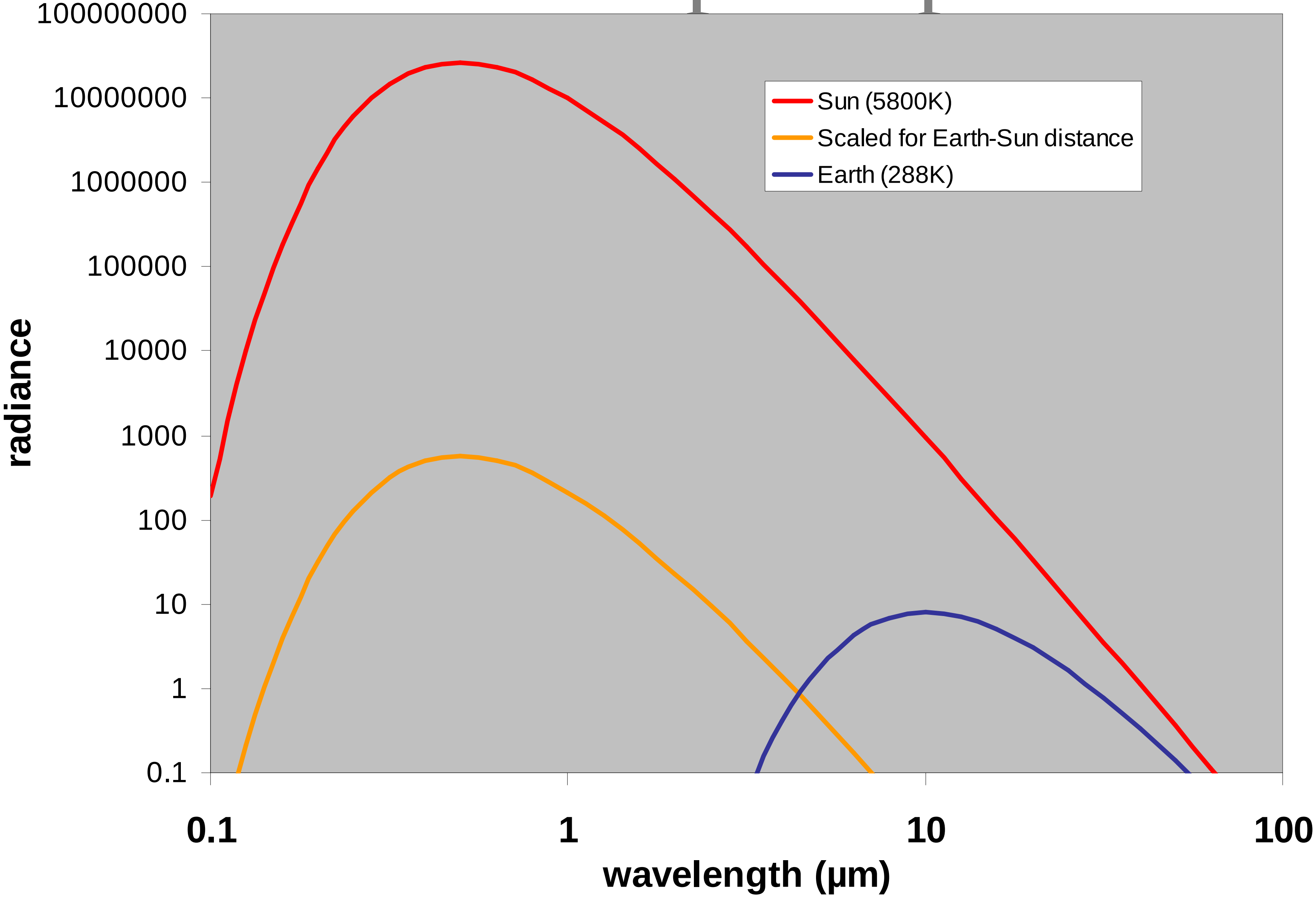
$$E = \pi\int_0^\infty L_\lambda d\lambda = \sigma T^4$$

Wien's displacement equation

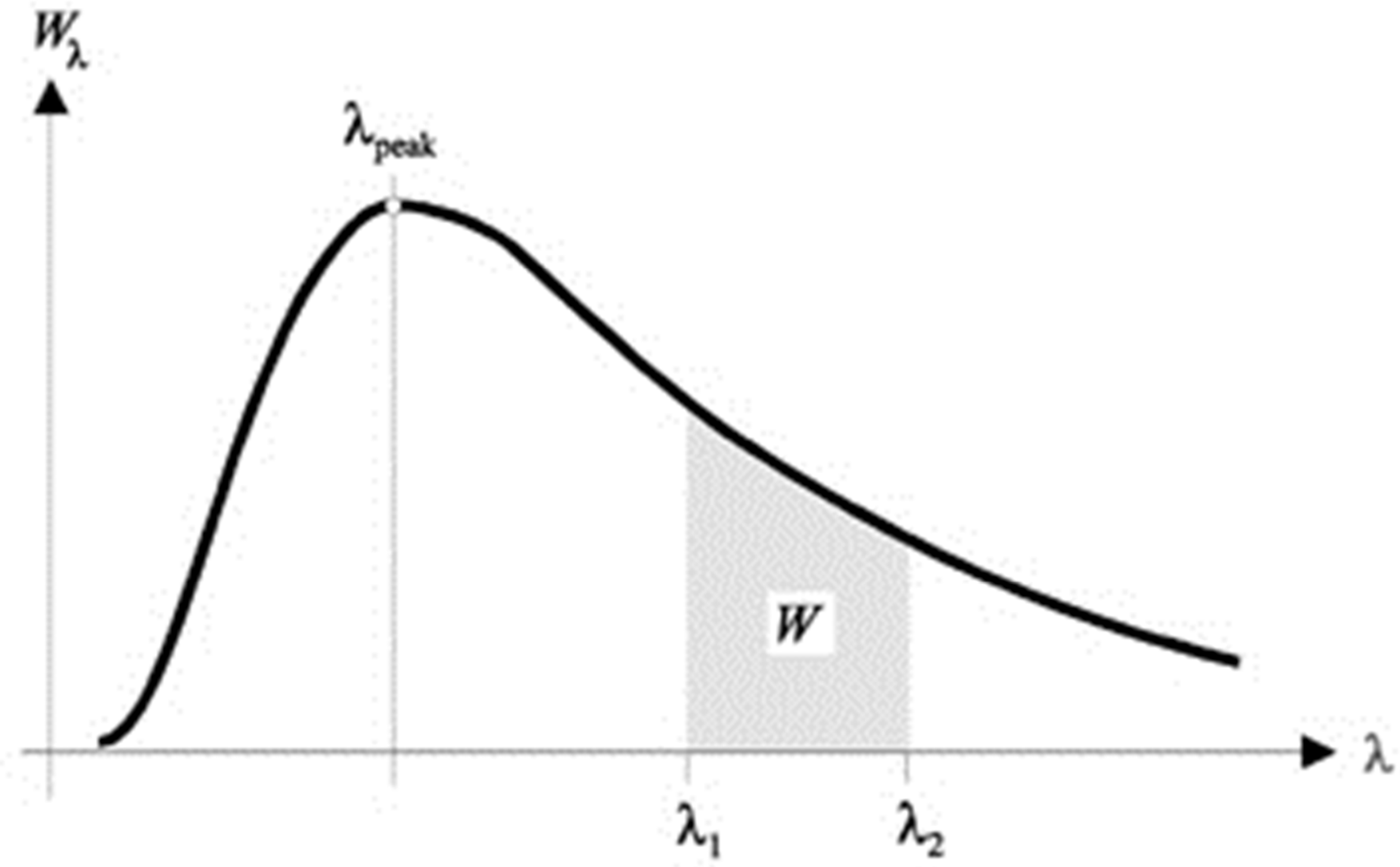
$$\lambda_{\max}(\mu\text{m}) = \frac{2897}{T}$$

c	speed of light	$3.00\times10^{8}\ \text{ms}^{-1}$
h	Planck's constant	$6.63\times10^{-34}\text{Js}$
k	Boltzmann's constant	$1.38\times10^{-23}\text{JK}^{-1}$
σ	Stefan-Boltzmann constant	$5.67\times10^{-8}\text{Wm}^{-2}\text{K}^{-4}$
L_λ	Spectral radiance	$\text{Wm}^{-2}\text{m}^{-1}\text{sr}^{-1}$

Radiation principles

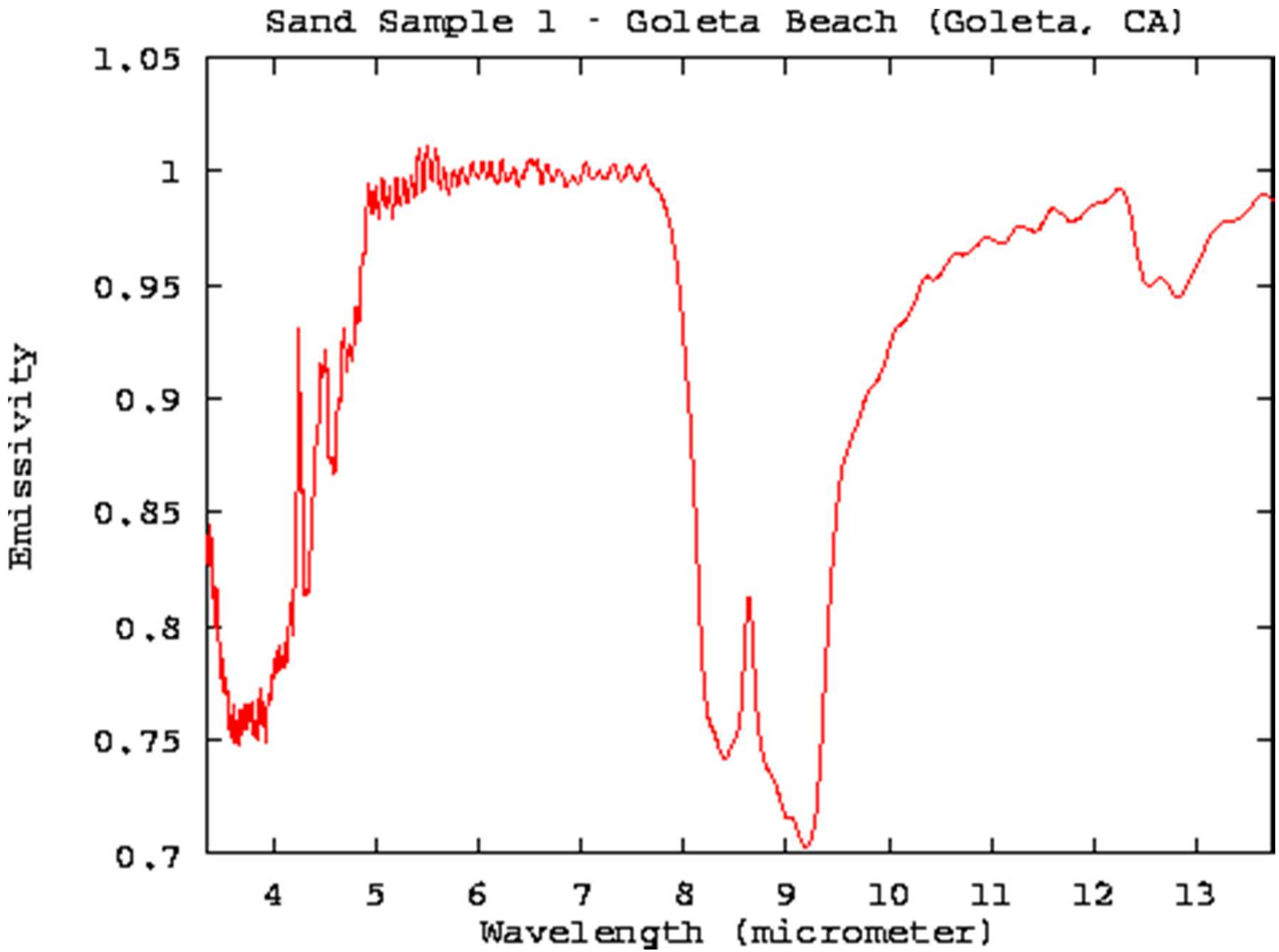


Spectral integration (narrow to broad band)

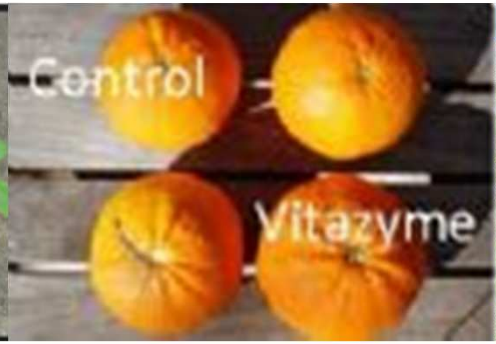


$$L = \varepsilon L_{\lambda}$$

Spectral emissivity library



Crop status and radiative behavior (1)



[7]

[8]

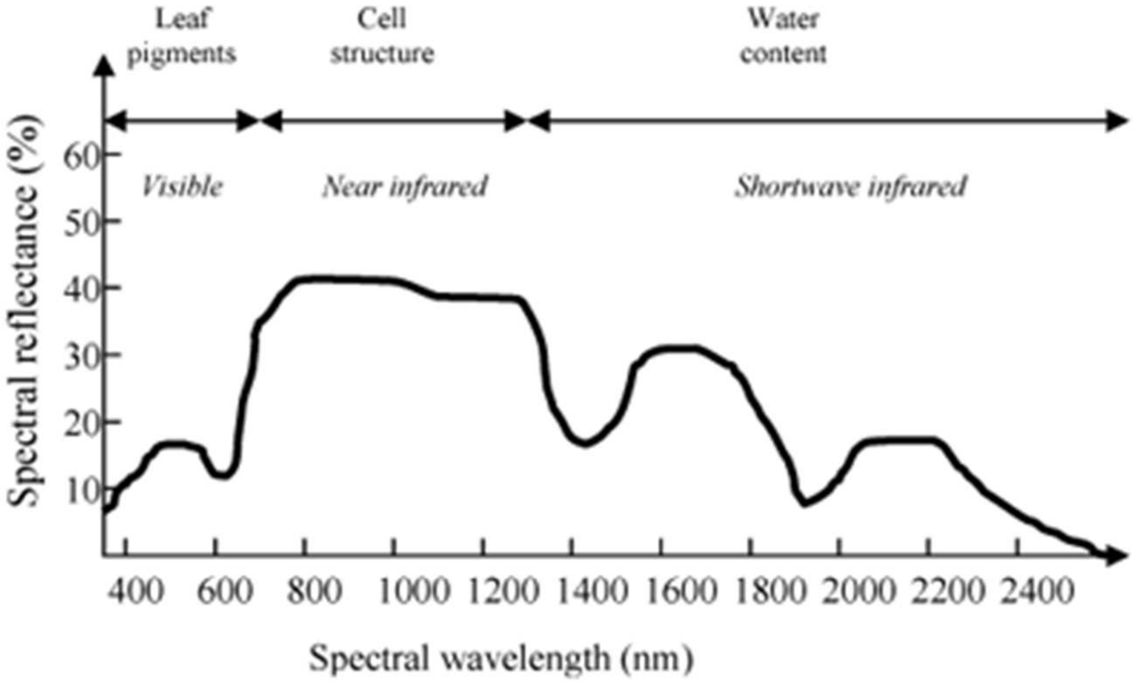
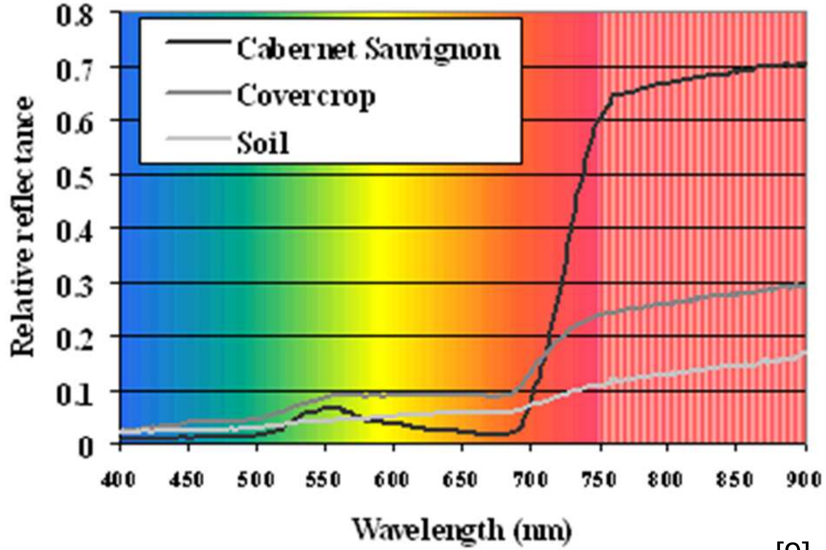


