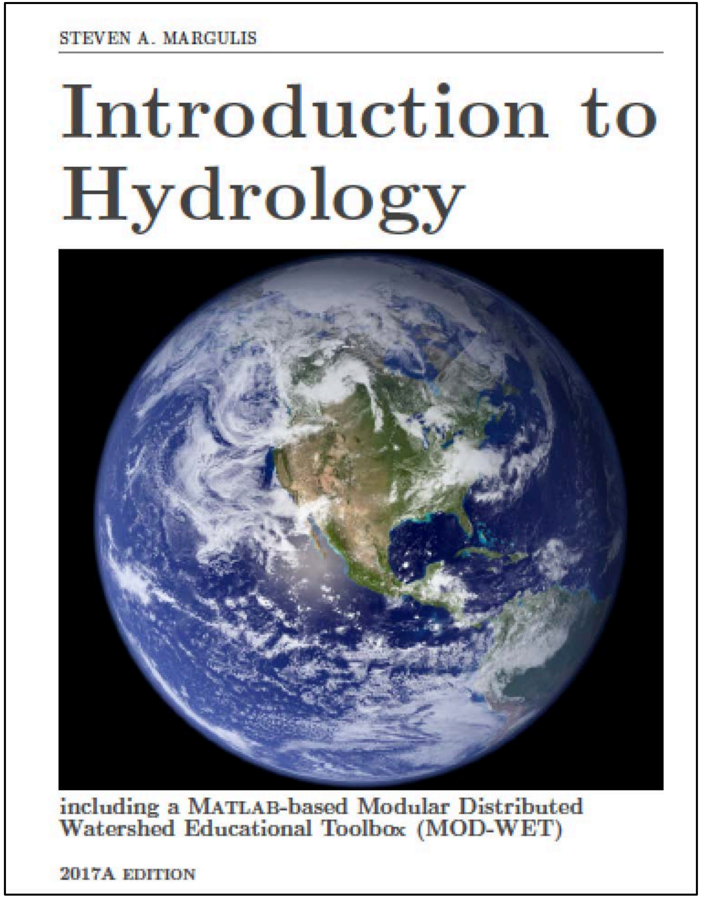
CIE5401: GIS and Remote Sensing for Water Resources Management

Lecture 5: Thermal Remote Sensing & Evapotranspiration

Susan Steele-Dunne

March 2018

Acknowledgements



- **Prof. Steven Margulis, UCLA**
- **Prof. Wim Bastiaanssen, UNESCO-IHE**
- **Betts, A.K. and Ball, J.H., 1998. FIFE surface climate and site-average dataset 1987–89. Journal of the Atmospheric Sciences, 55(7), pp. 1091-1108.**

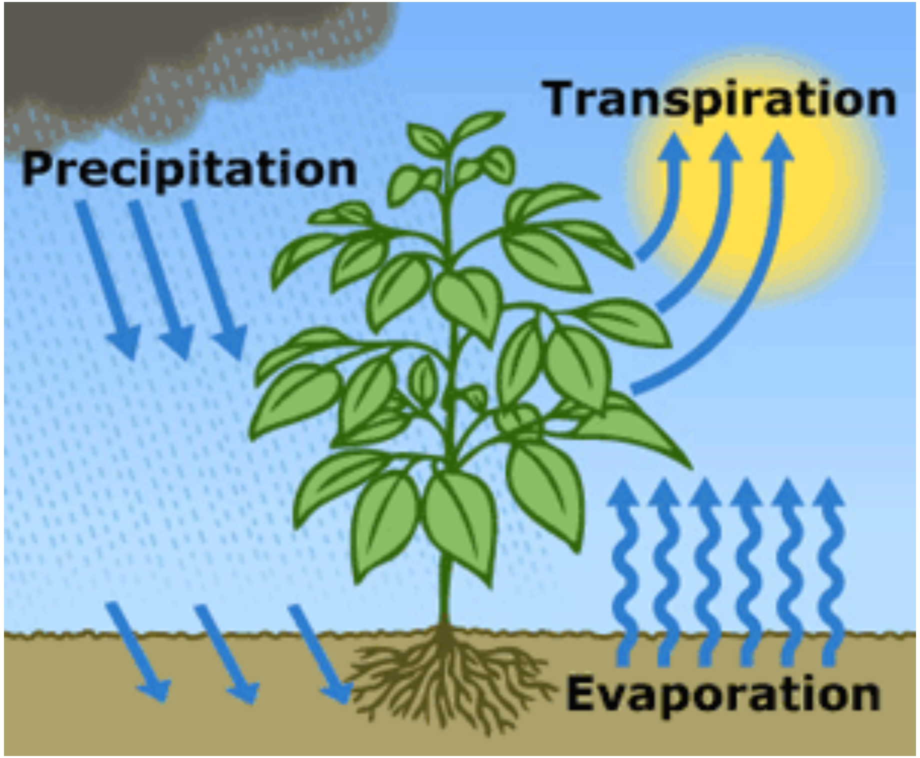
Learning Objectives

By the end of today's lecture, you will be able to:

- Explain what **ET** is, and why we need to observe it
- Understand and explain the difference between **shortwave and longwave radiation**
- Understand and be able to estimate the components of **net radiation** from RS
- Be able to estimate ET from RS data as the **residual of the energy balance**

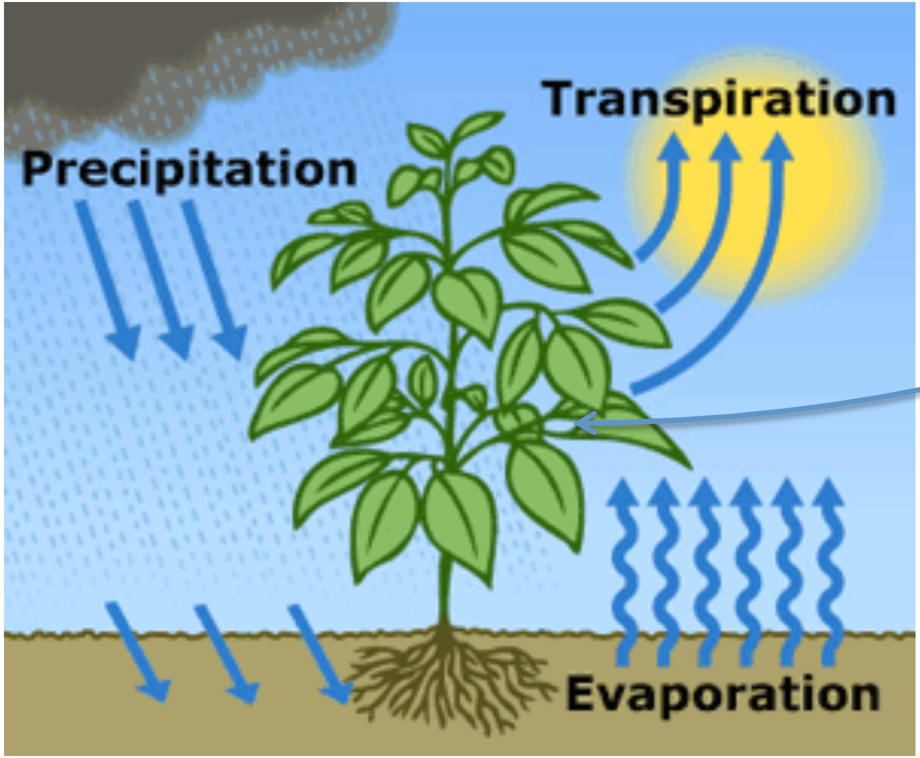
Evapotranspiration (ET) : What is it?

ET= Evaporation + Transpiration



Evapotranspiration (ET) : What is it?

