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→ 4th ADVANCED TRAINING COURSE IN LAND REMOTE SENSING

Introduction to thermal infrared remote sensing - Surface Energy Balance System Basics

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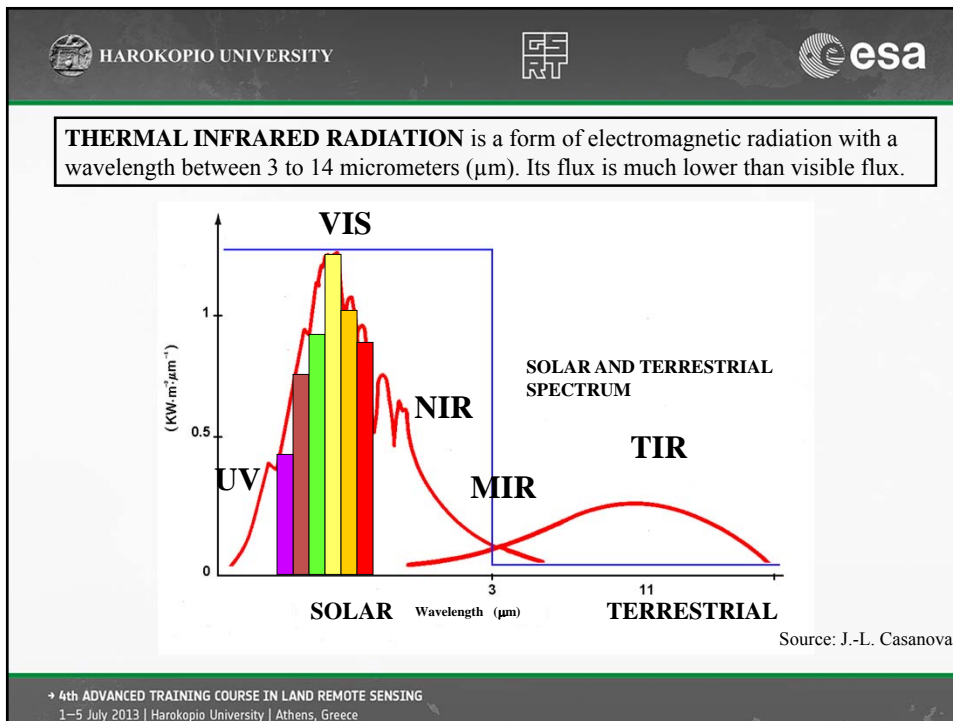
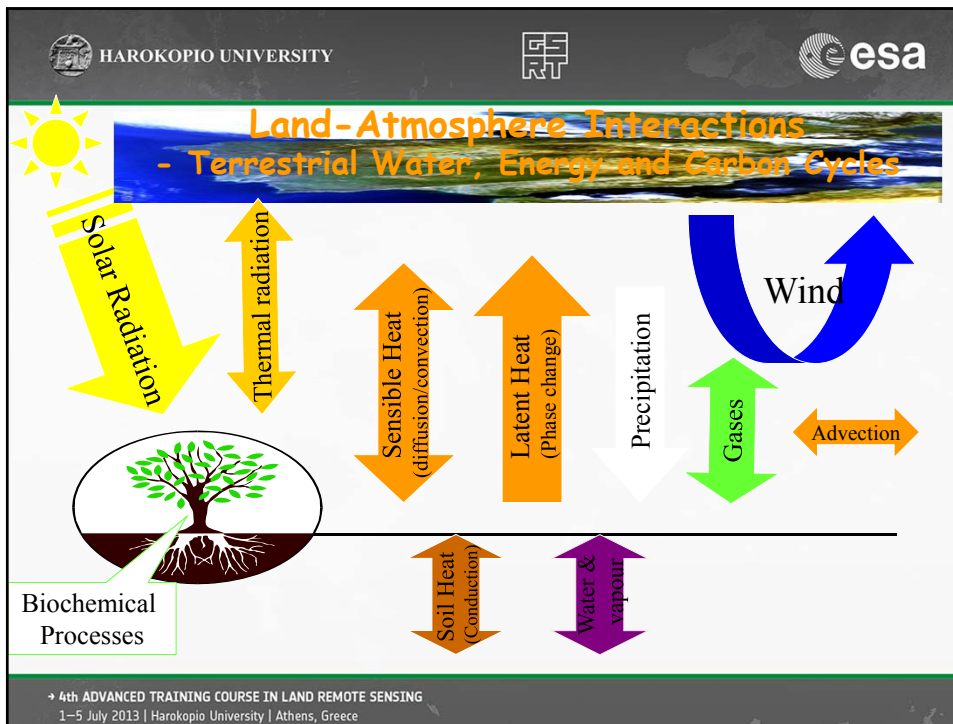
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Learning Objectives

1. To understand basic concepts of surface radiation budget
2. To understand basic measurements to derive surface radiation components
3. To be able to derive surface radiation components using different information
4. To familiarize with retrieval of surface parameters

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Some definitions

RADIANT POWER: The rate of flow of electromagnetic energy, *i.e.*, radiant energy, Φ (watts, *i.e.*, joules per second.)

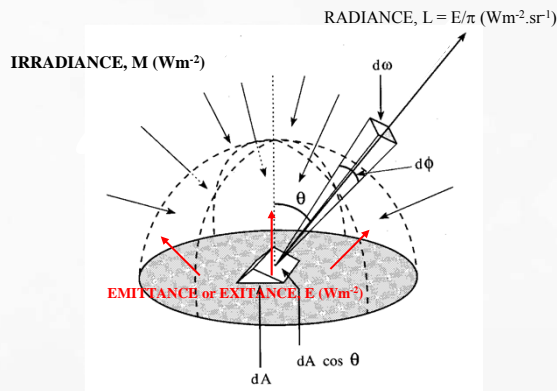
RADIANT EMITTANCE: Radiant power emitted into a full sphere, *i.e.*, 4π (steradians), by a unit area of a source, expressed in watts per square meter. *Synonym* radiant exitance, **flux**, radiant flux, E ($W\ m^{-2}$)

RADIANCE: Radiant power, in a given direction, per unit solid angle per unit of projected area of the source, as viewed from the given direction. *Note:* Radiance is usually expressed in watts per steradian per square meter, L ($W\ m^{-2}\cdot sr^{-1}$) = M/π

IRRADIANCE: Radiant power incident per unit area upon a surface. *Note:* Irradiance is usually expressed in watts per square meter, but may also be expressed in joules per square meter. *Synonym:* power density, **flux**, radiant flux, M (watts/ m^2).