Figure 1
Typical reflectance sensitivities as controlled by leaf pigments, cell structure and water content (adapted from Gaussman, 1977)



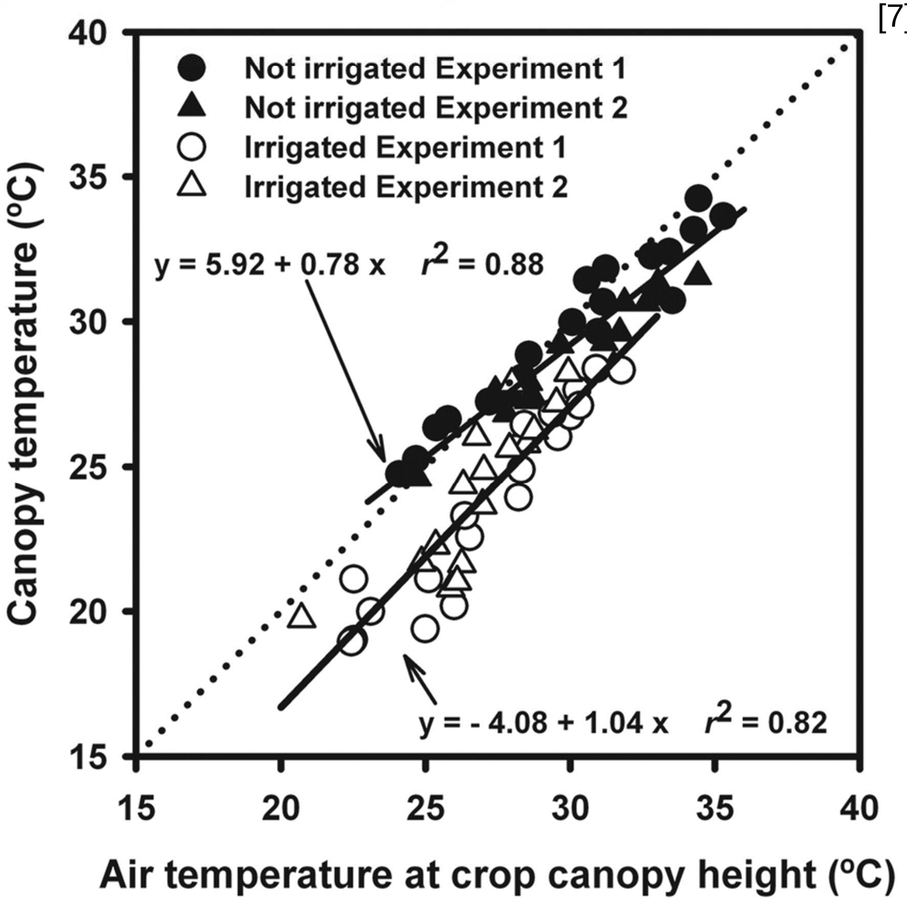
[9]

Crop health affects reflectivity, emissivity, temperature etc.

Crop status and radiative behavior (2)

[7]

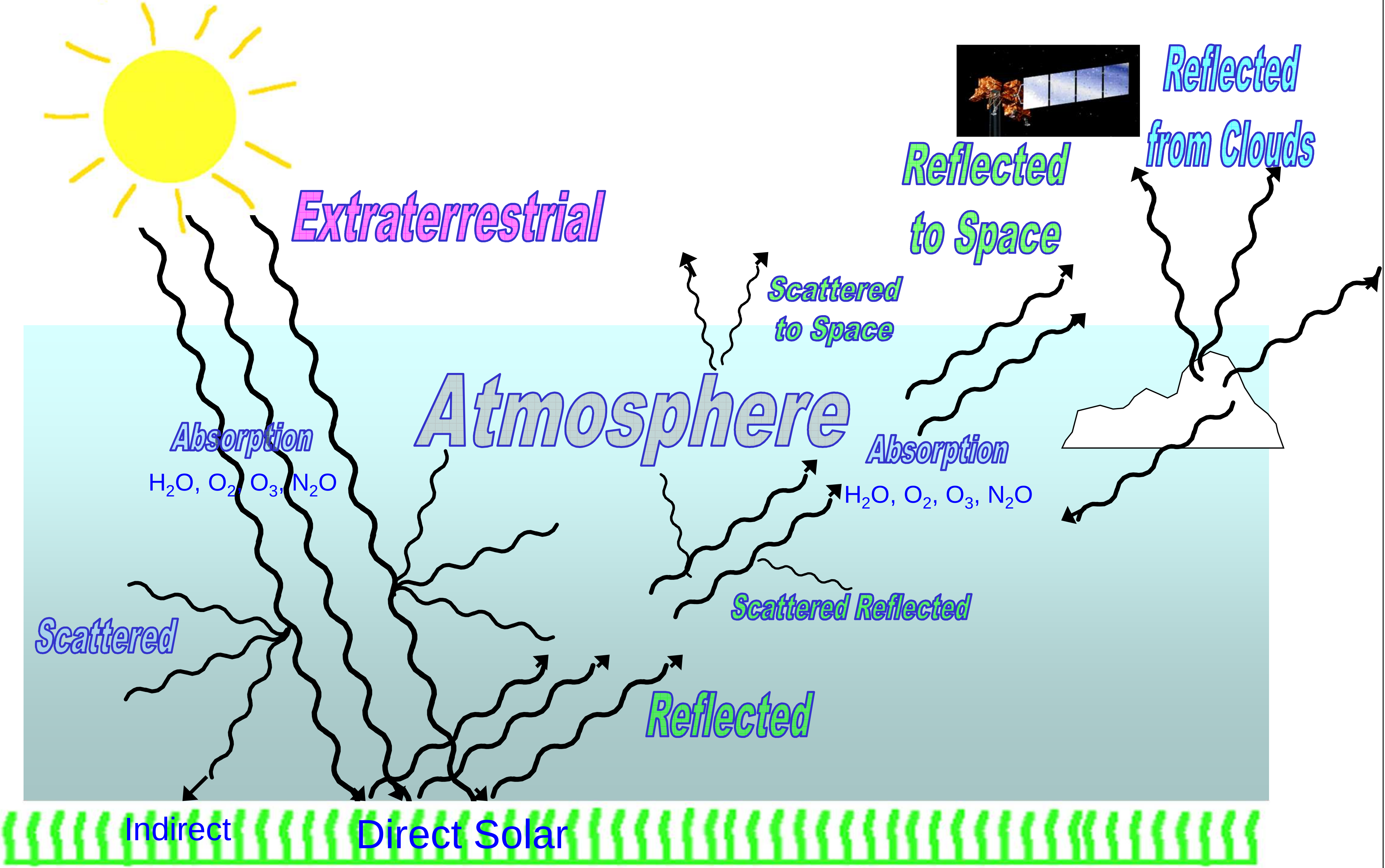
[8]



[10]

Crop health affects reflectivity, emissivity, temperature etc.

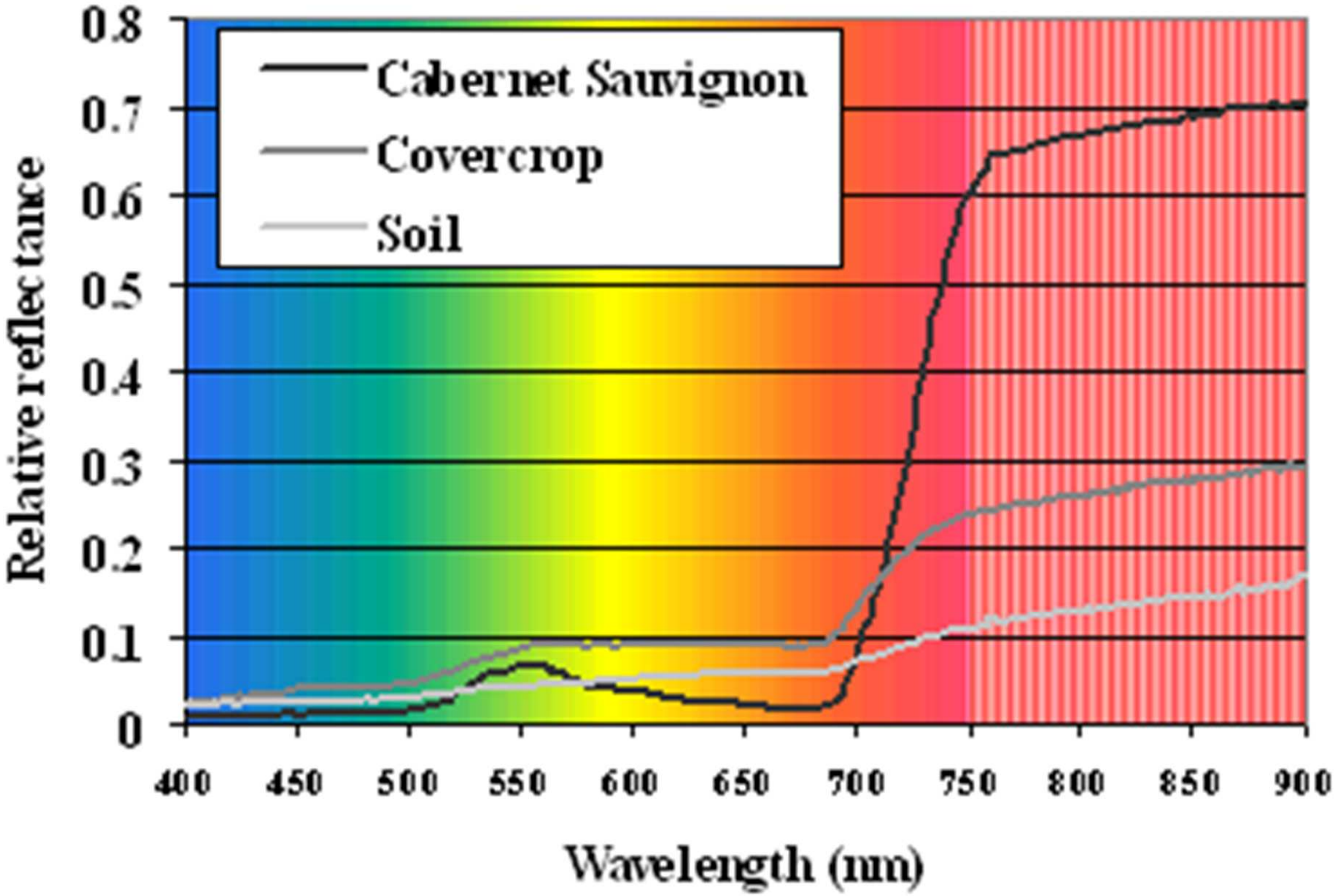
Disposition of Solar Radiation in the Atmosphere



$$\rho_{s,b} = \frac{\rho_{t,b} - \rho_{a,b}}{\tau_{in,b} \cdot \tau_{out,b}}$$

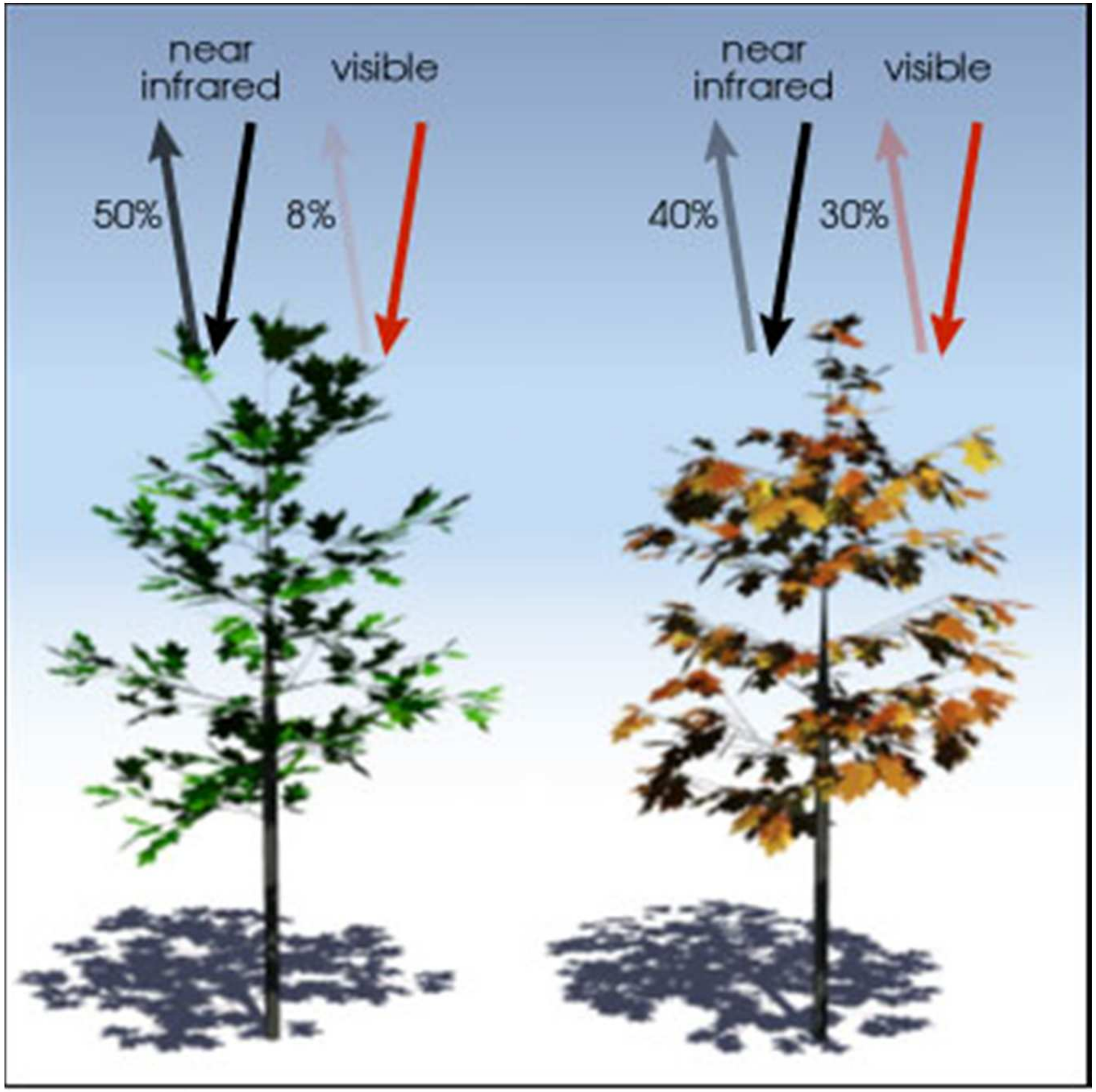
$$\tau_{in,b} = C_1 \exp\left[\frac{C_2 \cdot P_{air}}{K_t \cos\theta_h} - \frac{C_3 W + C_4}{\cos\theta_h}\right] + C_5$$