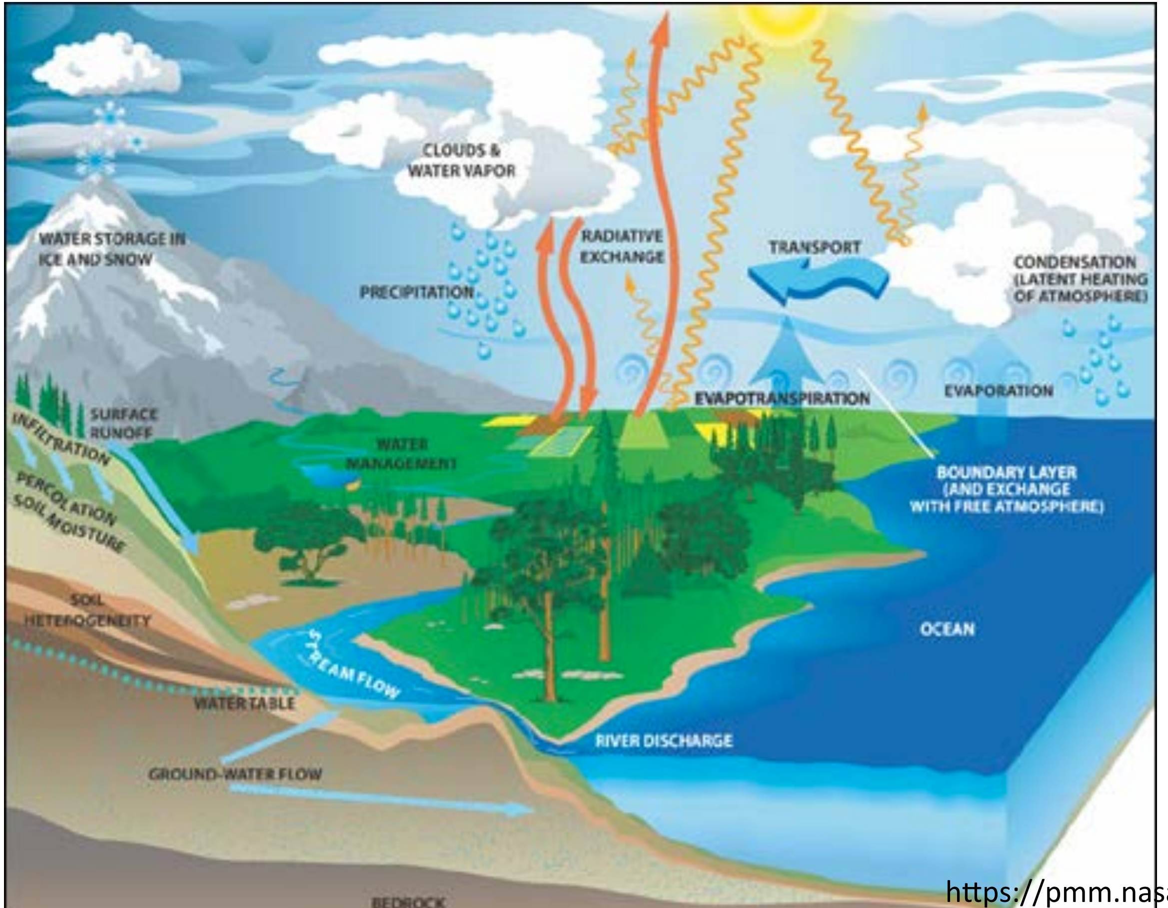
ET= Evaporation + Transpiration



Evaporation

Don't forget evaporation of intercepted water!

ET: Why do we need to know it?

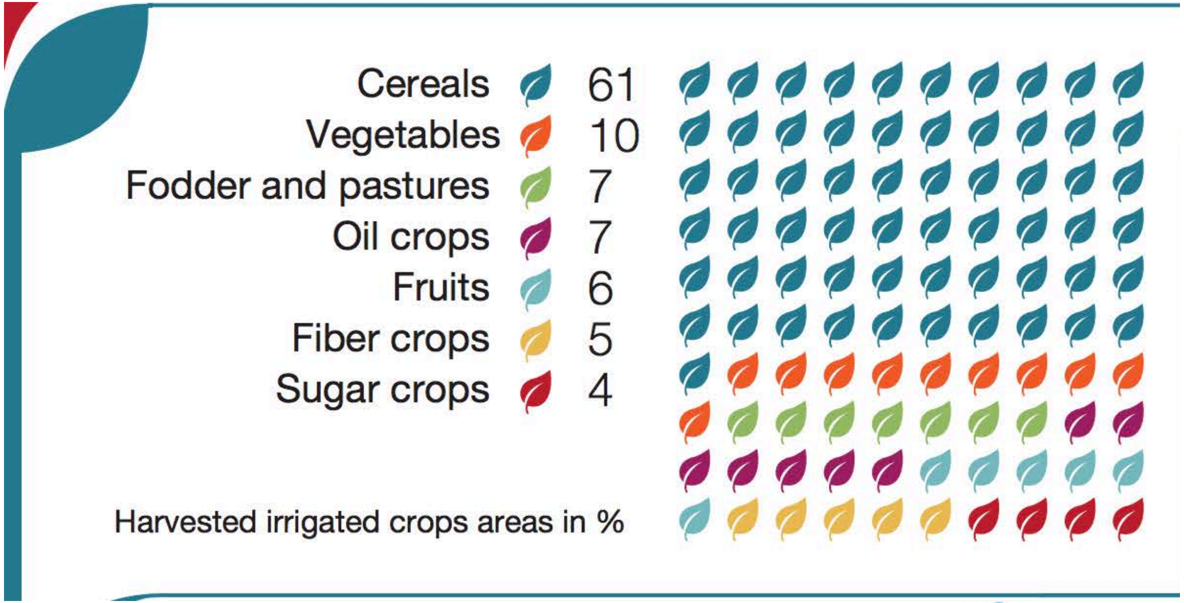


Long-term water balance

https://pmm.nasa.gov/education/articles/nasa-earth-science-water-cycle

ET: Why do we need to know it?

70% of water withdrawals are for irrigated agriculture
Irrigated crops account for 40% of worldwide crop production