Source: J.-L. Casanova

Graphical representation of emittance, radiance and irradiance



Source: J.-L. Casanova



Spectral magnitudes

All these magnitudes are usually expressed as spectral magnitudes, that is to say, referred to a wavelength

RADIANT POWER: P_λ ($\text{W}\cdot\mu\text{m}^{-1}$) or ($\text{W}\cdot\text{cm}^{-1}$)

RADIANT EMITTANCE: E_λ ($\text{W}\cdot\text{m}^{-2}\cdot\mu\text{m}^{-1}$) or ($\text{W}\cdot\text{cm}^{-1}\text{m}^{-2}$)

RADIANCE: L_λ ($\text{W}\cdot\text{m}^{-2}\cdot\text{sr}^{-1}\cdot\mu\text{m}^{-1}$) or ($\text{W}\cdot\text{cm}^{-1}\text{m}^{-2}\cdot\text{sr}^{-1}$) = E_λ/π

IRRADIANCE: M_λ ($\text{W}\cdot\text{m}^{-2}\cdot\mu\text{m}^{-1}$) or ($\text{W}\cdot\text{cm}^{-1}\text{m}^{-2}$).

Wavenumber (cm^{-1}) = number of wavelengths per cm = $10,000/\lambda$ (μm)

i.e. λ (μm) = $10,000/\text{wavenumber}$ (cm^{-1})

e.g. $1\ \mu\text{m} \sim 10,000\ \text{cm}^{-1}$; $10\ \mu\text{m} \sim 1,000\ \text{cm}^{-1}$...

Source: J.-L. Casanova



Thermal emission - the Planck's Law:

The theory to express the thermal emission is based on the black body concept: a **black body** is an object that absorbs all electromagnetic radiation at each wavelength that falls onto it. A black body however emits radiation as well, its magnitude depends on its temperature, and is expressed by the Planck's Law:

$$B(\lambda, T_s) = \frac{c_1 \lambda^{-5}}{\exp\left(\frac{c_2}{\lambda T_s}\right) - 1}$$

$c_1 = 1.19104 \cdot 10^8\ \text{W}\ \mu\text{m}^4\ \text{m}^{-2}\ \text{sr}^{-1}$

$c_2 = 1.43877 \cdot 10^4\ \mu\text{m}\ \text{K}$,

are the first radiation constant (for spectral radiance) and second radiation constant, respectively, $B(\lambda, T_s)$ is given in $\text{W}\ \text{m}^{-2}\ \text{sr}^{-1}\ \mu\text{m}^{-1}$ if λ the wavelength is given in μm .



Terminology in Thermal Remote Sensing

Thermodynamic (kinetic) temperature

Brightness temperature

Directional radiometric surface temperature & Directional emissivity

Hemispheric broadband radiometric surface temperature & Hemispherical broadband emissivity

Source: J. Norman, and F. Becker, 1995



Thermodynamic (kinetic) temperature

Thermodynamic (kinetic) temperature (T) is a macroscopic measure to quantify the thermal dynamic state of a system in thermodynamic equilibrium with its environment (no heat transfer) and can be measured with a infinitesimal thermometer in good contact with it.



By maximizing the total entropy (S) with respect to the energy (E) of the system, T is defined as

$$\frac{dS}{dE} = \frac{1}{T}$$

- which is consistent with the definition of the absolute temperature by the ideal gas law

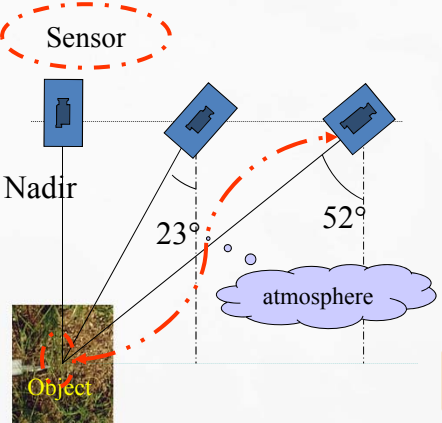
$$PV = RT$$

- where P is pressure, V volume, R the gas constant ($R=kN_0$, k is Boltzmann constant, N_0 number of molecules in a mole).

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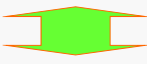
The Fundamental of Earth Observation

(Sensor - Object Radiative Relationship)



Sensor Response

A. How much radiation is detected?
B. When does it arrive?





Object Properties:

Its range, its combined temperature & Emissivity (or reflectivity) at different times, at different spatial resolution, at different wavelengths, at different direction, at different polarization

A: A Passive Sensor System
A+B: An Active Sensor System

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Brightness temperature

Brightness temperature ($T_{b,i}$) is a directional temperature obtained by equating the measured radiance ($R_{b,i}$) with the integral over wavelength of the Planck's black body function multiplied by the sensor response f_i .

$$R_{b,i}(\theta, \phi) = R(T_{b,i}(\theta, \phi)) = \int_{\lambda_1}^{\lambda_2} \frac{f_i(\lambda) C_1}{\lambda^5 \left(\exp\left(\frac{C_2}{\lambda T_{b,i}(\theta, \phi)}\right) - 1 \right)} d\lambda$$

$\int_{\lambda_1}^{\lambda_2} f_i(\lambda) d\lambda = 1$ is the detector relative response.