Spectral reflectance



[9]

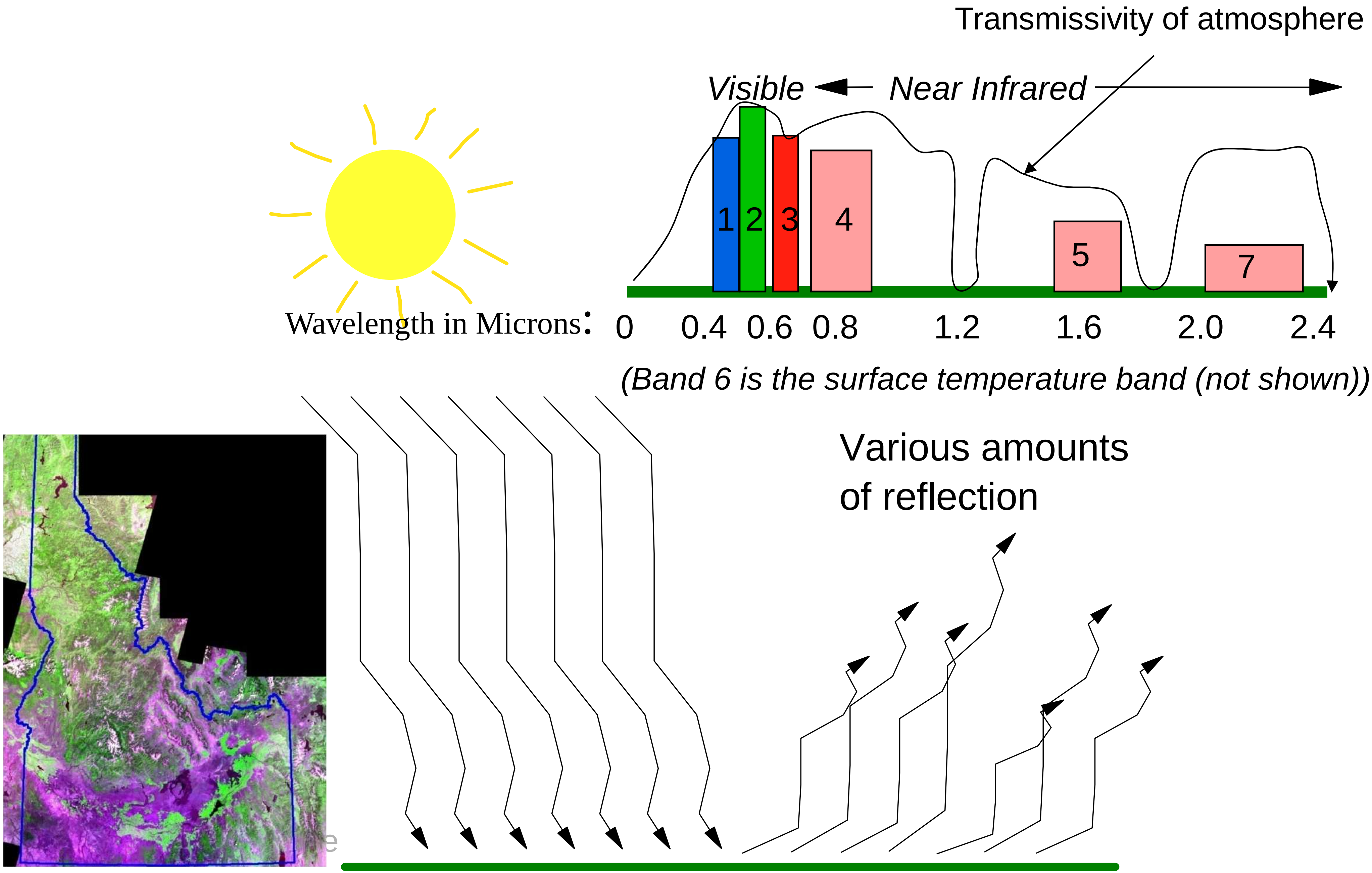
Normalized Difference Vegetation Index



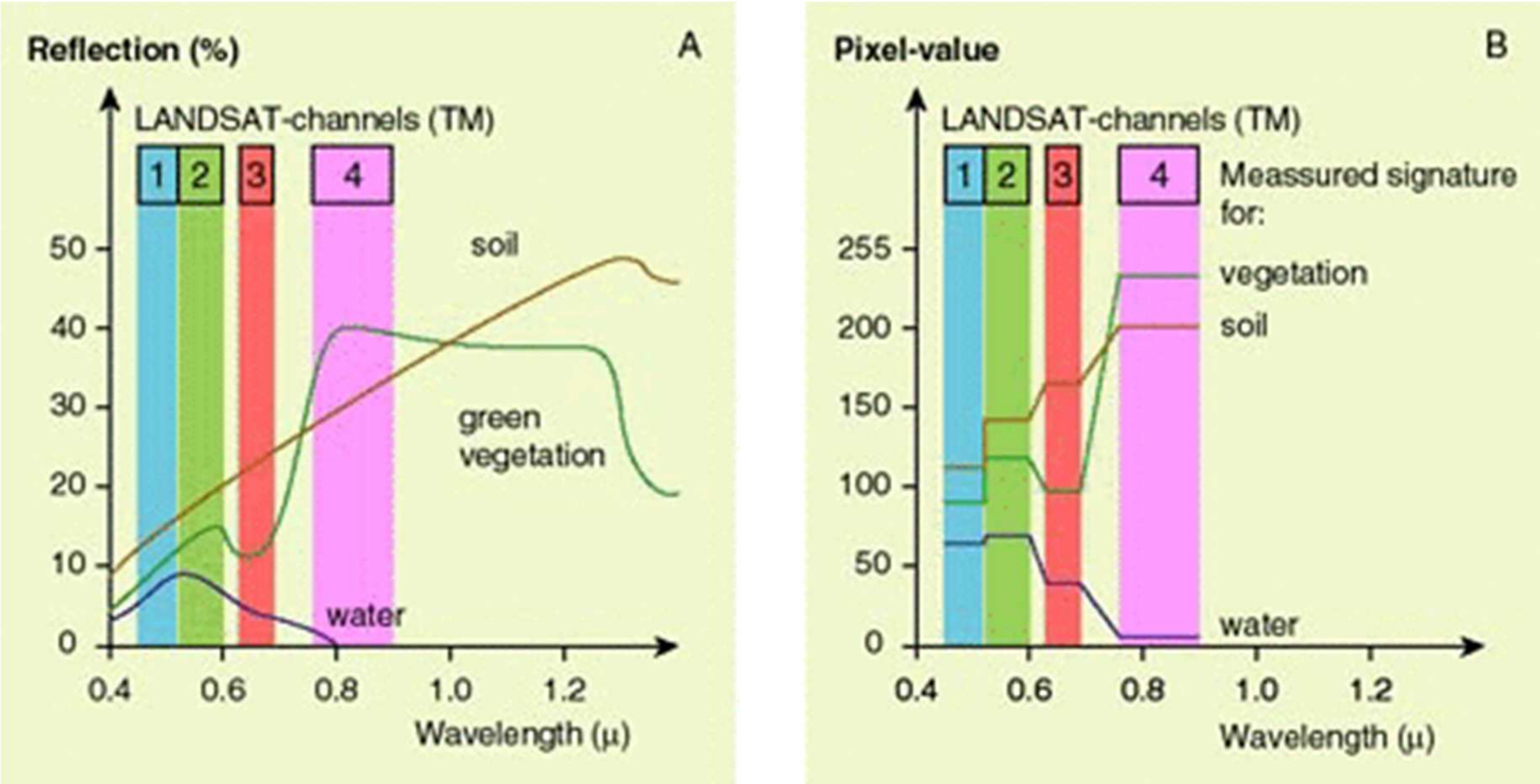
[11]

$$\frac{(0.50 - 0.08)}{(0.50 + 0.08)} = 0.72 \qquad \frac{(0.4 - 0.30)}{(0.4 + 0.30)} = 0.14$$

What Landsat sees



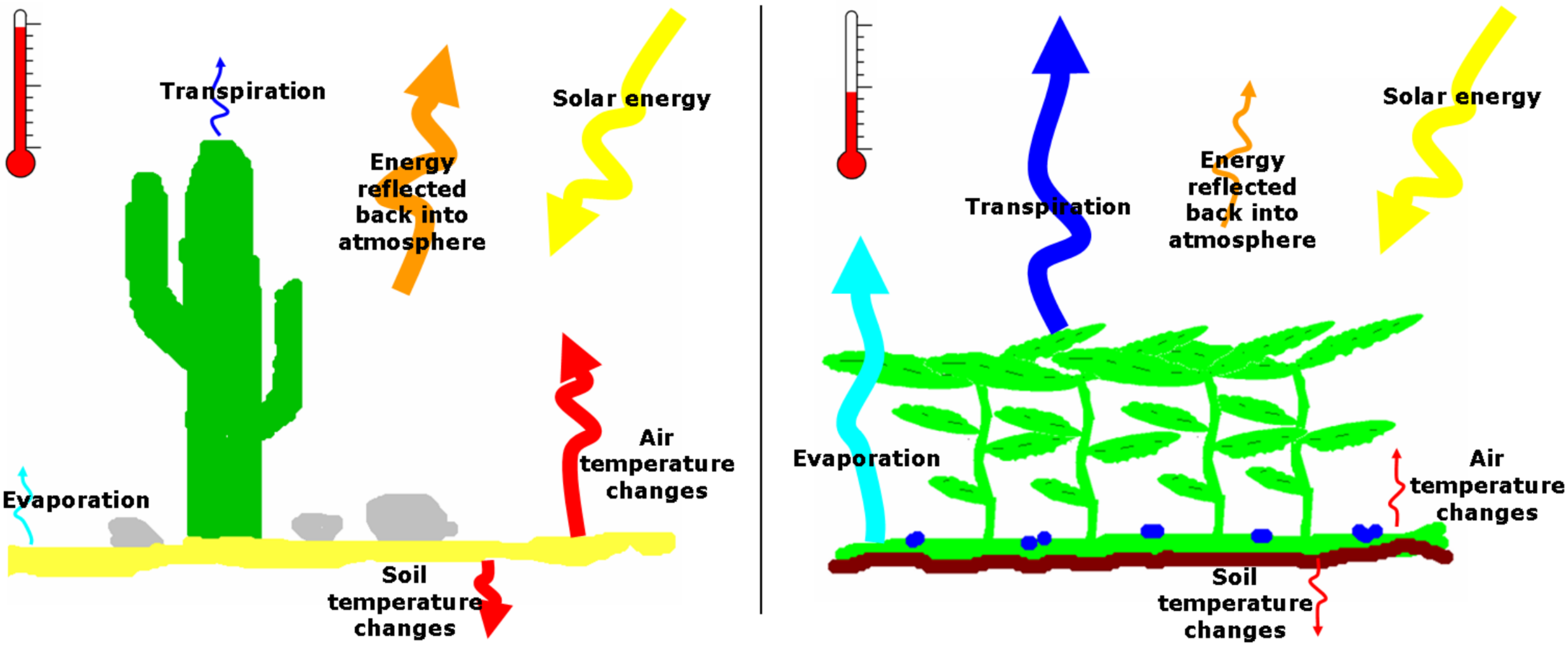
Spectral signatures



[12]