water footprint network

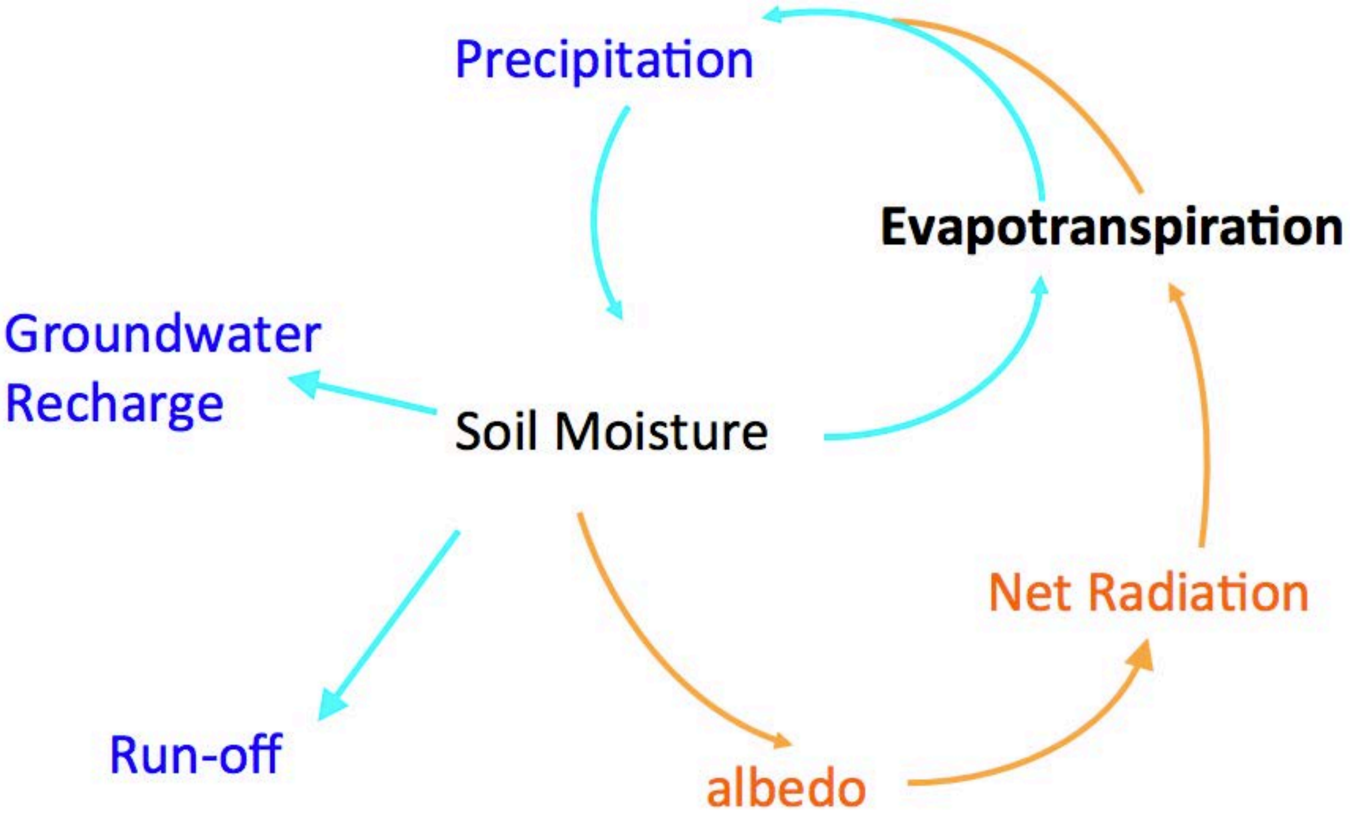
www.fao.org

http://waterfootprint.org

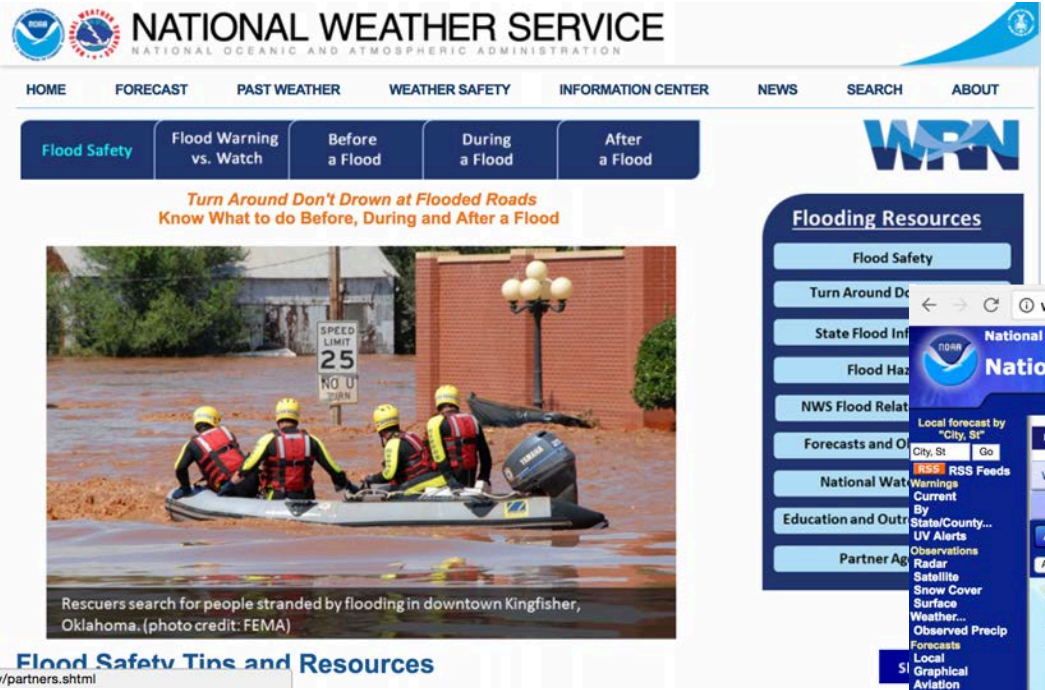
Table 1: Typical values for the volume of water required to produce common foodstuffs[37]

Foodstuff	**Quantity**	**Water consumption**
Apple	1 kg	822 litres
Banana	1 kg	790 litres
Beef	1 kg	15,415 litres
Beer	1 × 250ml glass	74 litres
Bio-diesel	1 litre	11,397 litres
Bread	1 kg	1,608 litres
Butter	1 kg	5,553 litres
Cabbage	1 kg	237 litres
Cheese	1 kg	3,178 litres
Chicken meat	1 kg	4,325 litres
Chocolate	1 kg	17,196 litres
Egg	1	196 litres
Milk	1 × 250ml glass	255 litres
Olives	1 kg	3,025 litres
Pasta (dry)	1 kg	1,849 litres
Pizza	1 unit	1,239 litres
Pork	1 kg	5,988 litres
Potatoes	1 kg	287 litres
Rice	1 kg	2,497 litres
Sheep Meat	1 kg	10,412 litres
Tea	1 × 250 ml cup	27 litres
Tomato	1 kg	214 litres
Wine	1 x 250ml glass	109 litres
Cotton	1 @ 250g	2,495 litres

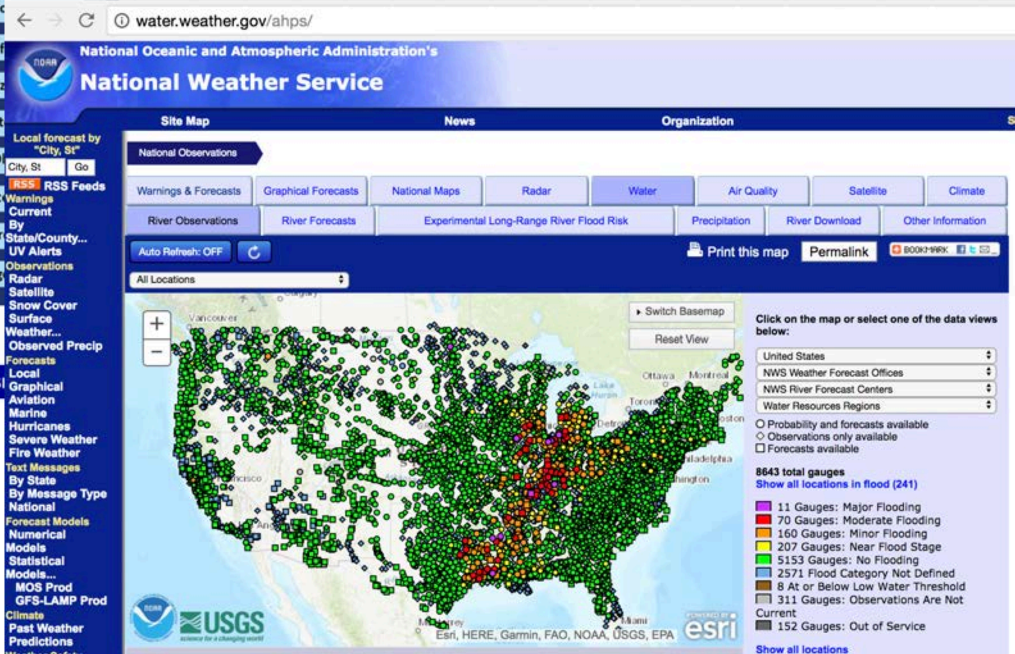
ET: Why do we need to know it?



ET: Why do we need to know it?



Influence on antecedent soil moisture



ET: Why do we need to know it?

Source of moisture for "downstream"