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Directional radiometric surface temperature & Directional emissivity

The spectral radiance (R_R) measured by a directional radiometer is the sum of the emitted black body radiance modified by the emissivity and the reflected radiation within an infinitesimal wavelength band.

$$R_{R,\lambda}(\theta, \phi) = \varepsilon_\lambda(\theta, \phi) R_{B,\lambda}(\theta, \phi)$$

$$+ \int_0^{2\pi} \int_0^{\pi/2} \rho_{b,\lambda}(\alpha, \beta, \theta, \phi) \cos(\alpha) L_\lambda(\alpha, \beta) \sin(\alpha) d\alpha d\beta$$

Bidirectional reflectance distribution function

Sky radiance

If the incident sky radiance is isotropic, we have

$$\int_0^{2\pi} \int_0^{\pi/2} \rho_{b,\lambda}(\alpha, \beta, \theta, \phi) \cos(\alpha) L_\lambda(\alpha, \beta) \sin(\alpha) d\alpha d\beta = \rho_\lambda(\theta, \phi) L_\lambda$$

Therefore for opaque bodies at thermal equilibrium,

$$\varepsilon_\lambda(\theta, \phi) = 1 - \rho_\lambda(\theta, \phi)$$



Hemispheric broadband radiometric surface temperature & Hemispherical broadband emissivity

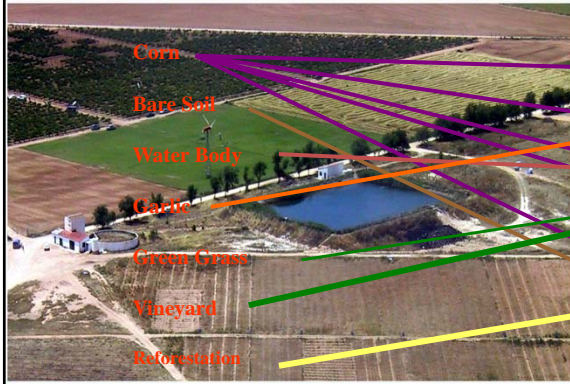
A hemispheric radiometric surface temperature is used to provide an estimate of the emitted radiance (R_l) over a broad wavelength and the full hemisphere of view

$$R_l = \int_0^{2\pi} \int_0^{\pi/2} \int_{\lambda_1}^{\lambda_2} \varepsilon_\lambda(\theta, \phi) R_{B,\lambda}(\theta, \phi) \sin(\theta) \cos(\theta) d\lambda d\theta d\phi = \varepsilon_\lambda \sigma T_R^4$$



In-Situ measurements of Surface Energy Balance- EAGLE/SPARC Campaign 2004, Barrax, Spain

- Situated in the area of La Mancha, in the west of the province of Albacete, 28 km from Albacete
- Geographic coordinates: 39° 3' N; 2° 6' W
- Altitude (above sea level): 700 m



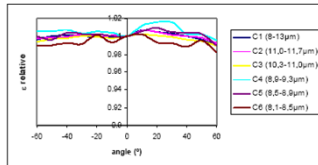
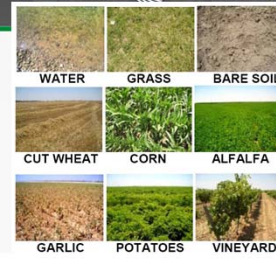
The Canopy from Different Perspectives



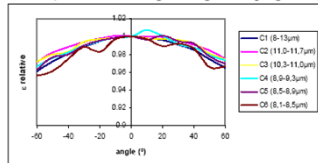


Factors Influencing the Emissivity ϵ

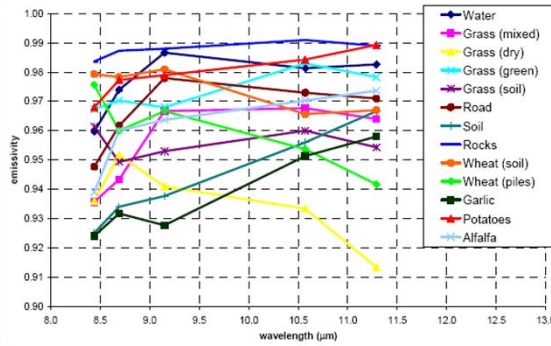
- The material (minerals, water etc.)
- The surface geometry (roughness of the surface)
- The wavelength of the radiation
- The view angle



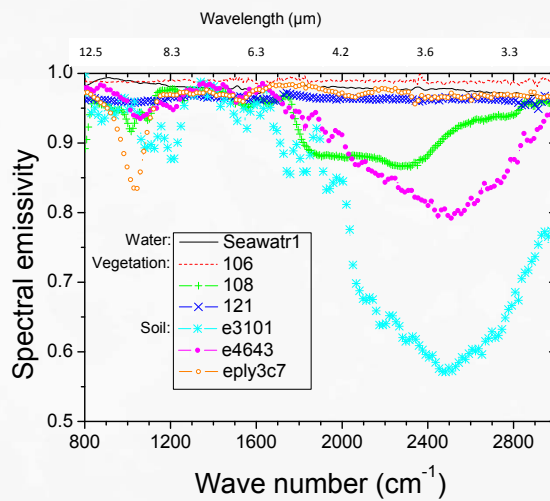
a) Bare soil during the night campaign



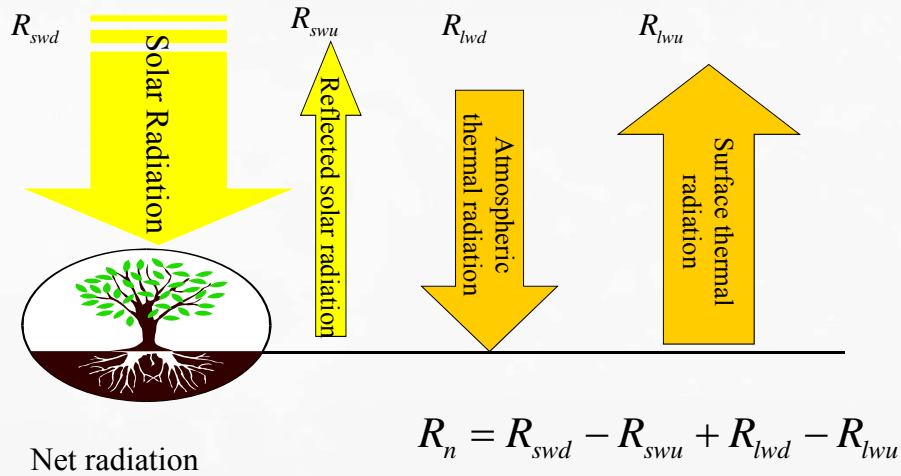
b) Green grass during the night campaign



Spectral emissivity extracted from MODIS UCSB Emissivity Library



Surface Radiation Budget - Measurements



Surface Radiation Budget - Measurements



CNR1 net radiometer:

Spectral response

- Pyranometer: 305 to 2800 nm
- Pyrgeometer: 5000 to 50000 nm

$$5 \mu m - 50 \mu m$$

$$(1 \mu m = 1000 nm)$$

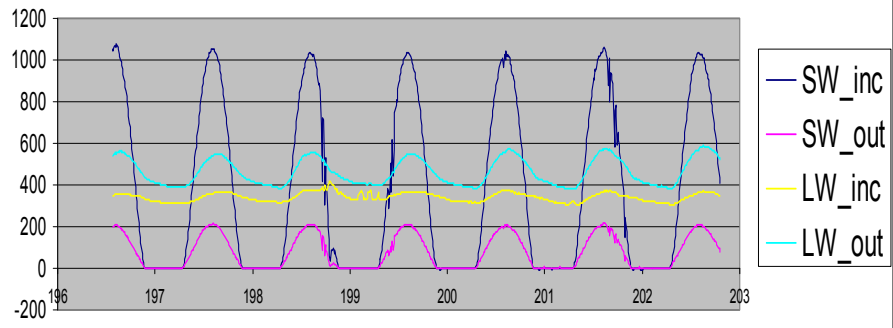
Radiation components:

1. incoming short-wave radiation
2. surface-reflected short-wave radiation
3. incoming (long-wave) thermal infrared radiation
4. outgoing (long-wave) TIR radiation

Albedo (whiteness): ratio of scattered to incident electromagnetic radiation

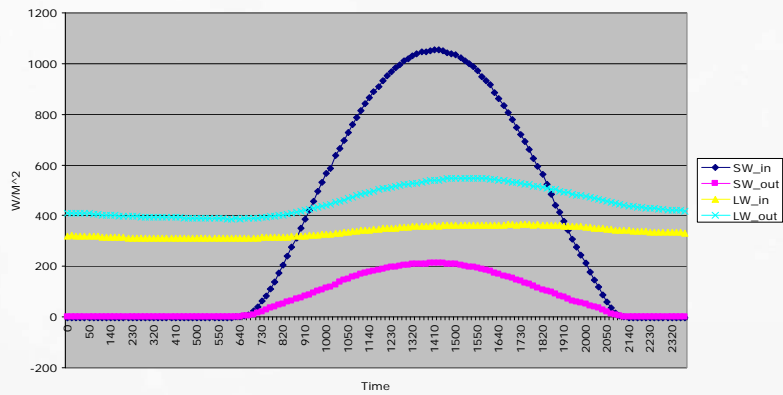
EAGLE/SPARC Campaign 2004, Barrax, Spain

Barrax 2004 Radiation @ Vineyard



EAGLE/SPARC Campaign 2004, Barrax, Spain

Radiation Components, Barrax, 15 July 2004



EAGLE/SPARC Campaign 2004, Barrax, Spain

Exercise:

1. Explain what are the influencing factors for the net radiation
2. Explain the pattern of the radiation components
3. Calculate the albedo from the radiation components



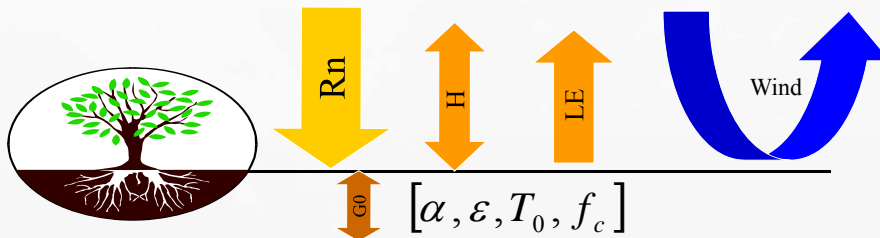
How is the net radiation consumed?

$$R_n = G_0 + H + LE + \Delta S$$

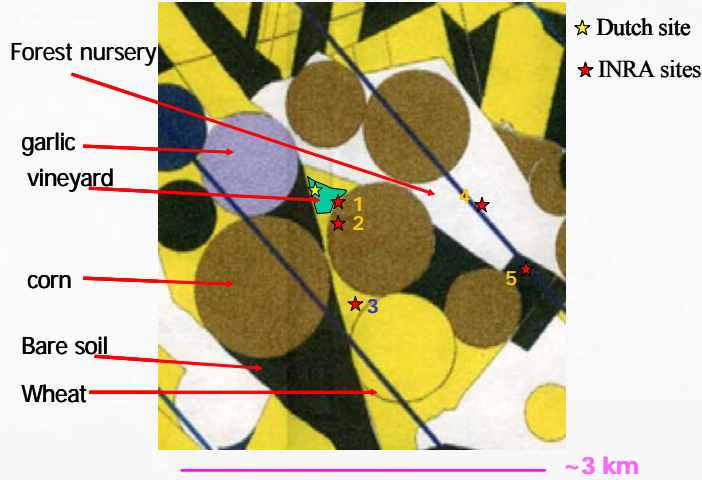
$$\Delta S \approx 0$$

Right hand side:

1. Soil heat flux (warming up of the soil layer)
2. Sensible heat flux (warming up of the air layer)
3. Latent heat flux (phase change, evaporation and transpiration)
4. Heat storage and biological activities



Locations of measurements

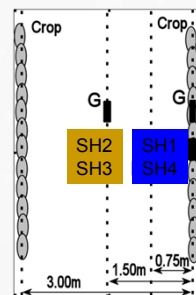


Source: Su et al., (2008)

Soil heat flux: measurements with soil heat flux plates

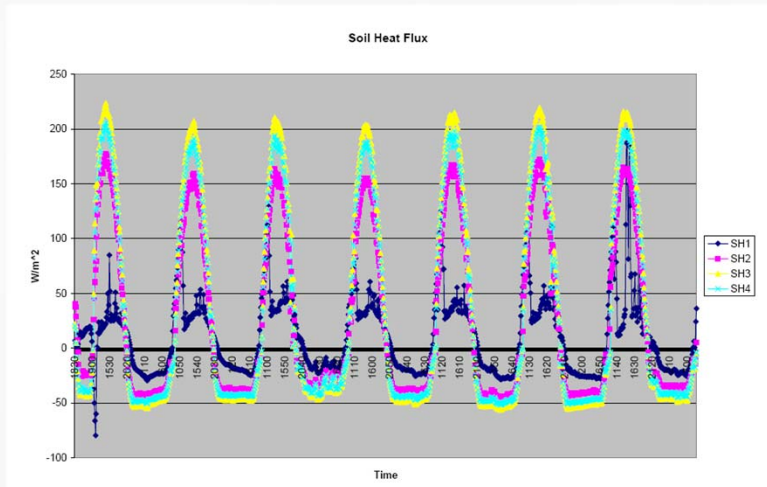
The soil heat fluxes were measured with 4 soil heat fluxes buried at a depth of 1cm below surface, with two placed in the middle of the row and two under the vine and shaded.