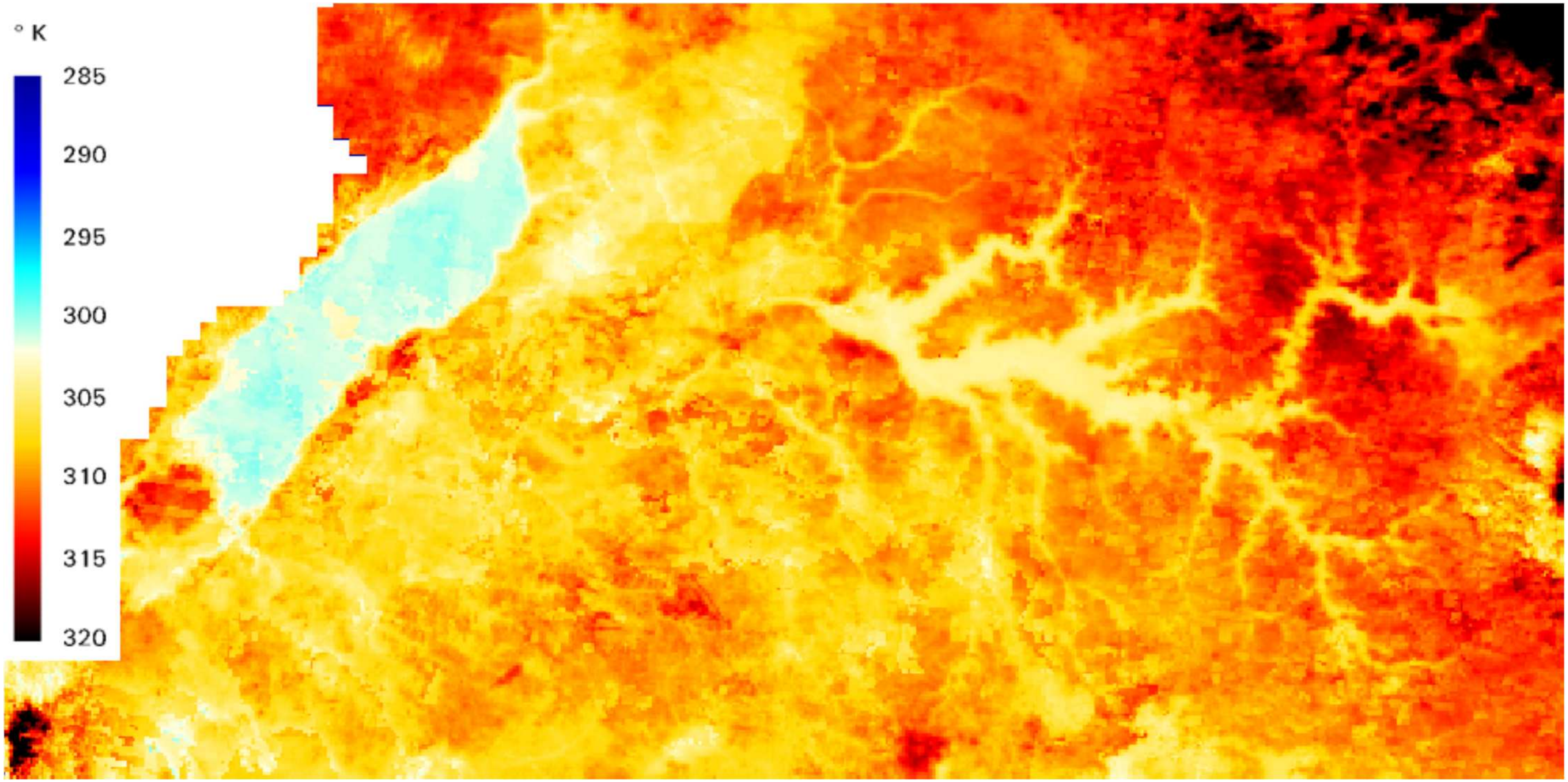

Alchanatis and Cohen, ARO, Israel
Alchanatis and Cohen, ARO, Israel

Temperature is function of ET

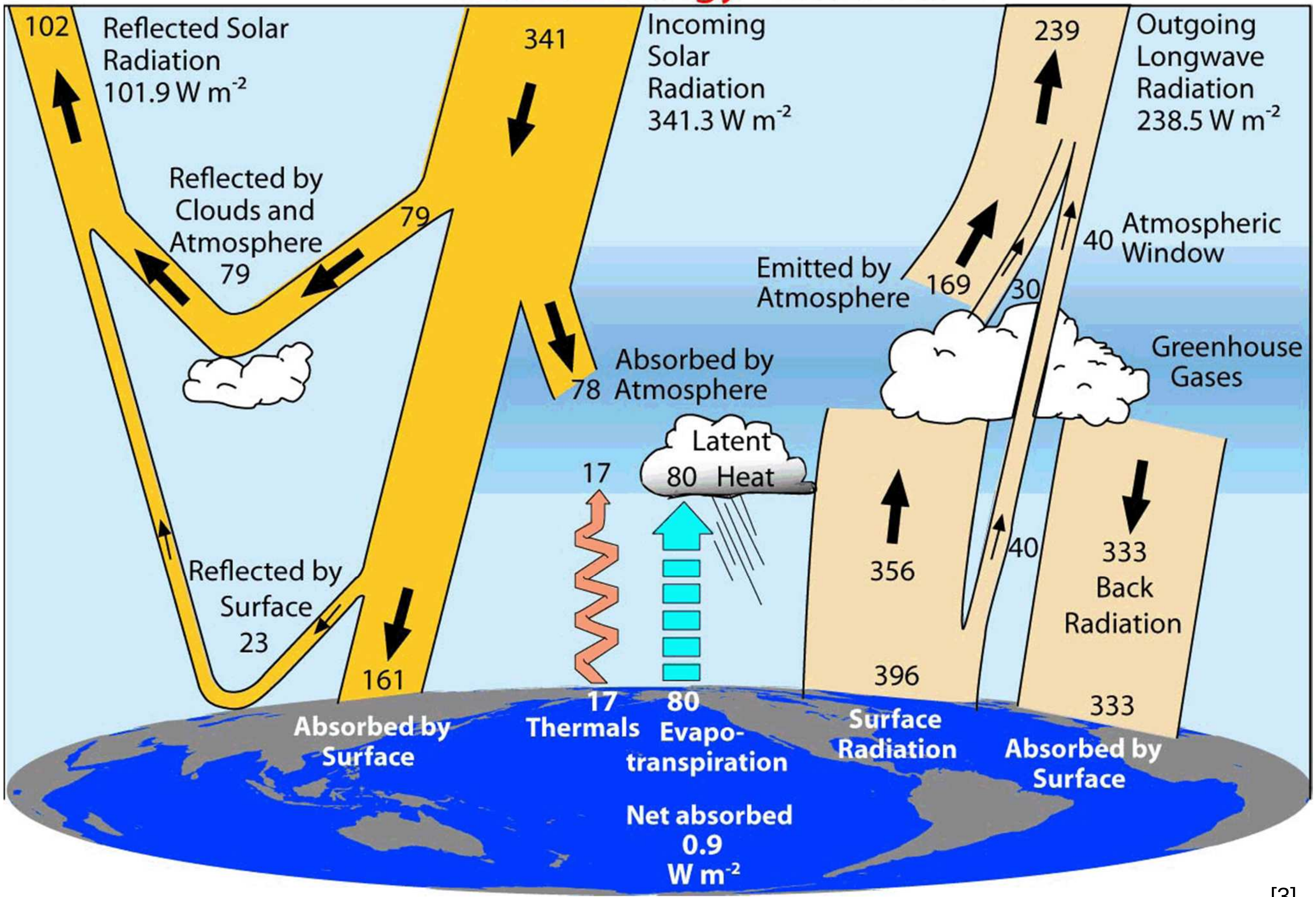


[13]

Surface temperature Lake Albert



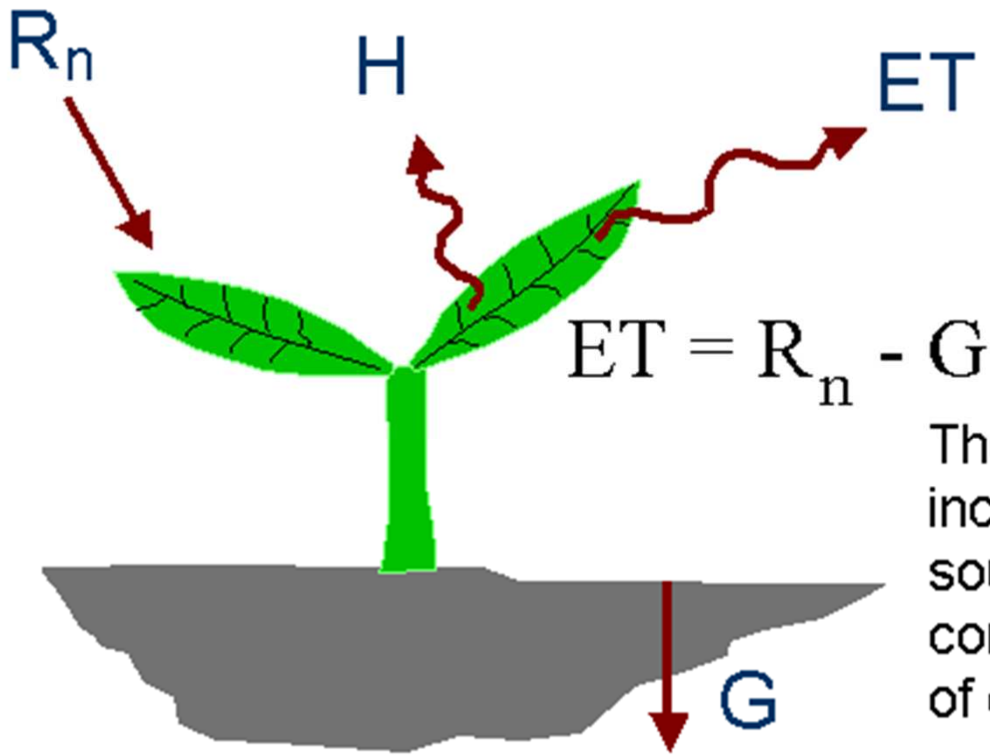
Global Energy Flows W m^{-2}



[3]

Surface energy balance

ET is calculated as a "residual" of the energy balance



$$ET = R_n - G - H$$

The energy balance includes all major sources (R_n) and consumers (ET, G, H) of energy

Energy and water conversions

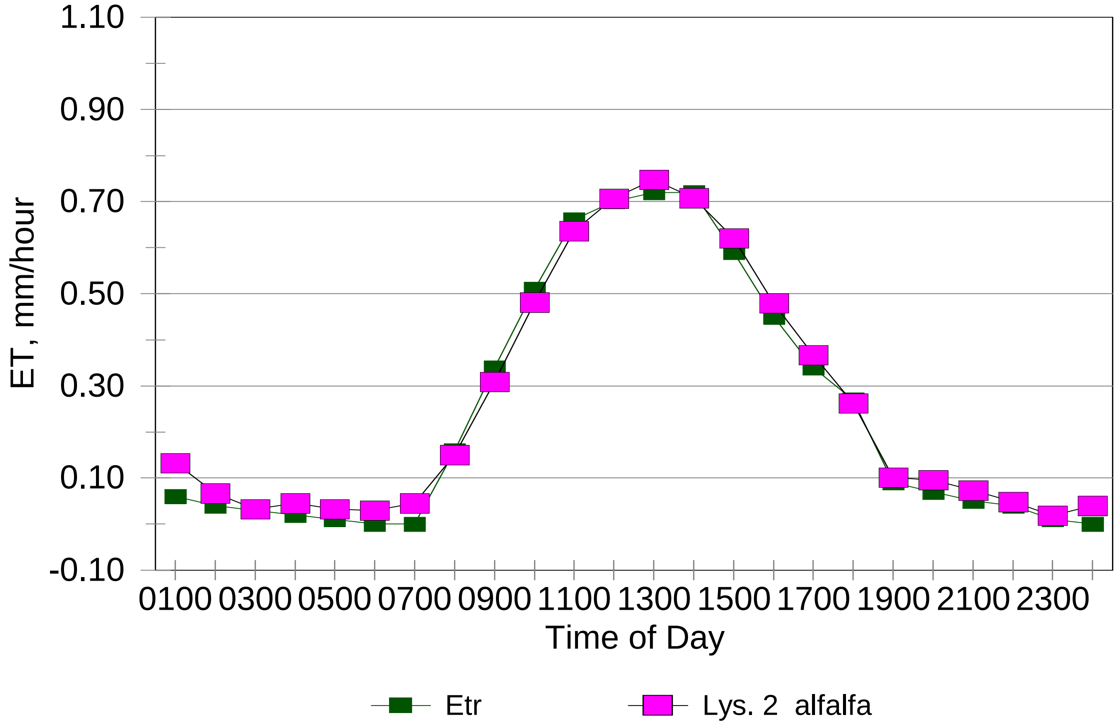
$$L = \rho_w \lambda_v ET$$

$$W m^{-2} (J m^{-2} s^{-1}) = \frac{kg}{m^3} \frac{J}{kg} \frac{m}{s}$$

$$\text{or } ET = \frac{L}{\rho_w \lambda_v}$$

$\lambda_v = 2{,}450{,}000\ J/kg$

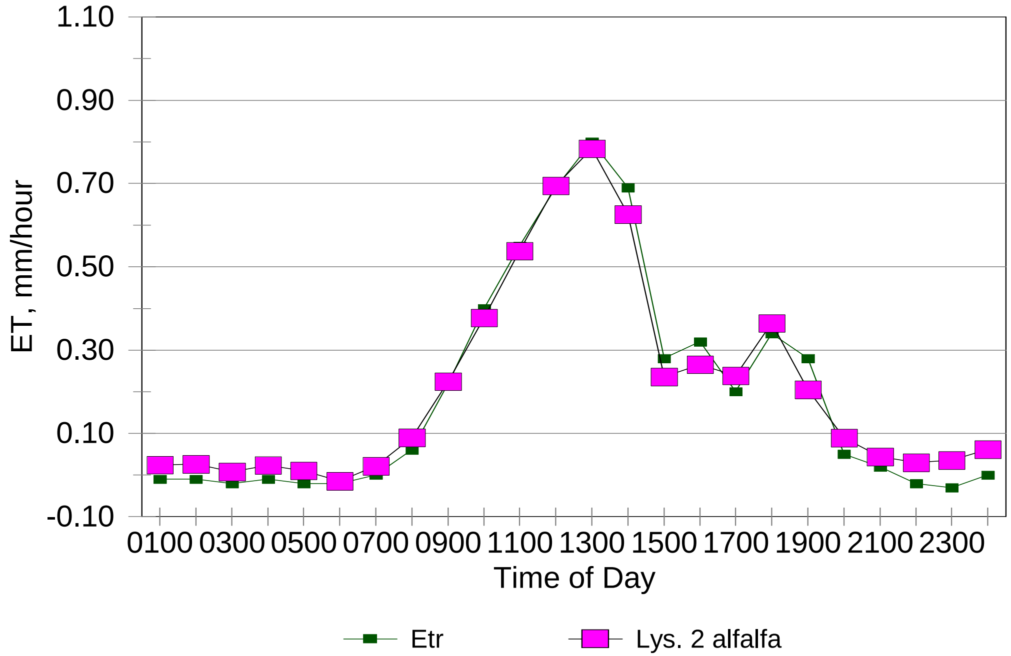
Kimberly Lysimeters - September 4,1990
Data from Dr. J.L Wright



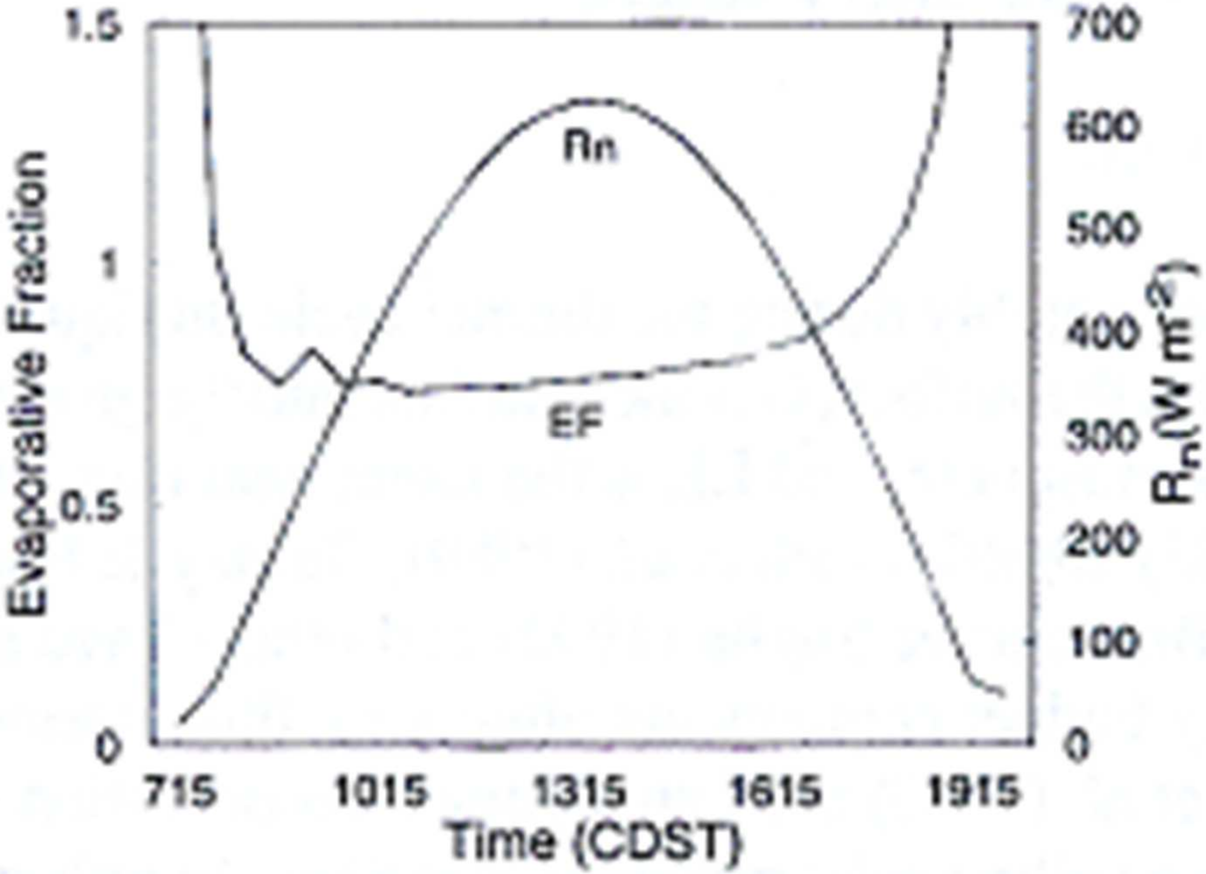
ASCE Standardized Penman-Monteith (alfalfa reference) at Kimberly, Idaho