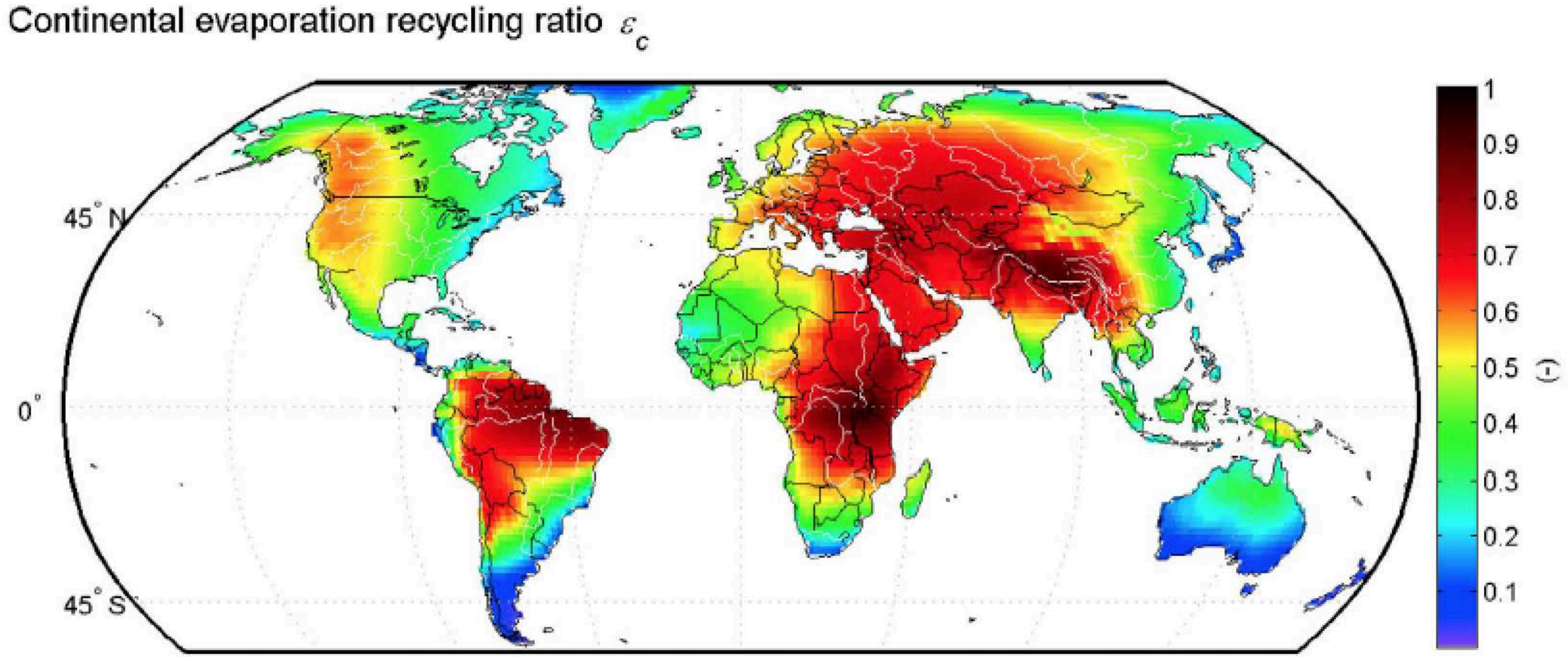


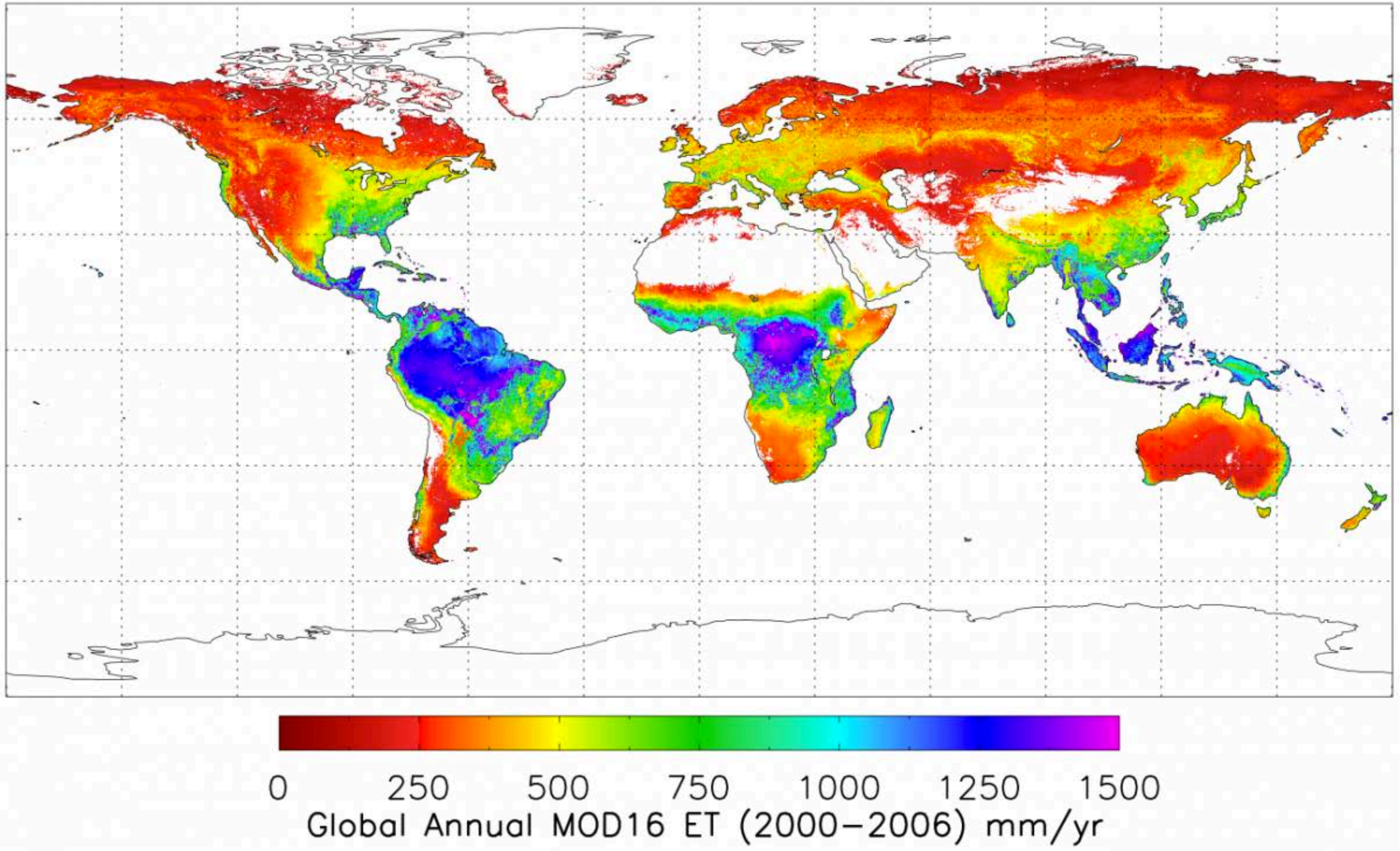
Figure 4. Average continental evaporation recycling ratio ε_c (1999–2008).

van der Ent, Schaefli, Savenije and Steele-Dunne (WRR, 2010)

ET: What do we need for ET to happen?

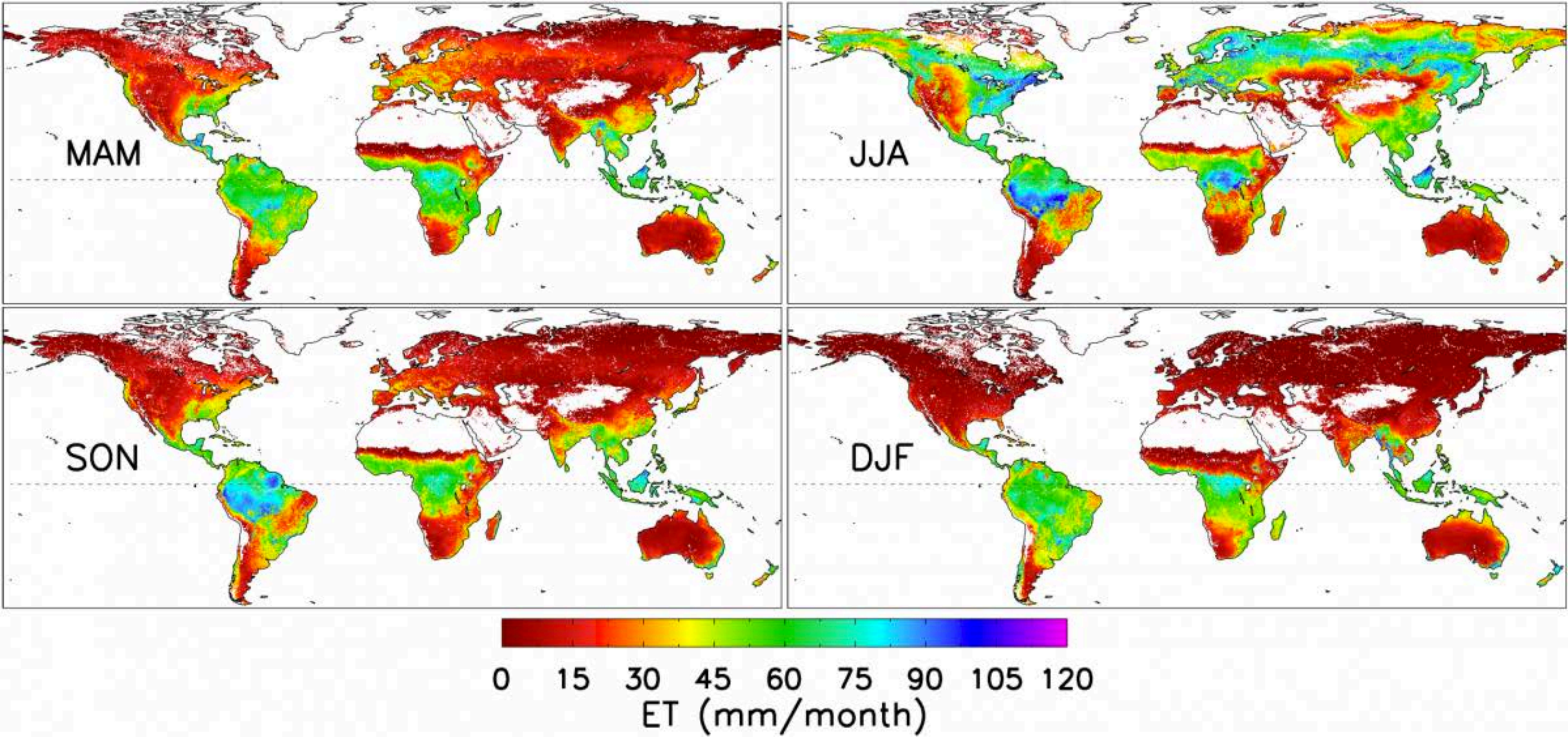
Jody Dole / Getty Images

ET: What do we need for ET to happen?