Soil heat flux plates:
SH1 and SH4 were in the shade
SH2 and SH3 were in the sunlit areas





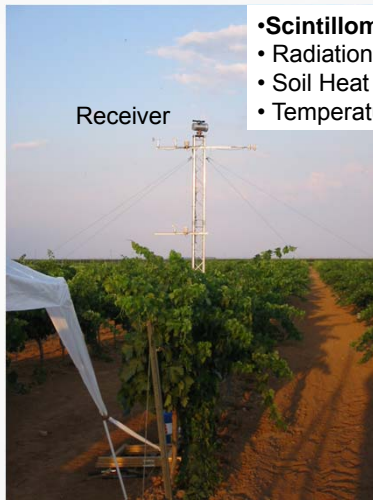
Soil heat flux: measurements with soil heat flux plates



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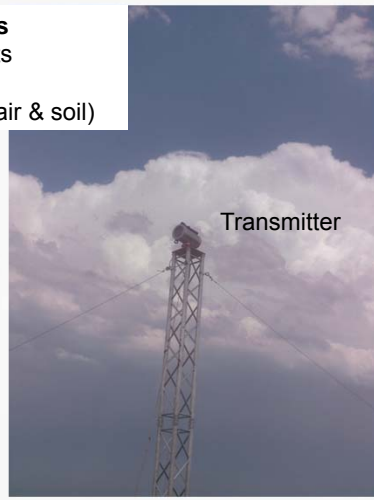


Sensible heat flux: scintillometer measurements



Receiver

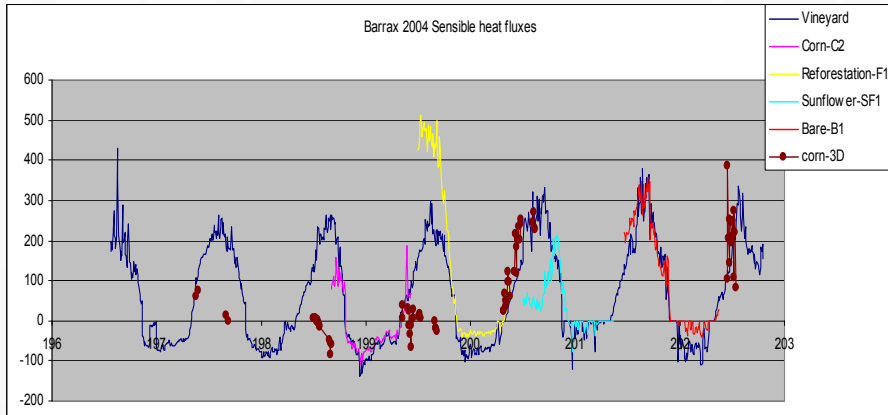
- Scintillometer, 2 Sets
- Radiation components
- Soil Heat flux plates
- Temperature profile (air & soil)



Transmitter

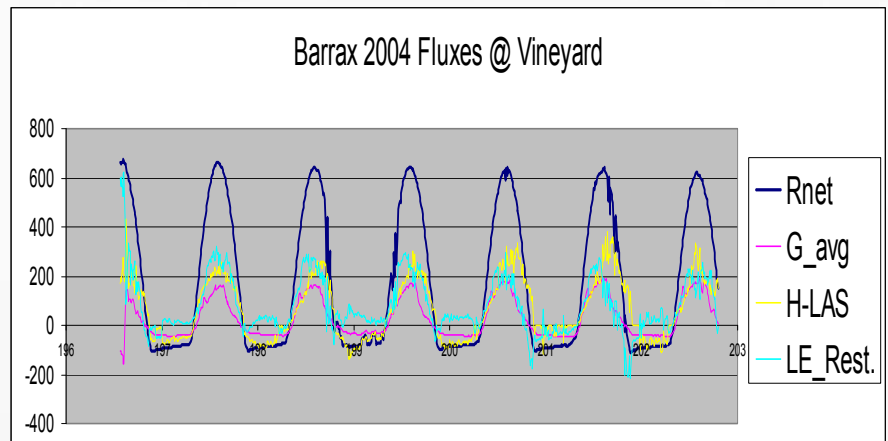
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Scintillometer Data, EAGLE/SPARC Campaign 2004, Barrax, Spain



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Scintillometer Data, EAGLE/SPARC Campaign 2004, Barrax, Spain



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Sensible & latent heat fluxes:
Eddy Covariance Measurements

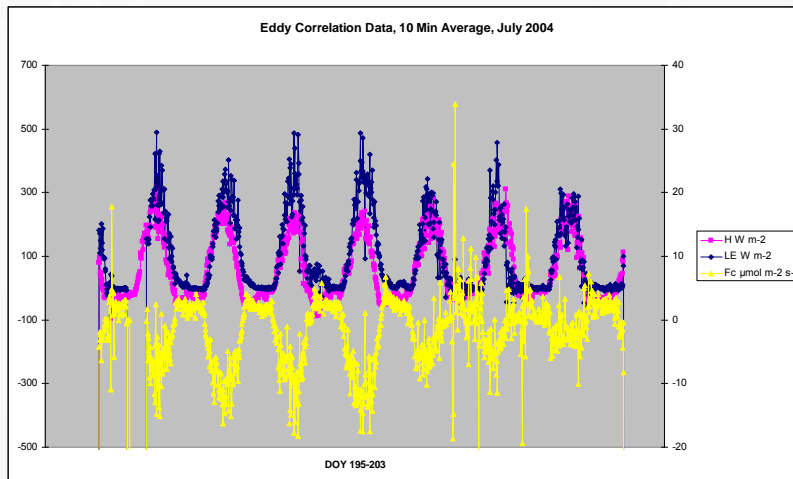


Canopy level measurements:

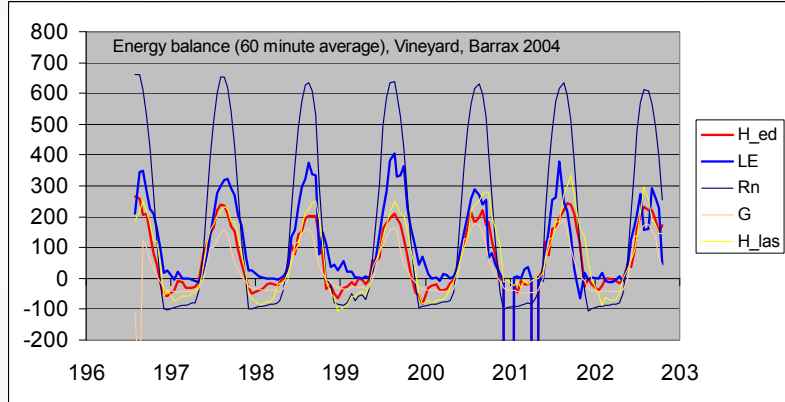
Eddy covariance system
(Gill 3D sonic + closed path Licor gasanalyser: CO₂ and H₂O + nitrogen reference gas + pneumatic mast + data loggers)

- Turbulence, sensible heat flux, H₂O, CO₂ fluxes
- CO₂ concentrations

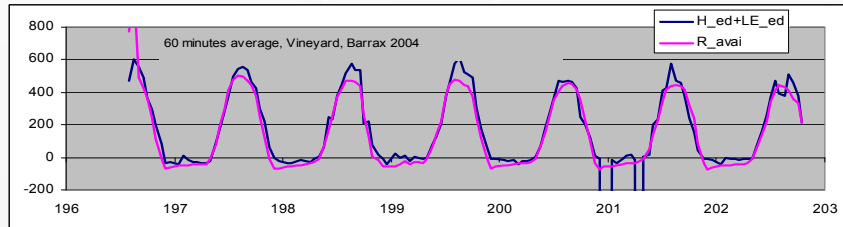
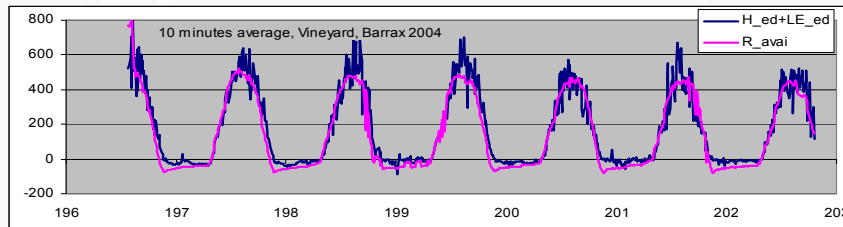
Flux data SPARC 2004





Energy balance components

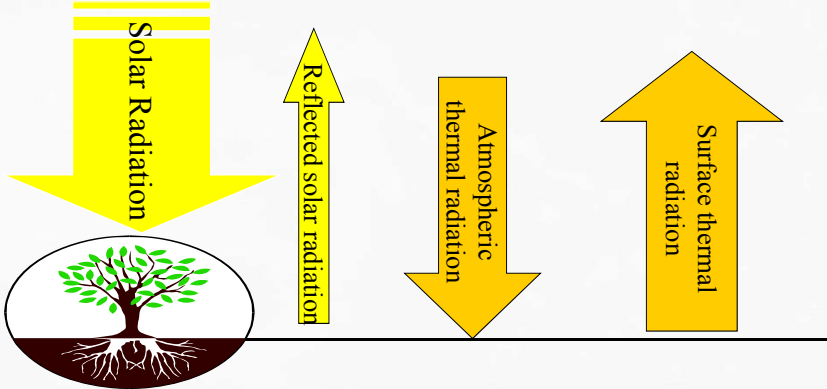


Energy balance closure ?? (Sum of H and LE exceeds the available energy)



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Surface Radiation Budget - Parameterisation

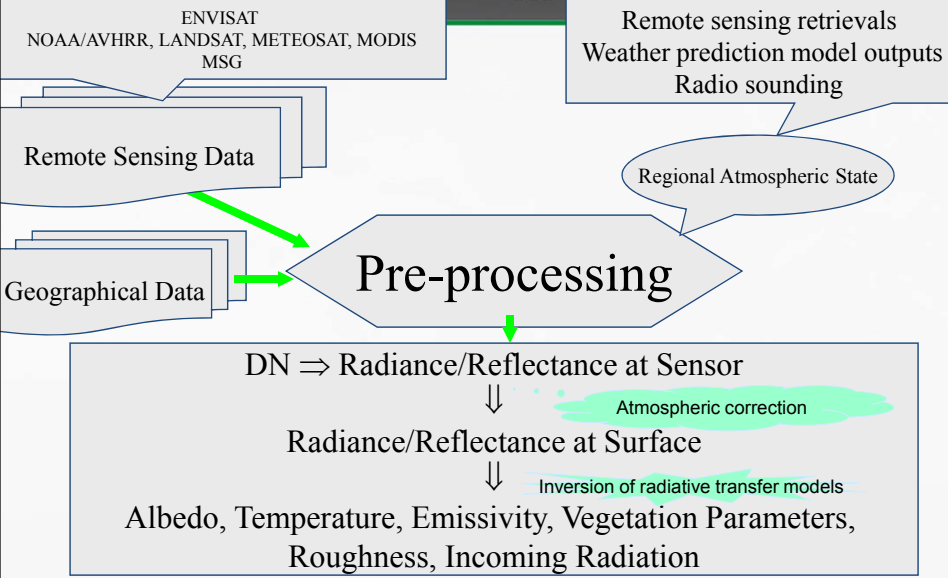


$$R_n = (1 - \alpha) \cdot R_{swd} + \varepsilon \cdot R_{lwd} - \varepsilon \cdot \sigma \cdot T_0^4$$

α : albedo
 ε : emissivity
 T_0 : Surface Temperature

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ENVIAT
 NOAA/AVHRR, LANDSAT, METEOSAT, MODIS
 MSG

Remote Sensing Data

Geographical Data

Pre-processing

DN \Rightarrow Radiance/Reflectance at Sensor
 \Downarrow Atmospheric correction
 Radiance/Reflectance at Surface
 \Downarrow Inversion of radiative transfer models
 Albedo, Temperature, Emissivity, Vegetation Parameters,
 Roughness, Incoming Radiation