- hourly time step

Kimberly Lysimeters -September 7, 1990

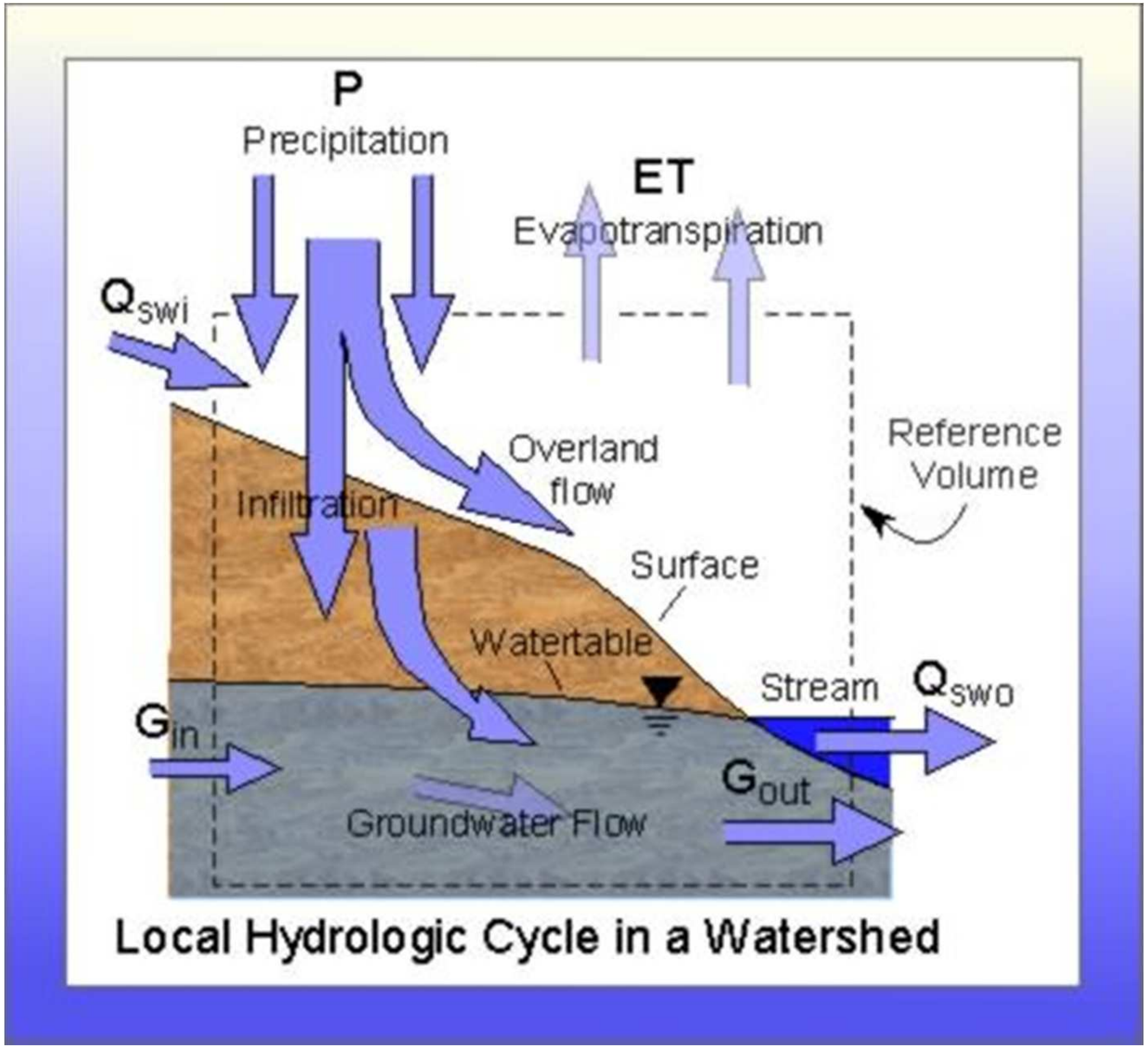


Evaporative fraction for time integration



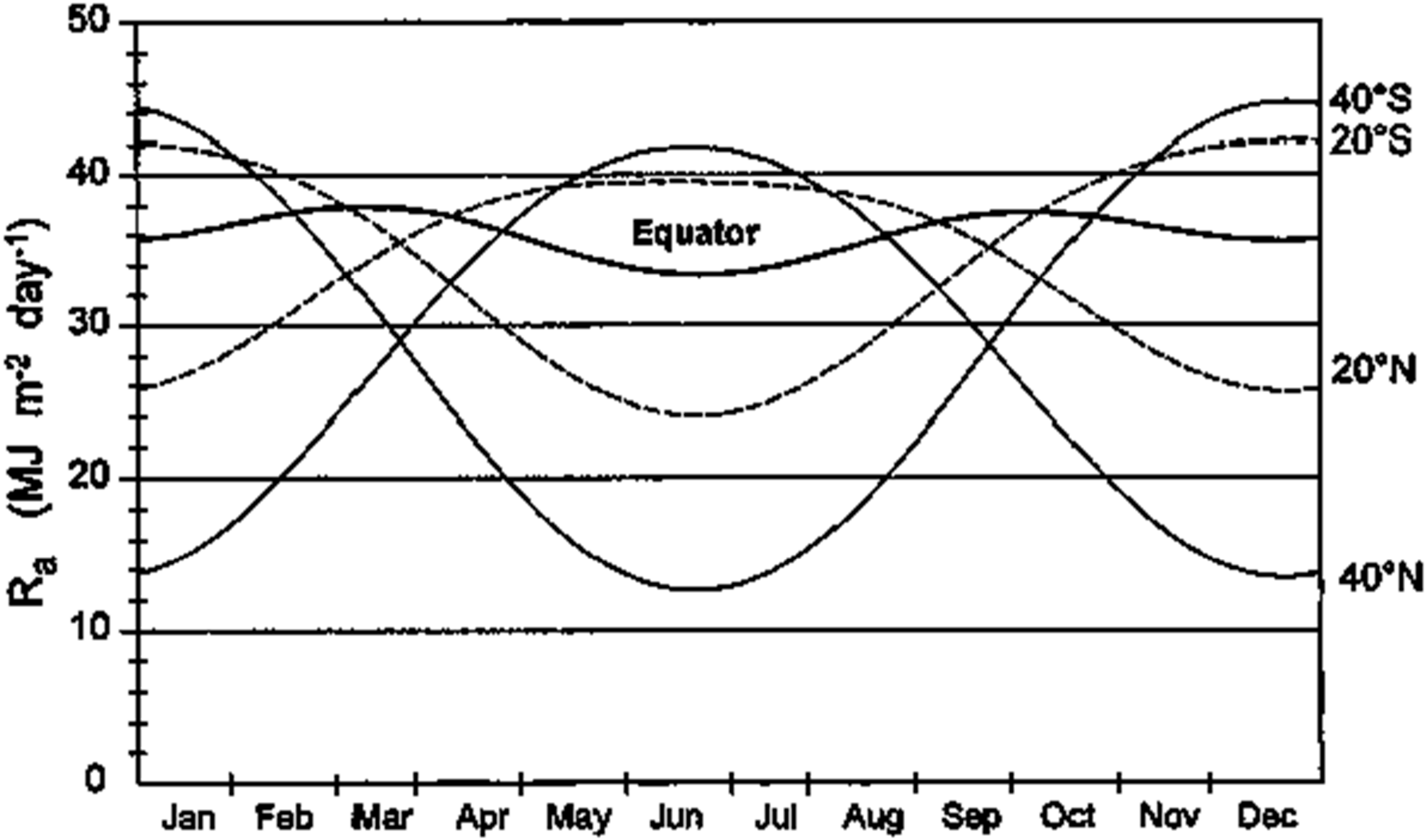
$$EF = LE / (R_n - G)$$

ET for hydrological studies



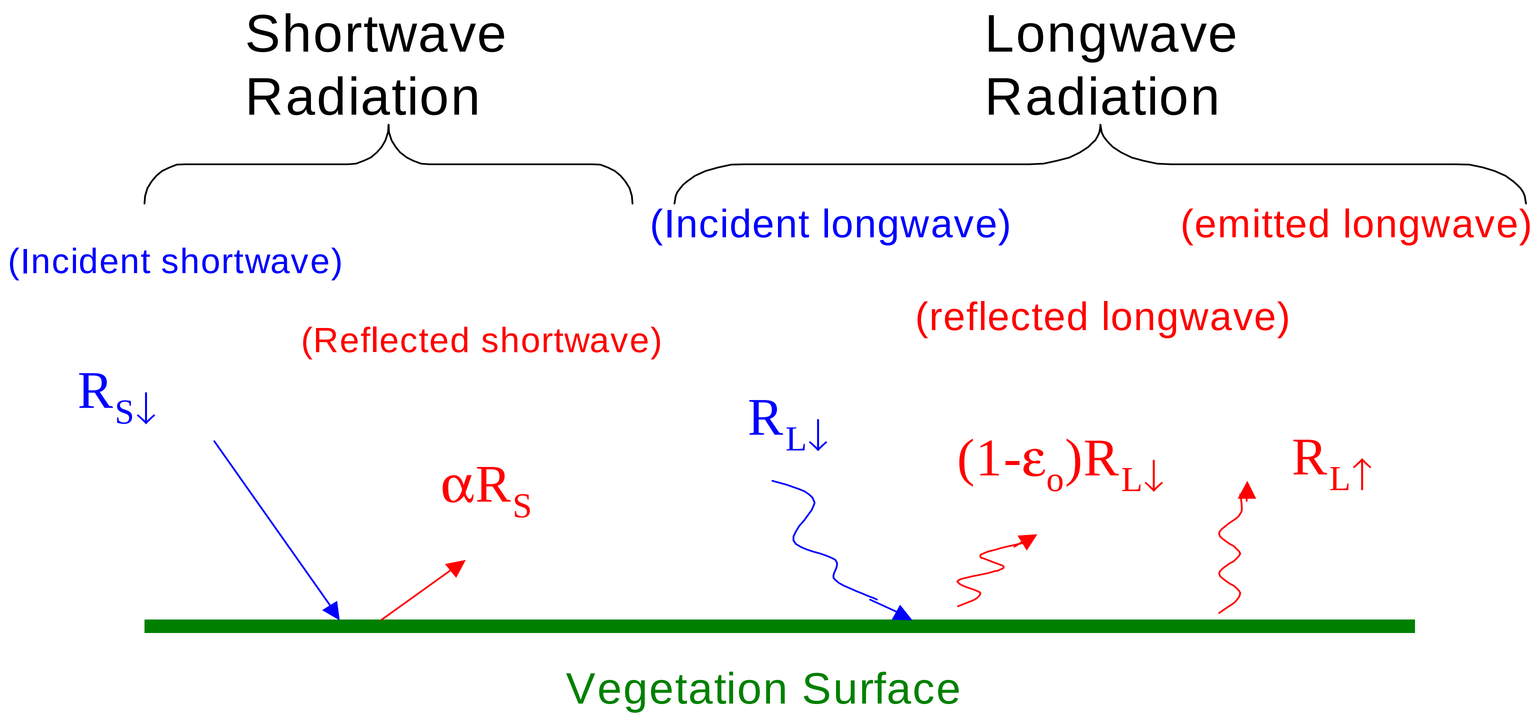
[15]

Extra-terrestrial radiation



Surface Radiation Balance

Surface Radiation Balance



Net Surface Radiation = Gains – Losses

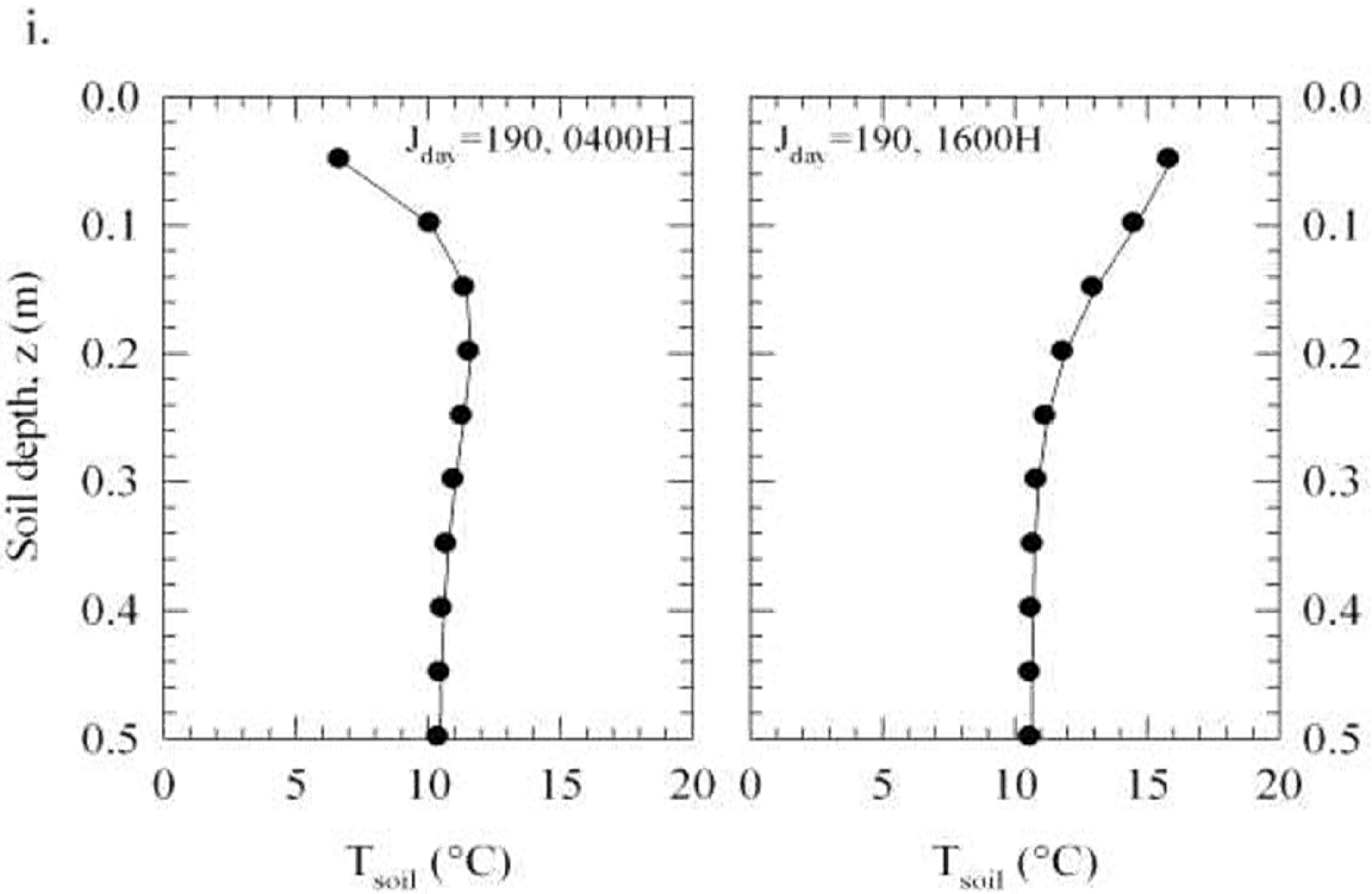
$$R_n = (1-\alpha)R_{S\downarrow} + R_{L\downarrow} - R_{L\uparrow} - (1-\varepsilon_o)R_{L\downarrow}$$