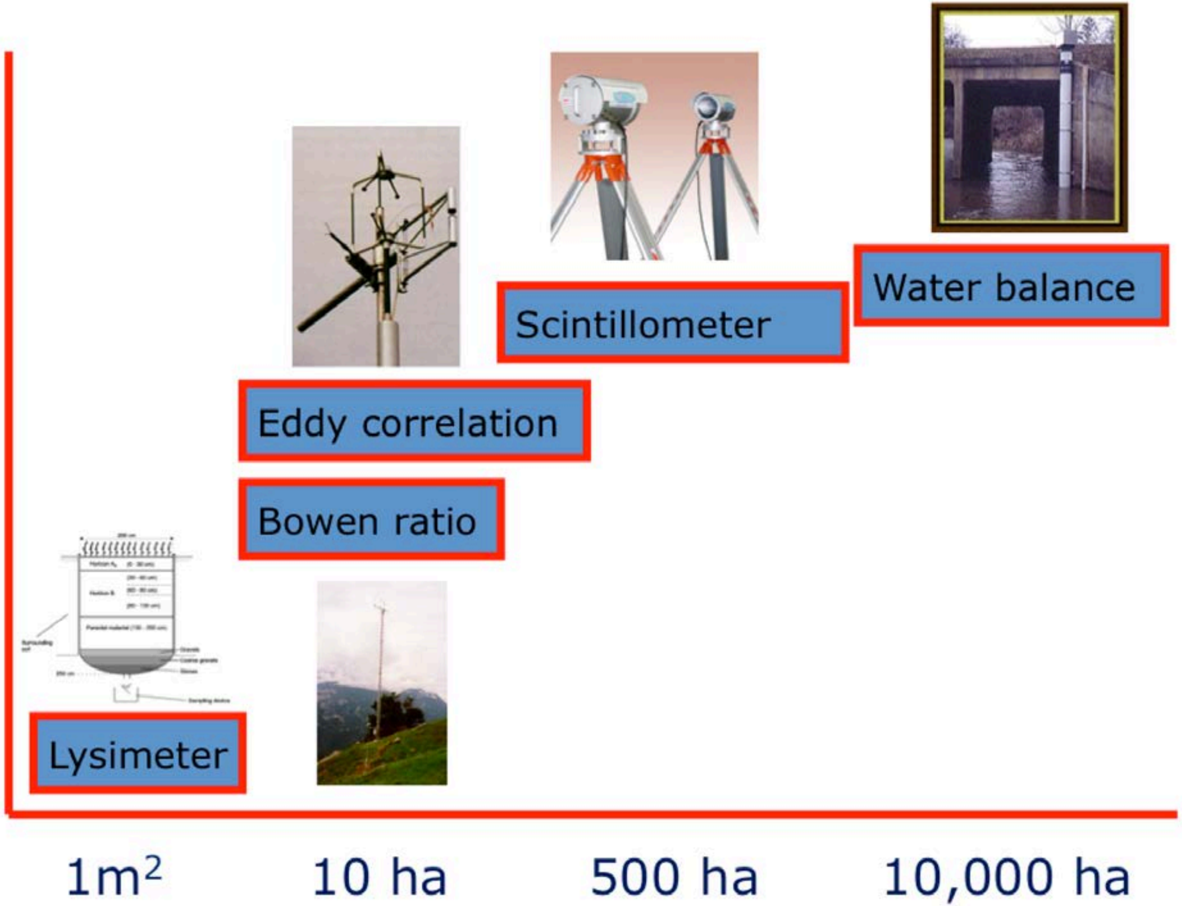
http://www.ntsg.umt.edu/project/modis/mod16.php

ET: What do we need for ET to happen?



http://www.ntsg.umt.edu/project/modis/mod16.php

ET: How can we measure it?



ET: How can we measure it?

High Resolution	Low Resolution
DisALEXI	ALEXI
ETLook	ETLook
SSEBop	SSEBop
SEBAL/METRIC	SEBS
S-SEBI	MOD16
EEFlux(Google)	CMRS-ET
	GLEAM

ET: How can we measure it?

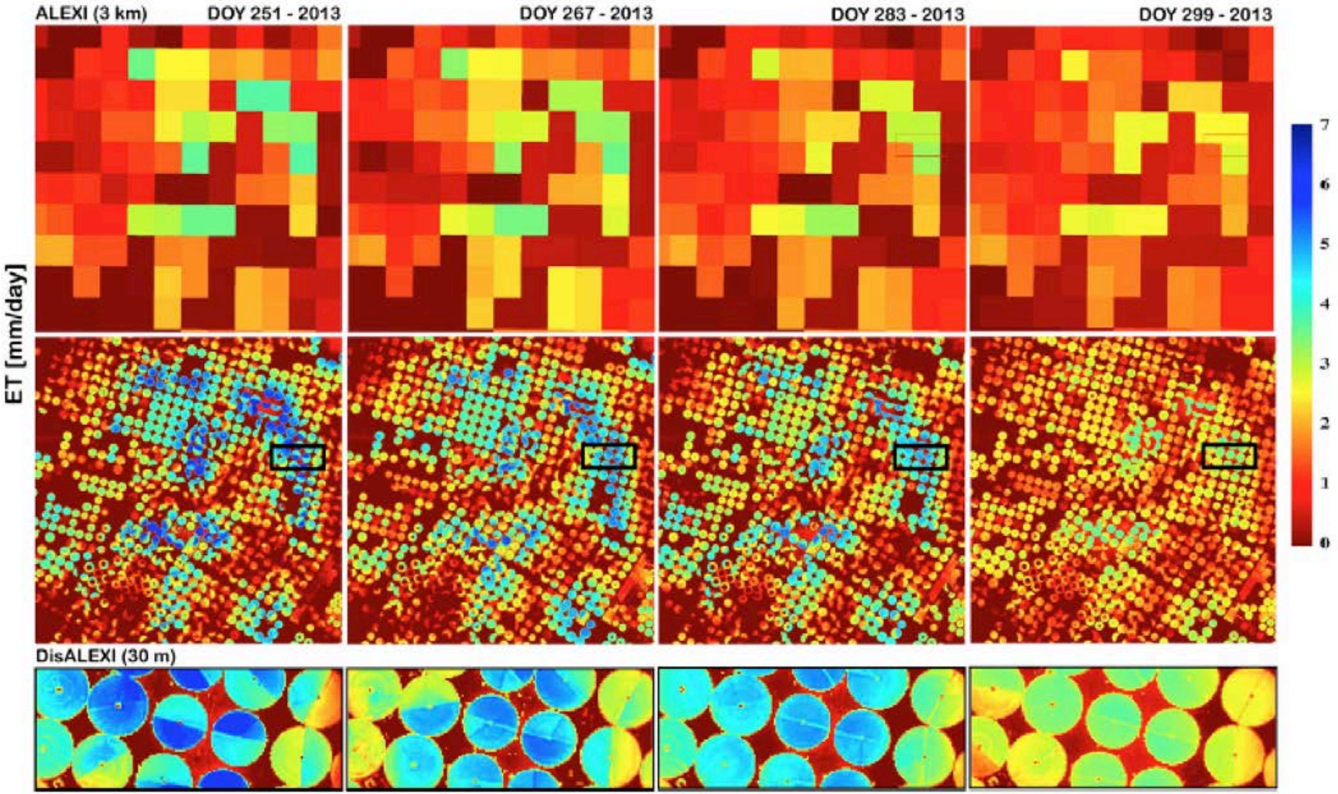
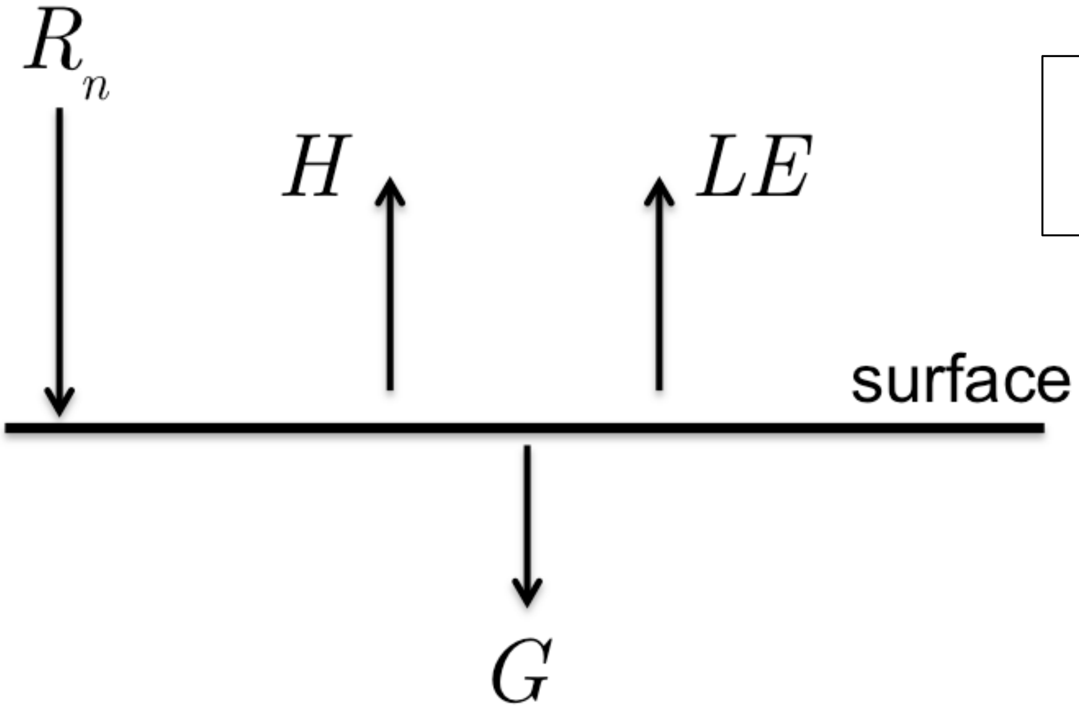