Remote sensing retrievals
 Weather prediction model outputs
 Radio sounding

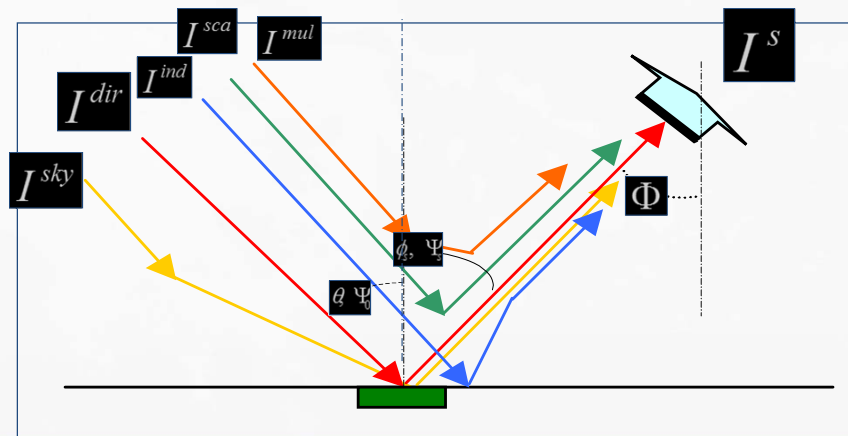
Regional Atmospheric State

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Derived Surface Parameters/variables

- Incoming global radiation
- Albedo
- Vegetation cover, Leaf Area Index
- Surface temperature
- Emissivity
- Roughness

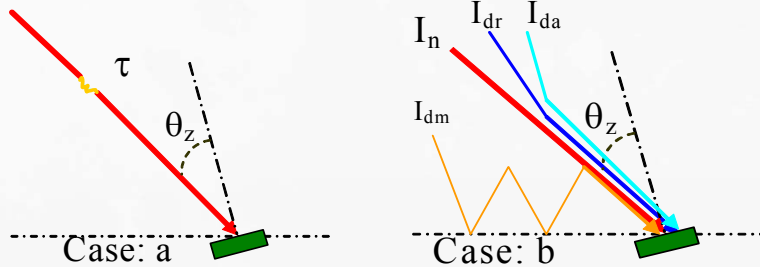
Components of reflected and scattered solar beams received at the satellite



Incoming global radiation

Input parameters:

- Group 1: date, time, location (latitude) and DEM (elevation, slope, aspect) to compute solar declination, eccentricity, solar zenith angle for a horizontal surface, solar azimuth angle, solar zenith angle on slopes
- Group2: weather condition - Optical properties of the atmosphere (at the time of calculation)



Incoming global radiation

- Case a: use total optical depth

$$I = I_{sc} \cdot e_0 \cdot \cos \theta_z \cdot \exp(-m \cdot \tau)$$

- where I_{sc} is the solar constant, e_0 the eccentricity factor, θ_z solar zenith angle, m air mass, τ the optical depth



Incoming global radiation (cont.)

Case b: use water-vapor / horizontal visibility

$$I = I_n + I_d$$

$$= I_n + I_{dr} + I_{da} + I_{dm} = (I_n + I_{dr} + I_{da}) \cdot \frac{1}{1 - \rho_g \cdot \rho'_a}$$

where the direct solar radiation is

$$I_n = 0.9751 \cdot I_{sc} \cdot e_0 \cdot \cos(\theta_z) \cdot \tau_r \cdot \tau_o \cdot \tau_g \cdot \tau_w \cdot \tau_a$$

etc.

References:

M. Iqbal (1983) An introduction to solar radiation, Academic Press, Toronto. p.188-191.

R. Bird and R.L. Hulstrom (1980) Direct insolation models, Trans. ASME J. Sol. Energy Eng., 103, 182-192.

R. Bird and R.L. Hulstrom (1981) A simplified clear sky model for direct and diffuse insolation on horizontal surfaces, SERI/TR-642-761, Solar Energy Research Institute, Golden, Colorado.



Surface Albedo & NDVI

Algorithms

- Calculate surface bidirectional reflectance of narrow band
- Derive surface broad-band albedo from narrow surface reflectance
- Derive NDVI from band RED & NIR surface reflectance
- (Ref. Lecture optical remote sensing)



Surface temperature

Algorithms

Land surface temperature derived by using a theoretical split-window algorithm

References: Sorino et al.(2004)



The radiative transfer equation for LST retrieval

The at-sensor radiance for a given wavelength (λ) s:

$$L_{\lambda\theta}^{at-sensor} = \left[\varepsilon_{\lambda\theta} B_{\theta}(\lambda, T_s) + (1 - \varepsilon_{\lambda\theta}) L_{\lambda}^{atm\downarrow} \right] \tau_{\lambda\theta} + L_{\lambda\theta}^{atm\uparrow}$$

where

- $\varepsilon_{\lambda\theta}$ is the surface emissivity,
- $B_{\theta}(\lambda, T_s)$ is the radiance emitted by a blackbody at temperature T_s of the surface,
- $L_{\lambda}^{atm\downarrow}$ is the downwelling radiance,
- $\tau_{\lambda\theta}$ is the total transmission of the atmosphere (transmittance) and
- $L_{\lambda\theta}^{atm\uparrow}$ is the upwelling atmospheric radiance. All these magnitudes also depend on the observation angle θ .



According to Sobrino et al. (1996), the upwelling and downwelling atmospheric radiance can be substituted, respectively, by:

$$L_{\lambda}^{atm \uparrow} = (1 - \tau_{i\theta}) B_i(T_a)$$

$$L_{\lambda}^{atm \downarrow} = (1 - \tau_{i53}) B_i(T_a)$$

where T_a is the effective mean atmospheric temperature and τ_{i53} is the total atmospheric path transmittance at 53 degrees.