$R_L = \varepsilon \sigma T^4$

ε=emissivity

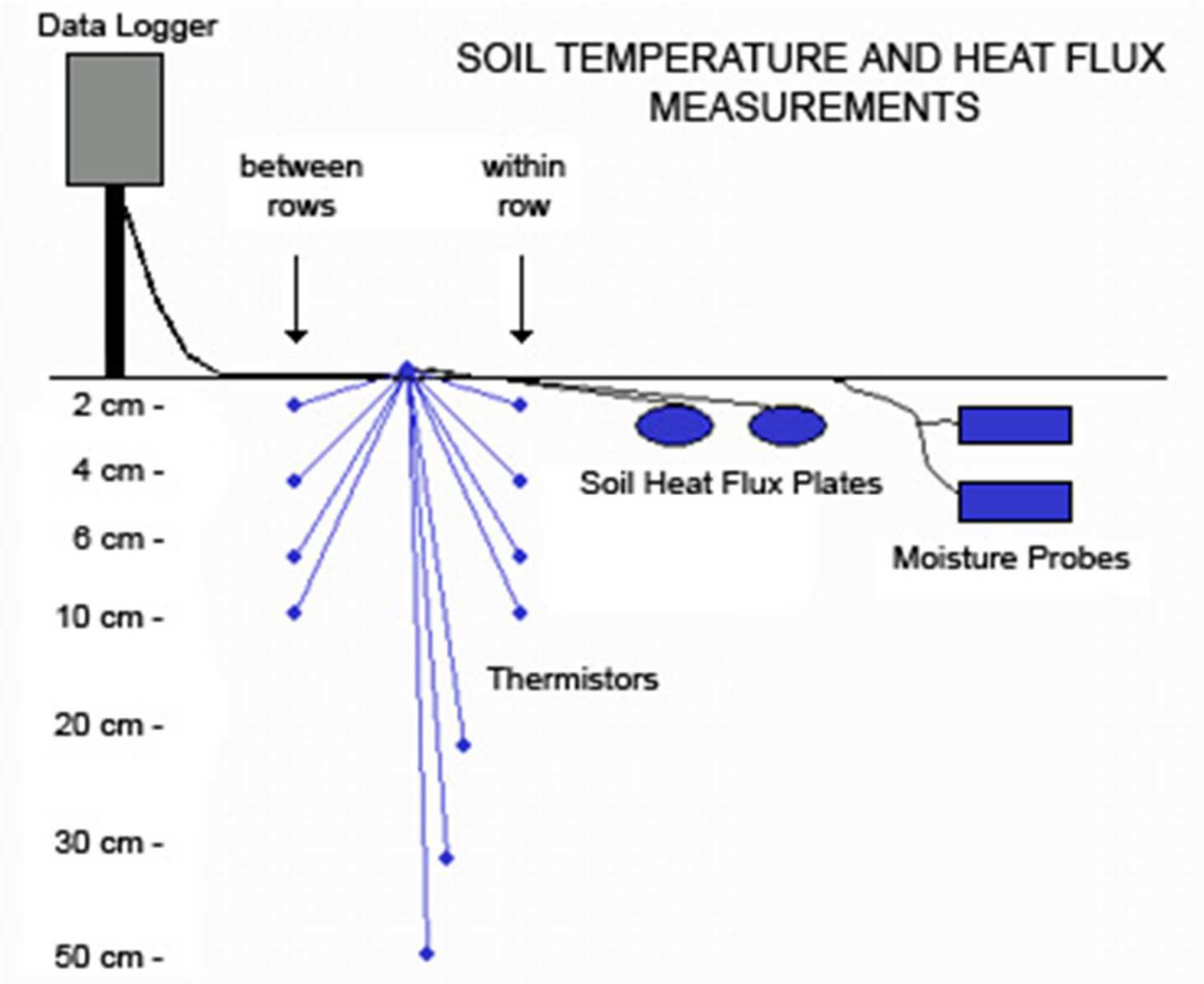
$\sigma = 5.67\ 10^{-8}$ Stefan Boltzmann

Soil heat flux



$$J_q = -K_q \frac{\partial T}{\partial x}$$

Soil heat flux



[16]

$$J_q = -K_q \frac{\partial T}{\partial x}$$

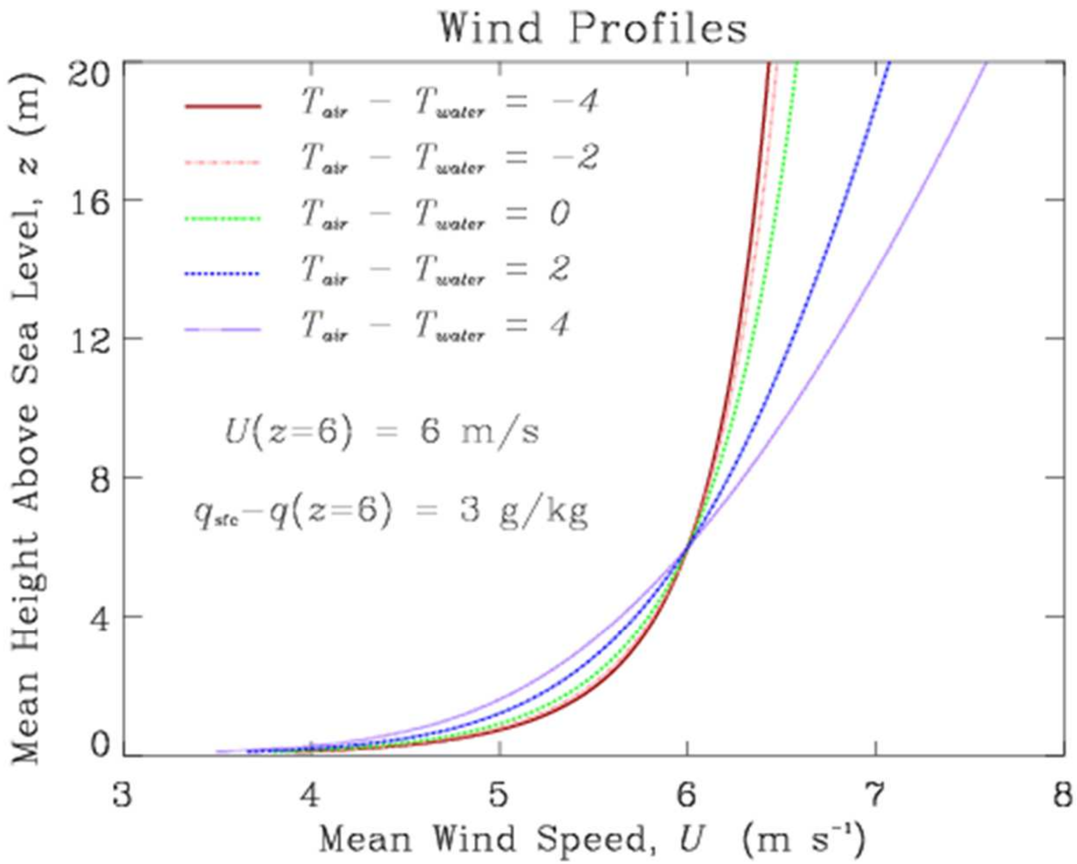
Soil heat flux

$$G = f\ R_n$$

- Fraction depends on direct exposure
- Fraction depends on pace of warming up

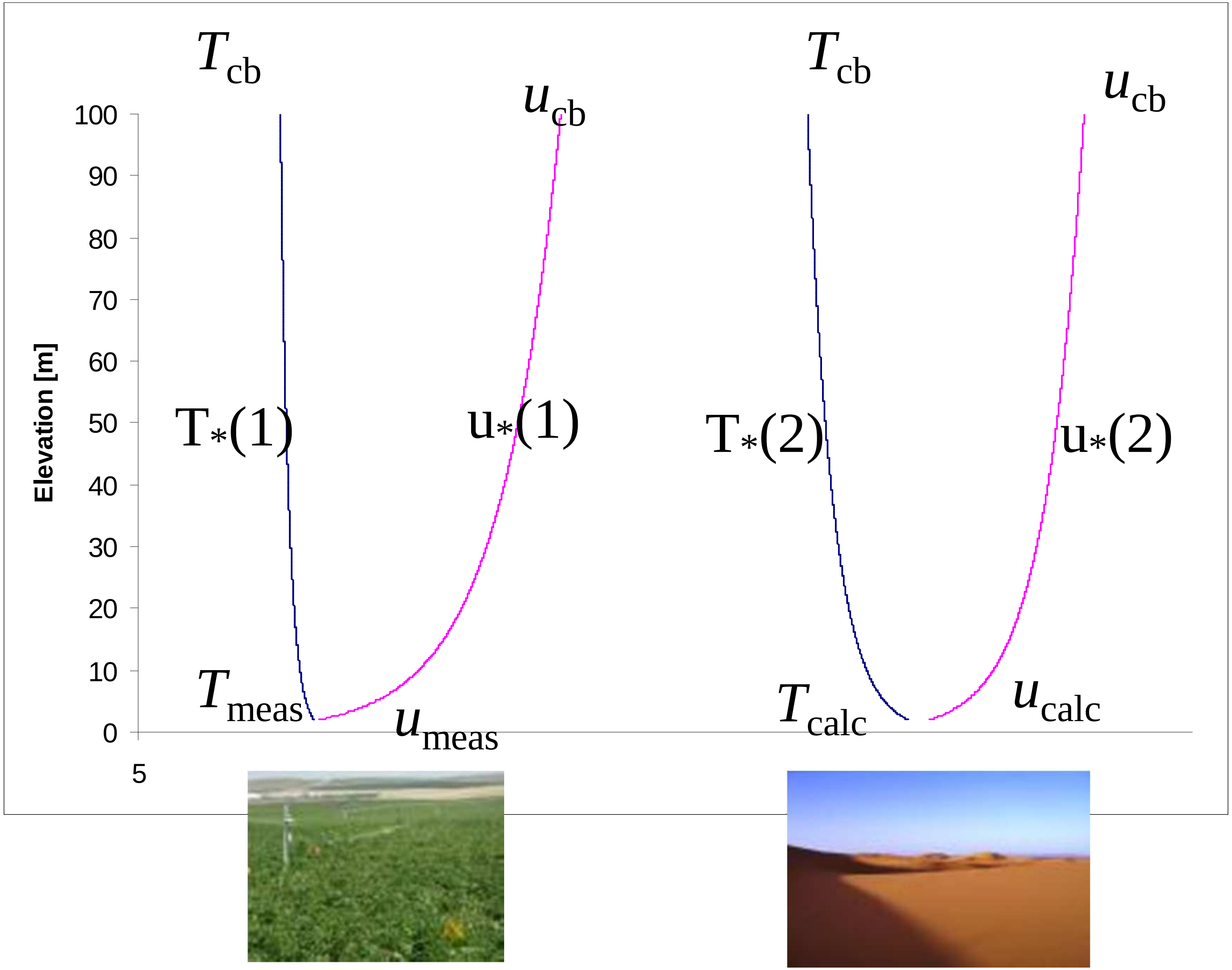
f = 0.4 for deserts
= 0.1 for crops
= 0.5 for water bodies
= 0.05 for forests

Logarithmic wind profile



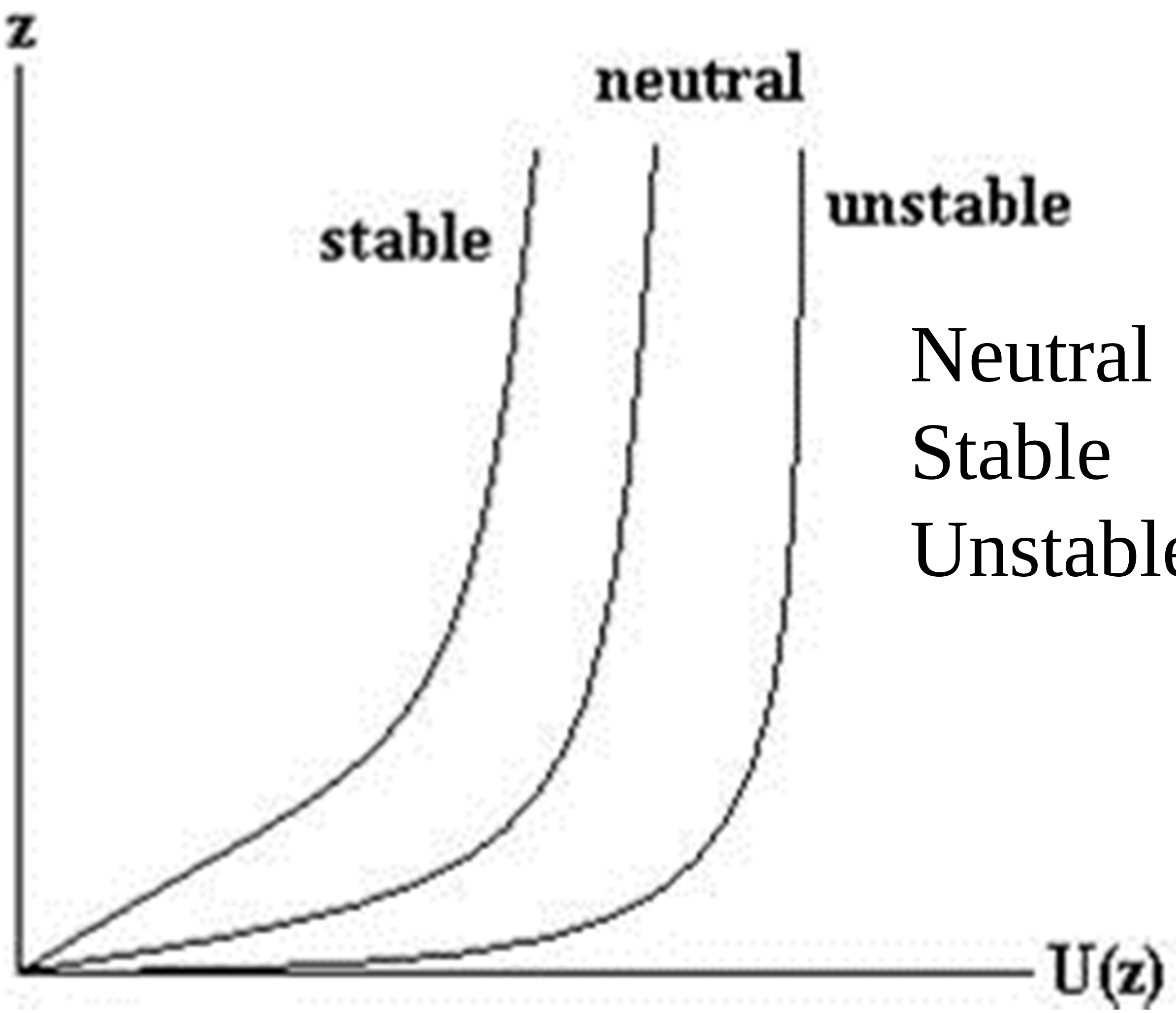
TU Delft

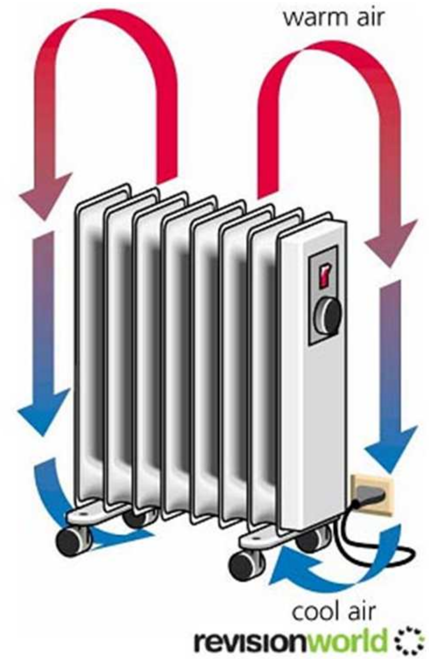
Flux – profile relationships for momentum, heat and vapor