Fig. 2. Sequence of ALEXI (3km) and DisALEXI (30m) evaporation maps over irrigated agriculture in the Al Jawf province. The disaggregation restores sub-pivot scale variations with a clear response of wetting and drying.

McCabe et al. (2015) (http://ieeexplore.ieee.org/document/7325901/?arnumber=7325901)

ET: How can we measure ET with Remote Sensing?

Monitor the Surface Energy Balance using Thermal Remote Sensing

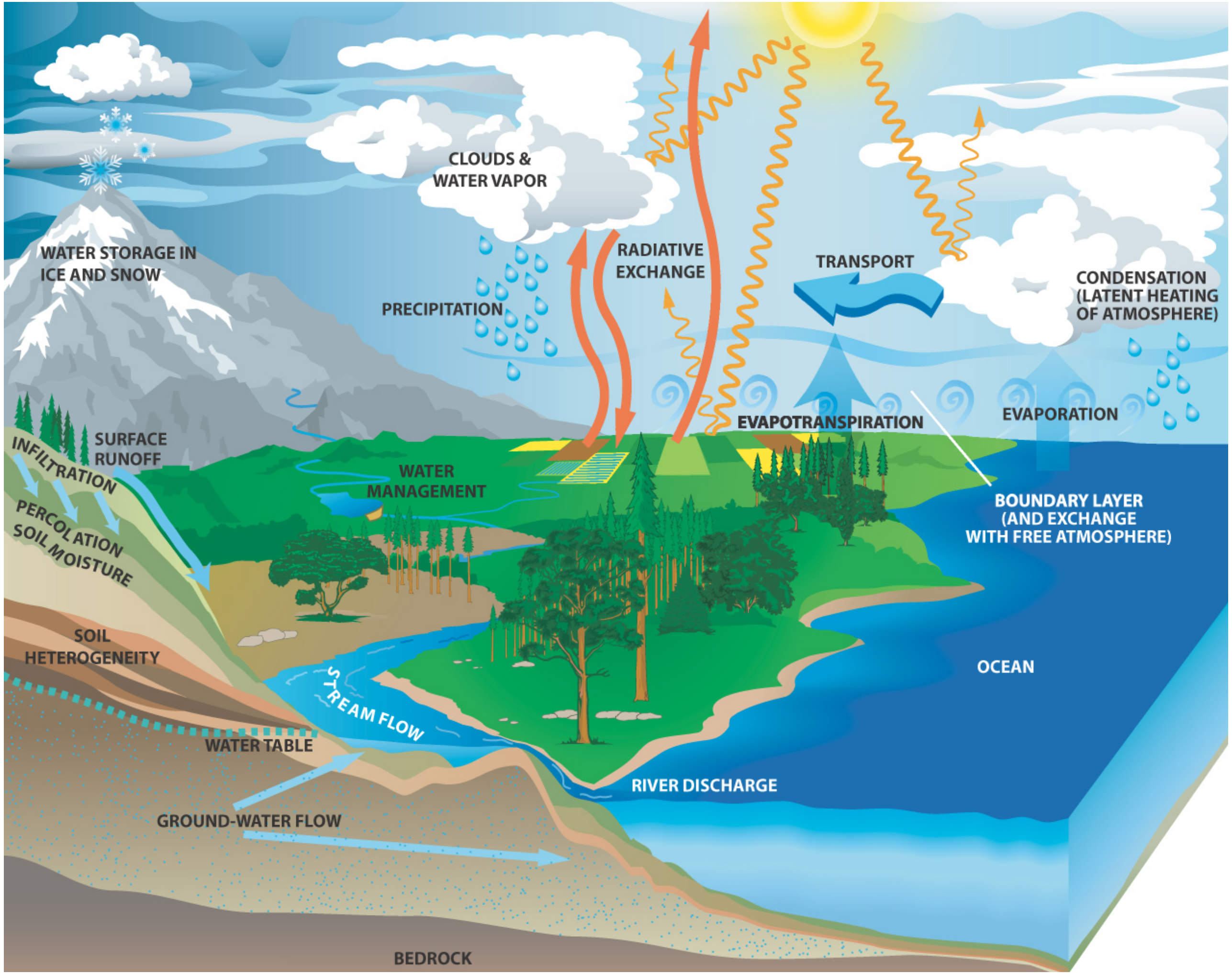


$$R_n = LE + H + G$$

Latent heat flux
(aka Evapotranspiration)