Split-window equations to derive land surface temperature

Substituting both atmospheric radiances in the radiative transfer equation, an algorithm involving temperatures can be obtained using a first-order Taylor series expansion of the Planck's law and writing the equation for i and j (i and j being two different channels observed at the same angle, Split-Window method):

$$T_s = T_i + A(T_i - T_j) - B_0 + (1 - \varepsilon_i) B_1 - \Delta \varepsilon_0 B_2$$

where A and B_i are coefficients that depend on atmospheric transmittances, ε_i is the mean value of the emissivities of channels i and j , $\Delta \varepsilon_0$ is the spectral variation, T_i and T_j are the brightness temperatures for two different channels with the same view angle.

This equation is the so-called split-window equation and gives a separation between the atmospheric and emissivity effects in the retrieval of surface temperature.



Split-window and dual-angle algorithms for AATSR sensor with values of the coefficients calculated by a minimization process

Numerical coefficients and errors for the Split-window algorithms
(Sobrino and Soria, 2006)

NAME	EXPRESSION	σ_{mod} (K)	σ_{noise} (K)	σ_{ϵ} (K)	σ_{WV} (K)	σ_{total} (K)
SW 1: quad	$T_s = T_{2n} + 0.61(T_{2n}-T_{1n}) + 0.31(T_{2n}-T_{1n})^2 + 1.92$	1.73	0.07	-	-	1.73
SW 2: quad, ϵ	$T_s = T_{2n} + 0.76(T_{2n}-T_{1n}) + 0.30(T_{2n}-T_{1n})^2 + 0.10 + 51.2(1-\epsilon)$	1.39	0.07	0.18	-	1.40
SW 3: quad, $\epsilon, \Delta\epsilon$	$T_s = T_{2n} + 1.03(T_{2n}-T_{1n}) + 0.26(T_{2n}-T_{1n})^2 - 0.11 + 45.23(1-\epsilon) - 79.95\Delta\epsilon$	1.05	0.09	0.59	-	1.20
SW 4: (W), $\epsilon, \Delta\epsilon, W$	$T_s = T_{2n} + (1.01 + 0.53W)(T_{2n}-T_{1n}) + (0.4-0.85W) + (63.4-7.01W)(1-\epsilon) - (111-17.6W)\Delta\epsilon$	0.59	0.10	0.83	0.45	1.12
SW 5: quad, $\epsilon, \Delta\epsilon, W$	$T_s = T_{2n} + 1.35(T_{2n}-T_{1n}) + 0.22(T_{2n}-T_{1n})^2 - (0.82-0.15W) + (62.6-7.2W)(1-\epsilon) - (144-26.3W)\Delta\epsilon$	0.93	0.11	1.06	0.20	1.43
SW 6: quad(W), $\epsilon, \Delta\epsilon, W$	$T_s = T_{2n} + (1.97+0.2W)(T_{2n}-T_{1n}) - (0.26-0.08W)(T_{2n}-T_{1n})^2 + (0.02-0.67W) + (64.5-7.35W)(1-\epsilon) - (119-20.4W)\Delta\epsilon$	0.52	0.15	0.89	0.37	1.10



Notation:

- n: Nadir view;
- f: Forward view;
- SW: Split-Window Method (two spectral channels at the same observation angle)
- quad: algorithm that includes a quadratic dependence on (Ti-Tj);
- (1): AATSR Channel 1 (12 μm);
- (2): AATSR Channel 2 (11 μm);
- W: algorithm with water vapor content dependence;
- ϵ : algorithm with emissivity dependence;
- $\Delta\epsilon$: algorithm including spectral or angular emissivity difference.



Emissivity

Algorithms

Estimation of surface emissivity using the theoretical model of Caselles and Sobrino (1989).

References:

V. Caselles and J.A. Sobrino (1989) Determination of frosts in orange groves from NOAA-9 AVHRR data, *RSE*, 29:135-146.

E. Valor and V. Caselles (1995) Mapping land surface emissivity from NDVI: Application to European, African, and South American Areas, *RSE*, 57:167-184.

Sobrino and Soria (2006)



Thresholds Method (NDVITHM)

A simplified method to emissivity, ϵ , using atmospherically corrected data in the visible and near infrared channels (Sobrino and Raissouni, 2000). Three different surface types: bare soil pixels ($NDVI < 0.2$), mixed pixels ($0.2 < NDVI < 0.5$) and fully vegetation pixels ($NDVI > 0.5$).

The NDVI is calculated with reflectivity values from the Red region (ρ_{red}) and Near Infrared (ρ_{nir}) region:

$$NDVI = \frac{\rho_{red} - \rho_{nir}}{\rho_{red} + \rho_{nir}}$$

AATSR channels centred in $0.67 \mu m$ and $0.87 \mu m$ used for ρ_{red} and ρ_{nir} respectively.

**Thresholds Method (NDVITHM)**

The final expressions obtained for this method are for bare soil pixels ($NDVI < 0.2$),

$$\begin{aligned}\varepsilon &= 0.9825 - 0.051 \rho_{red} \\ \Delta\varepsilon &= -0.0001 - 0.041 \rho_{red}\end{aligned}$$

for mixed pixels ($0.2 \leq NDVI \leq 0.5$),

$$\begin{aligned}\varepsilon &= 0.971 + 0.018 f_c \\ \Delta\varepsilon &= 0.006 (1 - f_c)\end{aligned}$$

and for vegetation pixels ($NDVI > 0.5$),

$$\varepsilon = 0.990$$

with f_c being the vegetation proportion, given by

$$f_c = \left(\frac{NDVI - NDVI_{min}}{NDVI_{max} - NDVI_{min}} \right)^2$$

where $NDVI_{min} = 0.2$ and $NDVI_{max} = 0.5$. The main constraint of this method is that it can not be used to extract water emissivity values because it is not possible to apply the NDVI and f_c equations for water pixels.

**Roughness**

Total roughness $Z_0 = \sqrt{Z_{0or}^2 + Z_{0vg}^2}$

Orographic roughness $Z_{0or} = \frac{1}{p_{size}} \cdot v$

Vegetation roughness $Z_{0vg} = f(h, f_c)$

(h - vegetation height, f_c – fractional coverage)

**Questions:**

- 1. What is surface radiation budget**
- 2. List some methods to derive surface radiation components**
- 3. What information is needed in order to derive surface radiation components using the above mentioned methods**
- 4. What are the essential surface parameters in determination of surface radiation balance**

**References/Further Readings**

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Field experimental data access:

**SPARC2004, SEN2FLEX2005, EAGEL2006 data,
REFLEX2012 data**

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