Effect of buoyancy on turbulent transport

height





Neutral =no convection
Stable = heat towards land
Unstable= heat away from land

wind speed

Sensible Heat Flux (H)

$$H = (\rho \times c_p \times dT) / r_{ah}$$

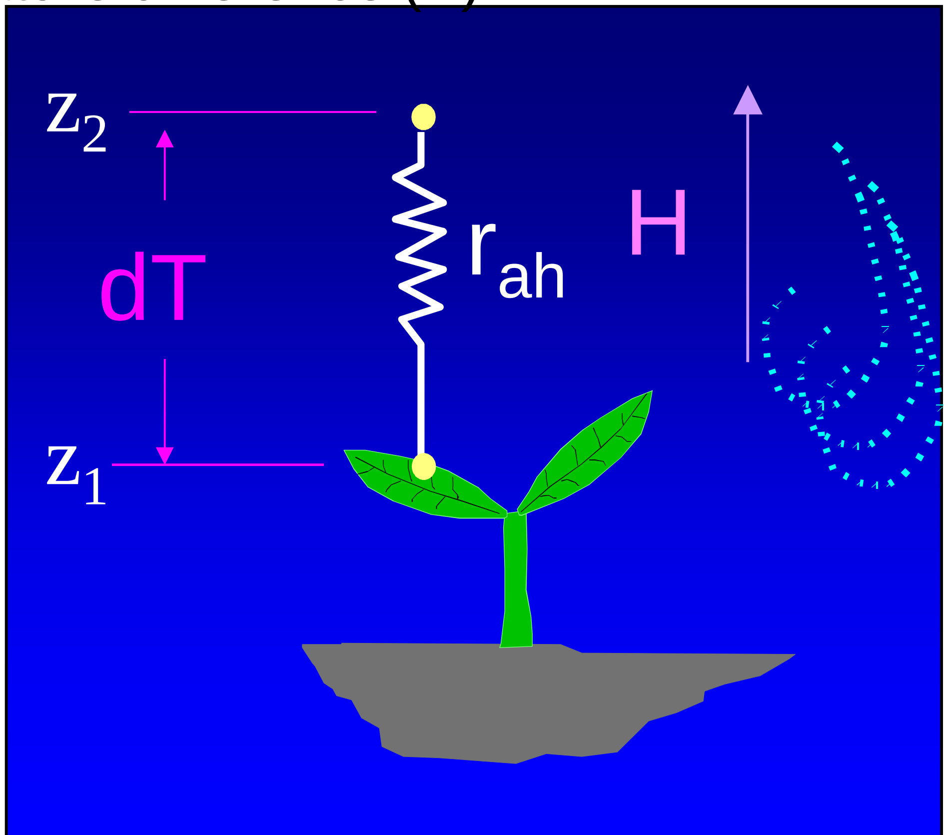
dT = “floating” near surface temperature difference (K)

r_{ah} = the aerodynamic resistance from z_1 to z_2

$$r_{ah} = \frac{\ln\left(\frac{z_2}{z_1}\right) - \Psi_{h(z_2)} + \Psi_{h(z_1)}}{u_* \times k}$$

u_* = friction velocity

k = von karmon constant (0.41)



Stability correction

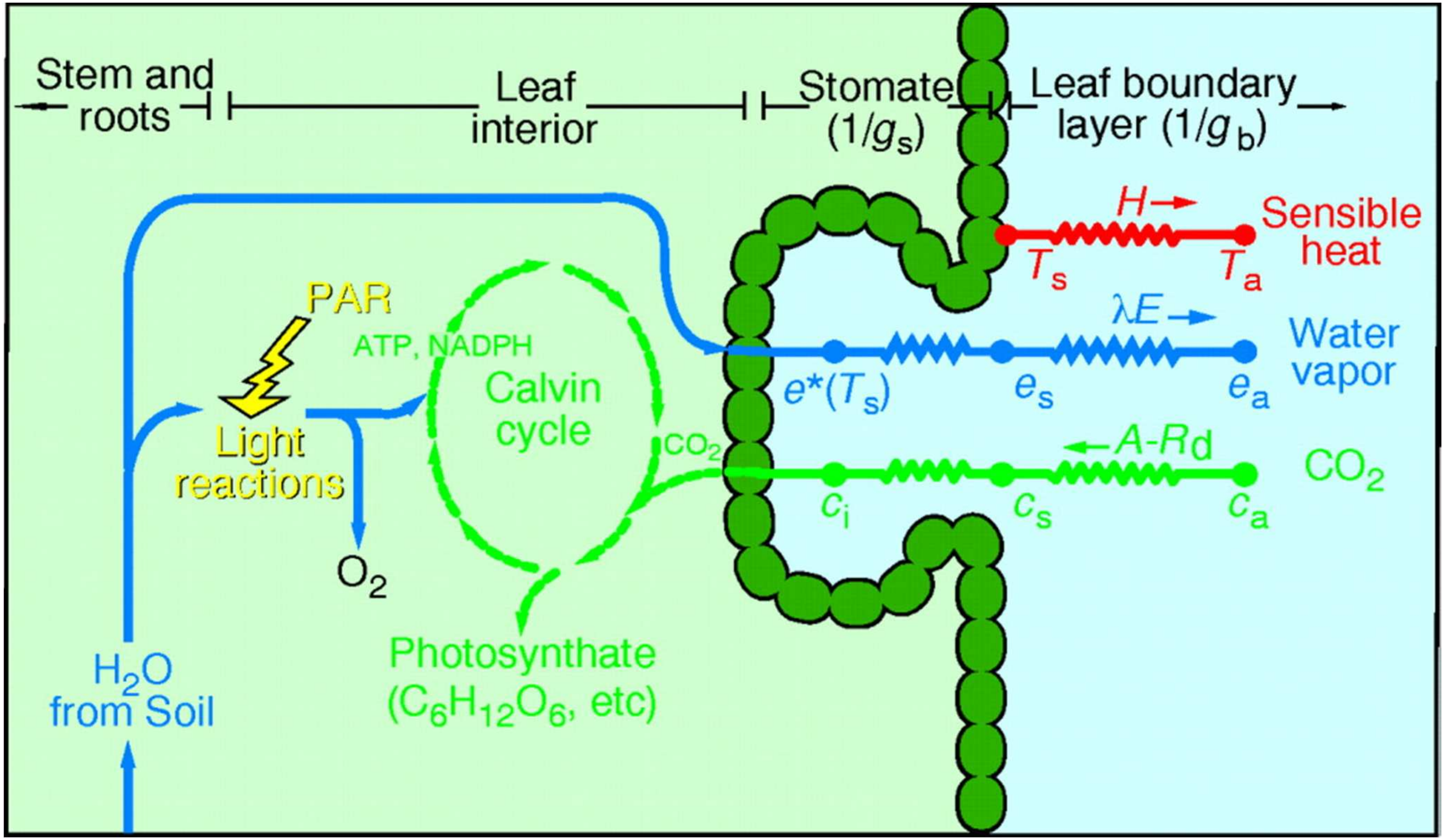
$$u^* = \frac{u_{200} k}{\ln\left(\frac{200}{z_{0m}}\right) - \Psi_{m(200m)}}$$

$$r_{ah} = \frac{\ln\left(\frac{z_2}{z_1}\right) - \Psi_{h(z_2)} + \Psi_{h(z_1)}}{u_* \times k}$$

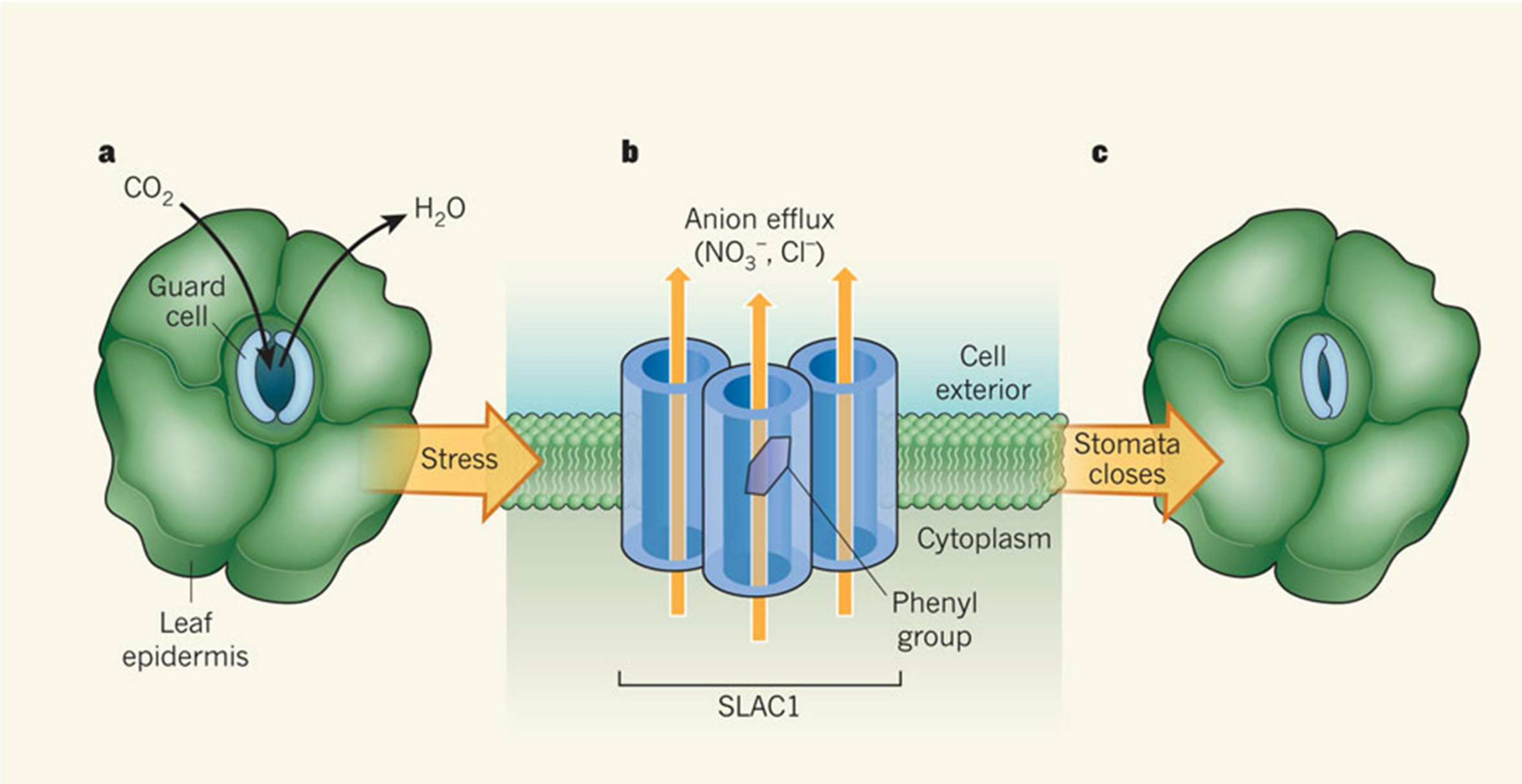
- New values for dT are computed for the "anchor" pixels.
- New values for a and b are computed.
- A corrected value for H is computed.
- The stability correction is repeated until H stabilizes.

Evaporation from vegetation

$$L = \beta \left[\frac{e^*(T_s) - e_a}{r_a + r_c} \right] \frac{\rho_a c_p}{\gamma}$$

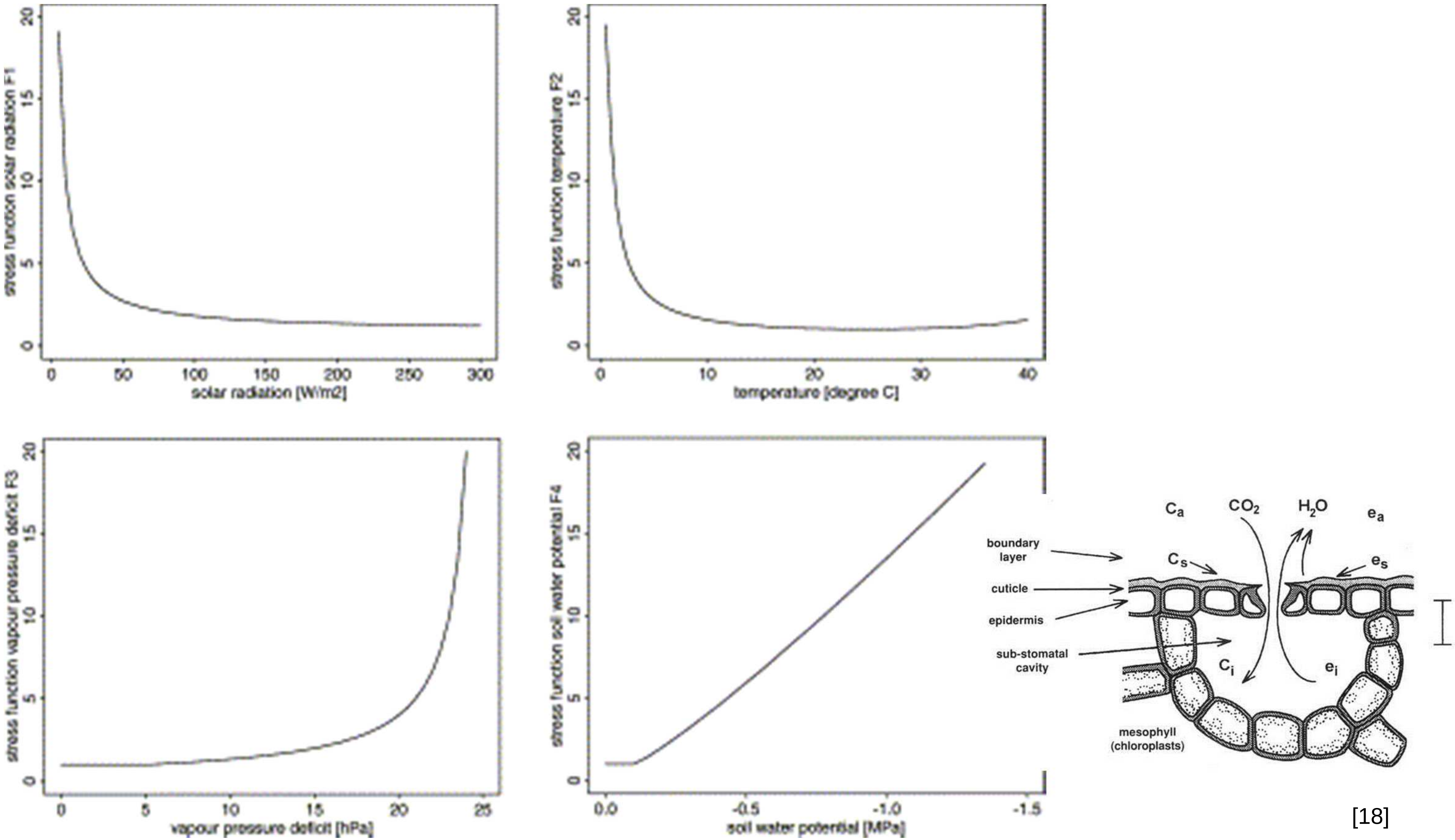


Stomatal regulation



[17]

Stomatal regulation



[18]

Canopy Resistance Model

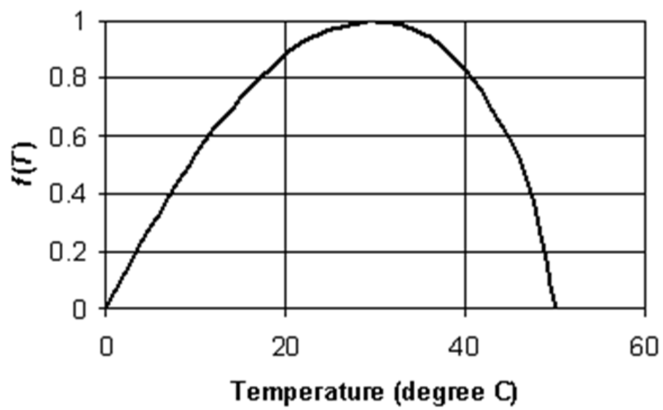
$$1 / r_c = f_1(T)\, f_2(\mathrm{VPD})\, f_3(\mathrm{PAR})\, f_4(\psi) / r_{cMIN}$$