Lecture Outline

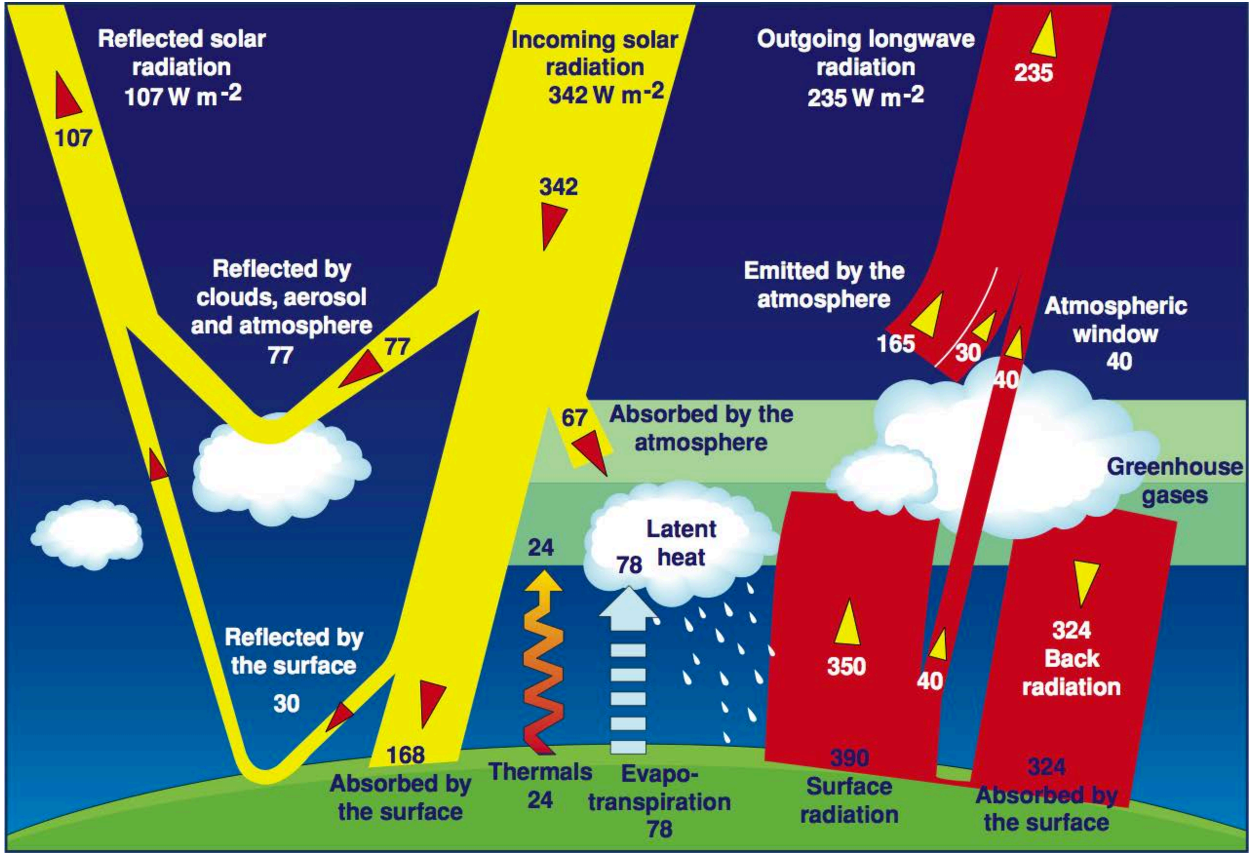
- Introduction
- Radiation Basics
- Surface Energy Balance
- The SEBAL Approach
- Guest Lectures: Yang Lu (TU Delft), NEO



What drives the Hydrological Cycle?

(Margulis, 2017)

Radiative energy from the sun!

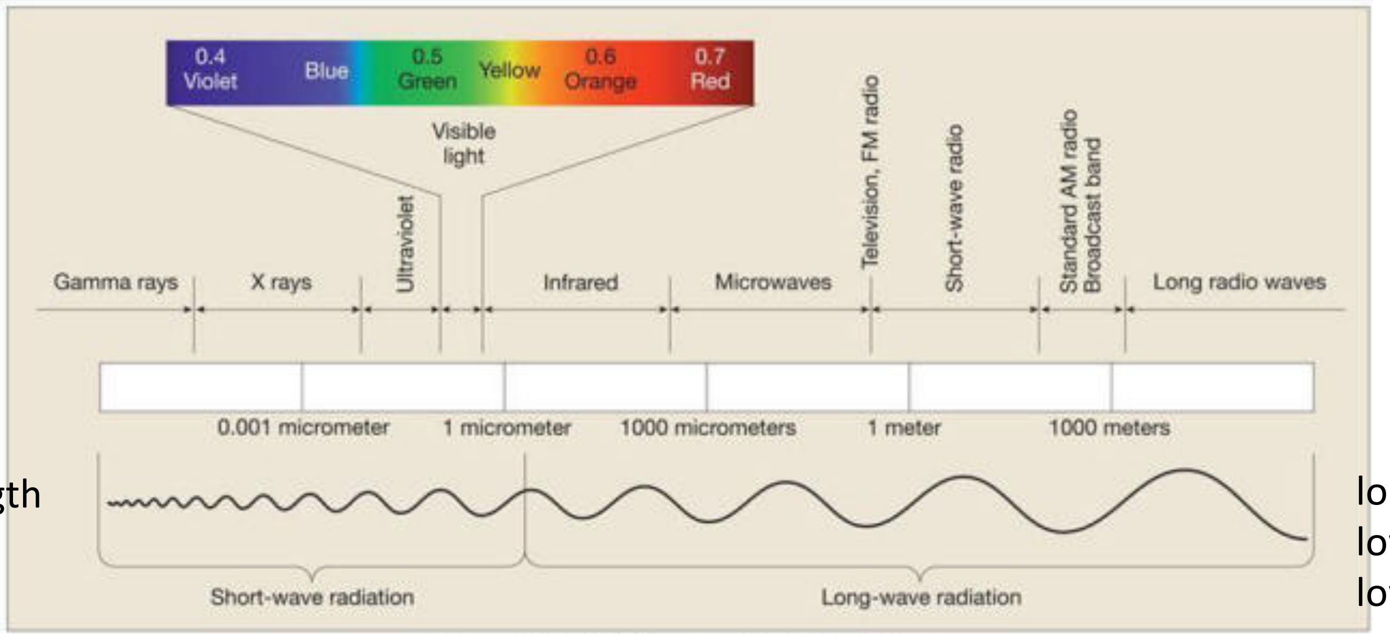


(Credit: Jeffrey T. Kiehl and Kevin Trenberth)
https://ceres.larc.nasa.gov/ceres_brochure.php?page=2

Radiation Basics: Electromagnetic Spectrum

Radiation is a form of energy carried by electromagnetic (EM) waves.

short wavelength
high frequency
high energy



long wavelength
low frequency
low energy

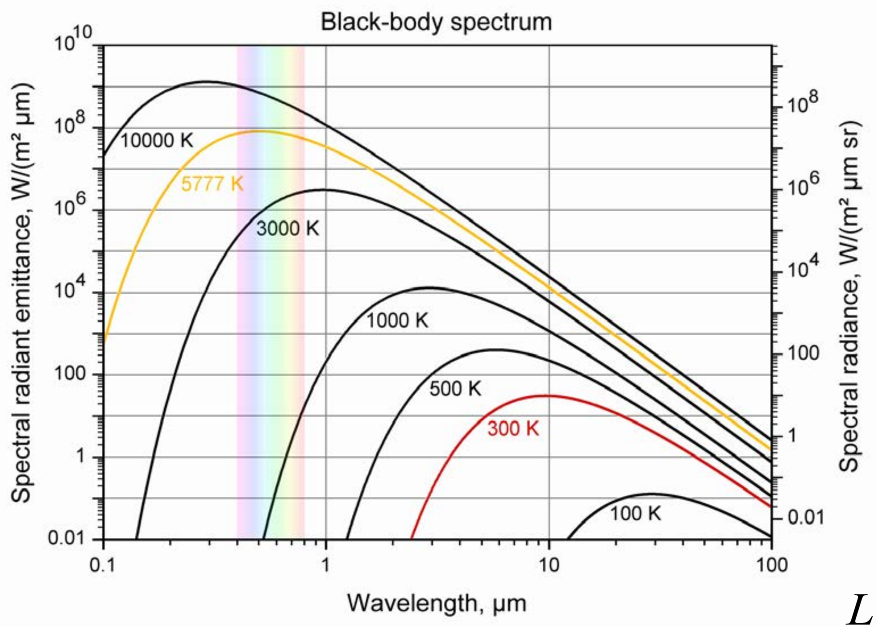
$$\lambda \nu = c$$

$\lambda \equiv$ wavelength [m]

$c \equiv$ speed of light $[3.0 \times 10^{8}\ \text{m/s}]$

$\nu \equiv$ frequency $[\text{s}^{-1} = \text{Hz}]$

Radiation Basics: Planck function



Planck function as a function of temperature and wavelength (en.wikipedia.org/wiki/File:BlackbodySpectrum_loglog_150dpi_en.png).