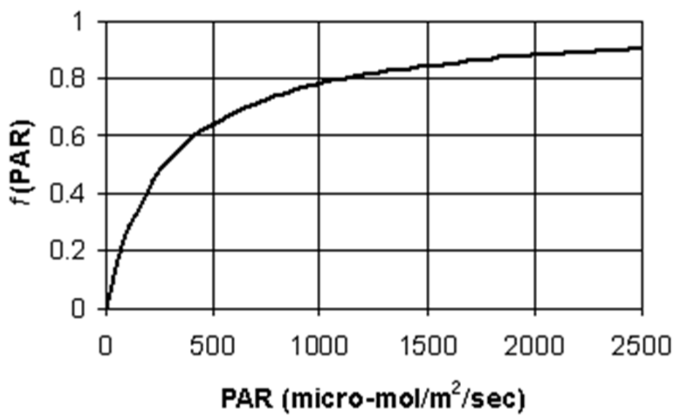
Temperature

Humidity

Solar radiation

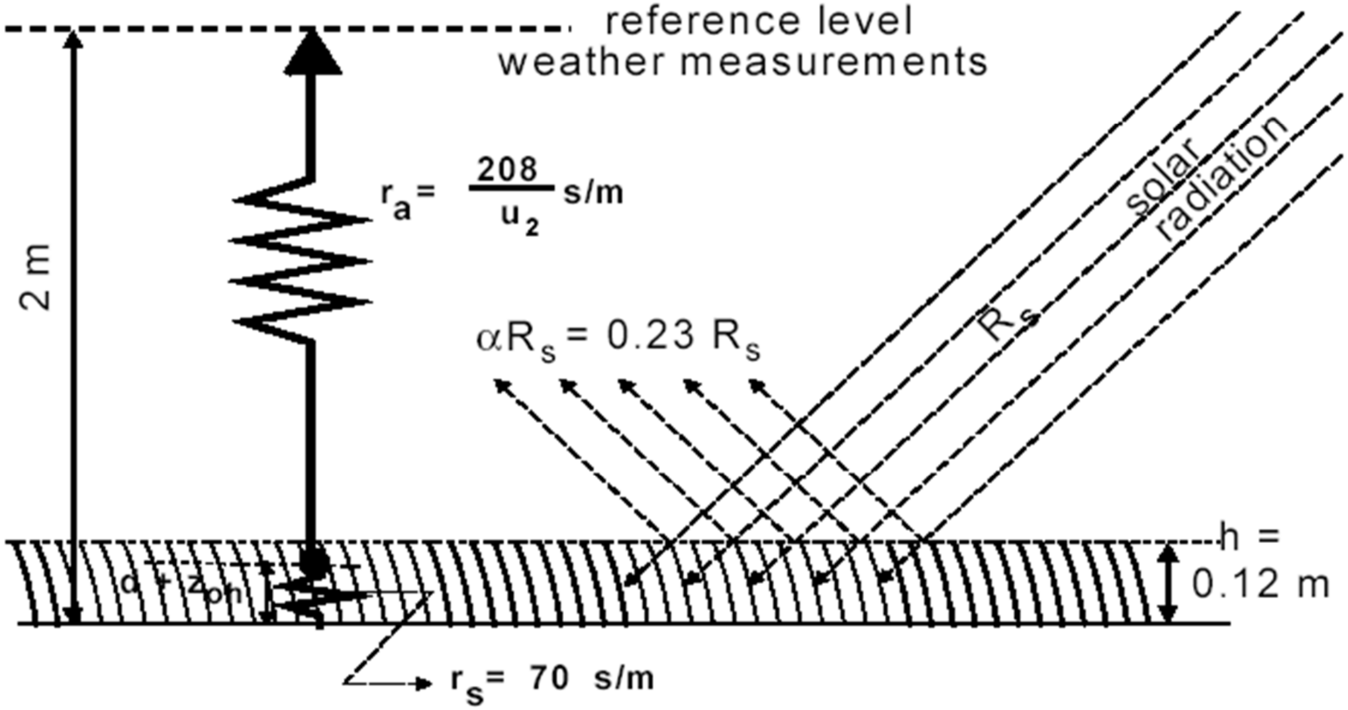
Soil water





Reference ET

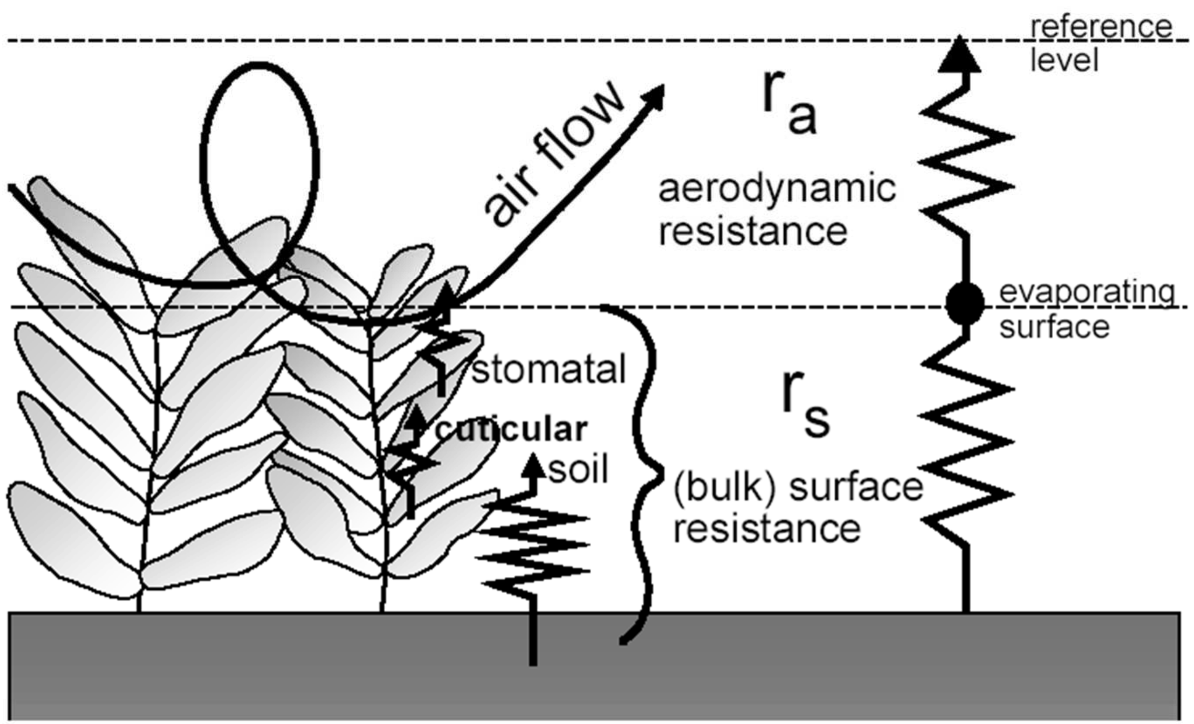
FIGURE 9
Characteristics of the hypothetical reference crop



[19]

Penman-Monteith for ET_{ref} (ET_0)

FIGURE 7
Simplified representation of the (bulk) surface and aerodynamic resistances for water vapour flow



[19]

The Penman-Monteith form of the combination equation is:

$$\lambda ET = \frac{\Delta(R_n - G) + \rho_a c_p \frac{(e_s - e_a)}{r_a}}{\Delta + \gamma\left(1 + \frac{r_s}{r_a}\right)} \qquad (3)$$

TU Delft

Aerodynamic resistance

BOX 4
The aerodynamic resistance for a grass reference surface

For a wide range of crops the zero plane displacement height, d [m], and the roughness length governing momentum transfer, z_{om} [m], can be estimated from the crop height h [m] by the following equations:

$$d = 2/3\ h$$

$$z_{om} = 0.123\ h$$

The roughness length governing transfer of heat and vapour, z_{oh} [m], can be approximated by:

$$z_{oh} = 0.1\ z_{om}$$

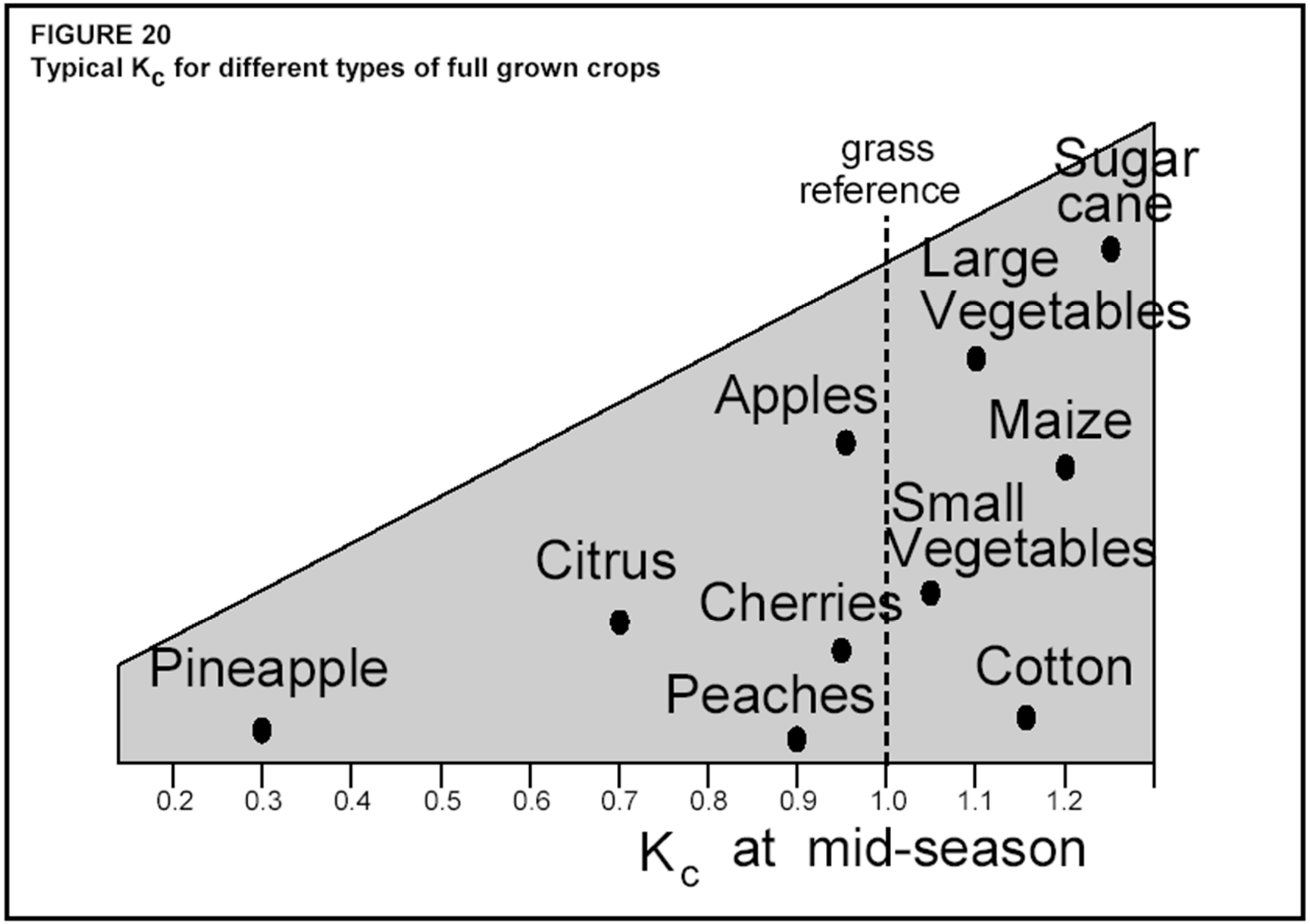
Assuming a constant crop height of 0.12 m and a standardized height for wind speed, temperature and humidity at 2 m ($z_m = z_h = 2$ m), the aerodynamic resistance r_a [s m^{-1}] for the grass reference surface becomes (Eq. 4):

$$r_a = \frac{\ln\left[\frac{2-2/3(0.12)}{0.123(0.12)}\right]\ln\left[\frac{2-2/3(0.12)}{(0.1)0.123(0.12)}\right]}{(0.41)^2 u_2} = \frac{208}{u_2}$$

where u_2 is the wind speed [m s^{-1}] at 2 m.

[19]

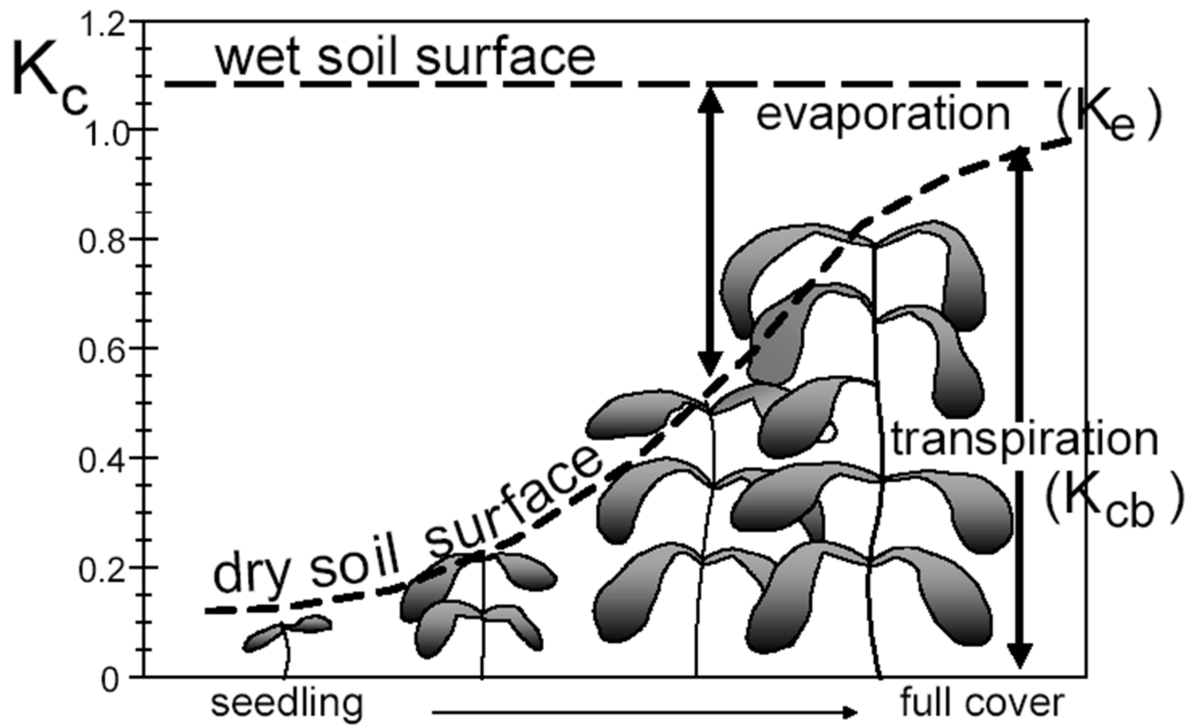
Potential ET for correction of grass



[19]

Crop coefficient

FIGURE 22
The effect of evaporation on K_c. The horizontal line represents K_c when the soil surface is kept continuously wet. The curved line corresponds to K_c when the soil surface is kept dry but the crop receives sufficient water to sustain full transpiration



[19]

Sources images

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