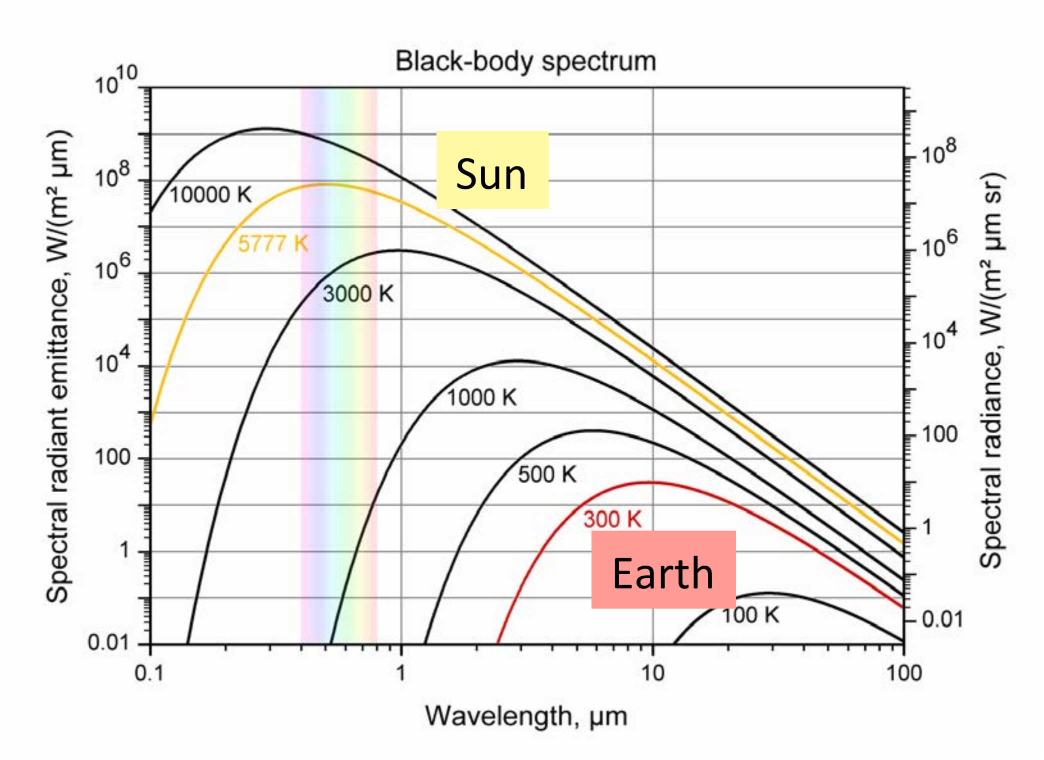
The Planck function:

The amount of energy radiated per unit area per unit wavelength by a blackbody:

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

L_λ	Spectral radiance	$\mathrm{Wm^{-2}m^{-1}sr^{-1}}$
c	speed of light	$3.00\times10^{8}\ \mathrm{ms^{-1}}$
h	Planck's constant	$6.63\times10^{-34}\mathrm{Js}$
k	Boltzmann's constant	$1.38\times10^{-23}\mathrm{JK^{-1}}$
σ	Stefan-Boltzmann constant	$5.67\times10^{-8}\mathrm{Wm^{-2}K^{-4}}$
T	Temperature	K

Radiation Basics: Planck Function



The Planck function:

(1) The higher the temperature, the more radiation it emits at every wavelength

(2) The wavelength at which the maximum intensity occurs depends on the wavelength. **Wien's displacement Law:**

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

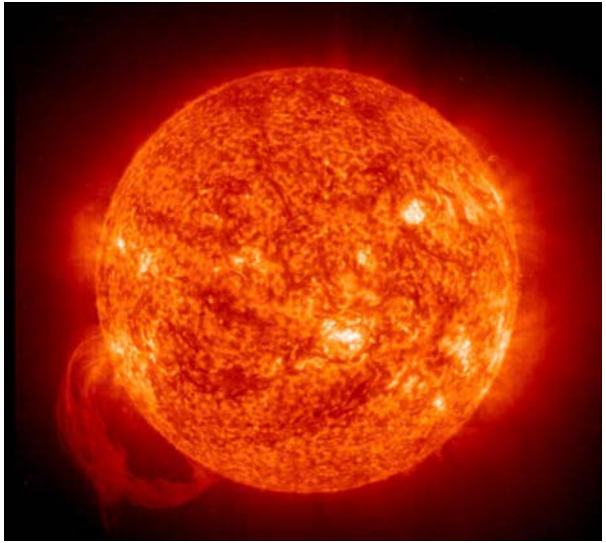
Planck function as a function of temperature and wavelength (en.wikipedia.org/wiki/File:BlackbodySpectrum_loglog_150dpi_en.png).

Radiation Basics: Stefan-Boltzmann Equation

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

Integrated Radiative Flux from a blackbody (W m^{-2})
=> Integrate across all wavelengths

$$\sigma \equiv \text{Stefan-Boltzmann constant} = 5.67 \times 10^{-8}\ \text{W m}^{-2}\ \text{K}^{-4}$$



$$\sigma T_{sun}^4 \simeq (5.67 \times 10^{-8}\,\text{W m}^{-2}\ \text{K}^{-4})(5780\ \text{K})^4 = 6.33 \times 10^{7}\,\text{W m}^{-2}$$

Radiation Basics: Graybodies

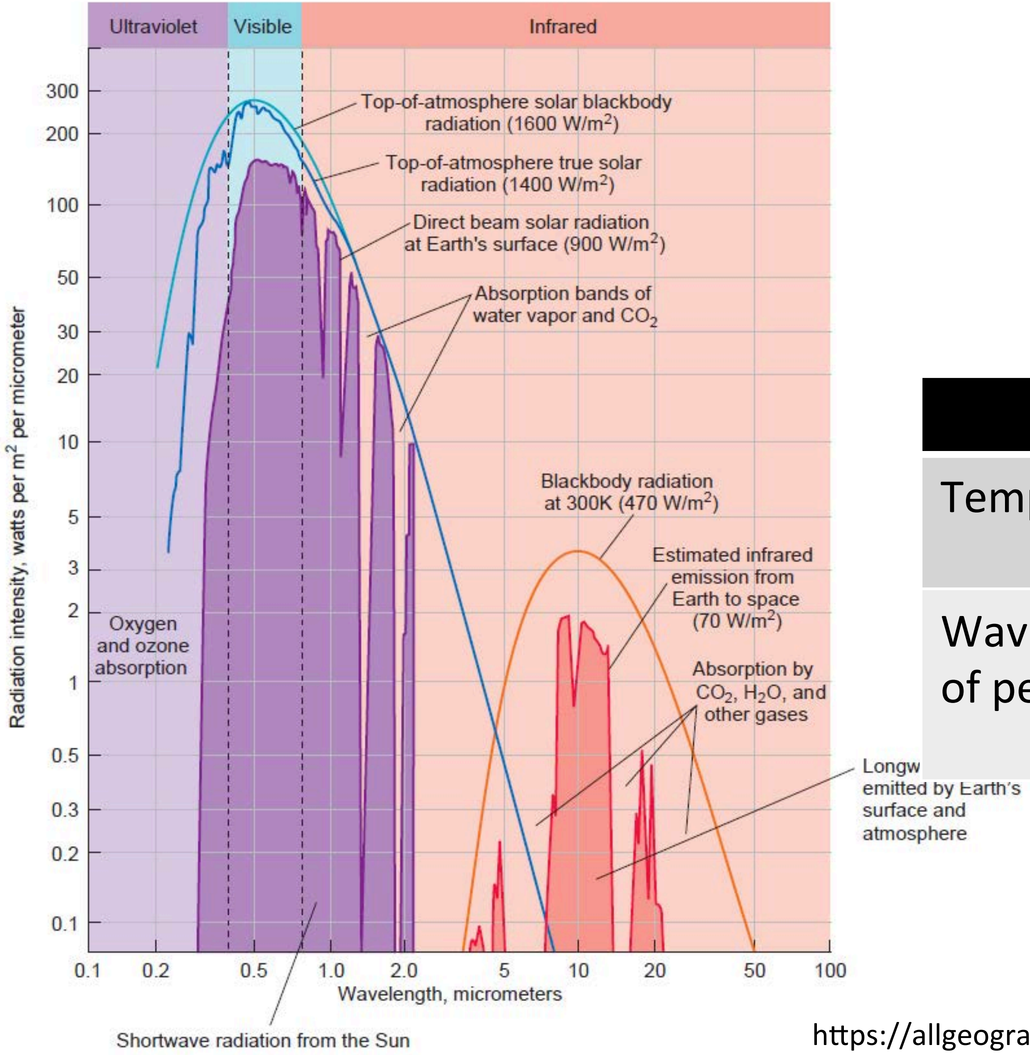
$$R = \varepsilon \sigma T^4$$

$\varepsilon \equiv$ broadband emissivity [–]

Most natural media are "graybodies", i.e. less efficient emitters than blackbodies

TABLE 3.1. TYPICAL BROADBAND EMISSIVITIES FOR VARYING LAND SURFACE TYPES (FROM ARYA, 2001)

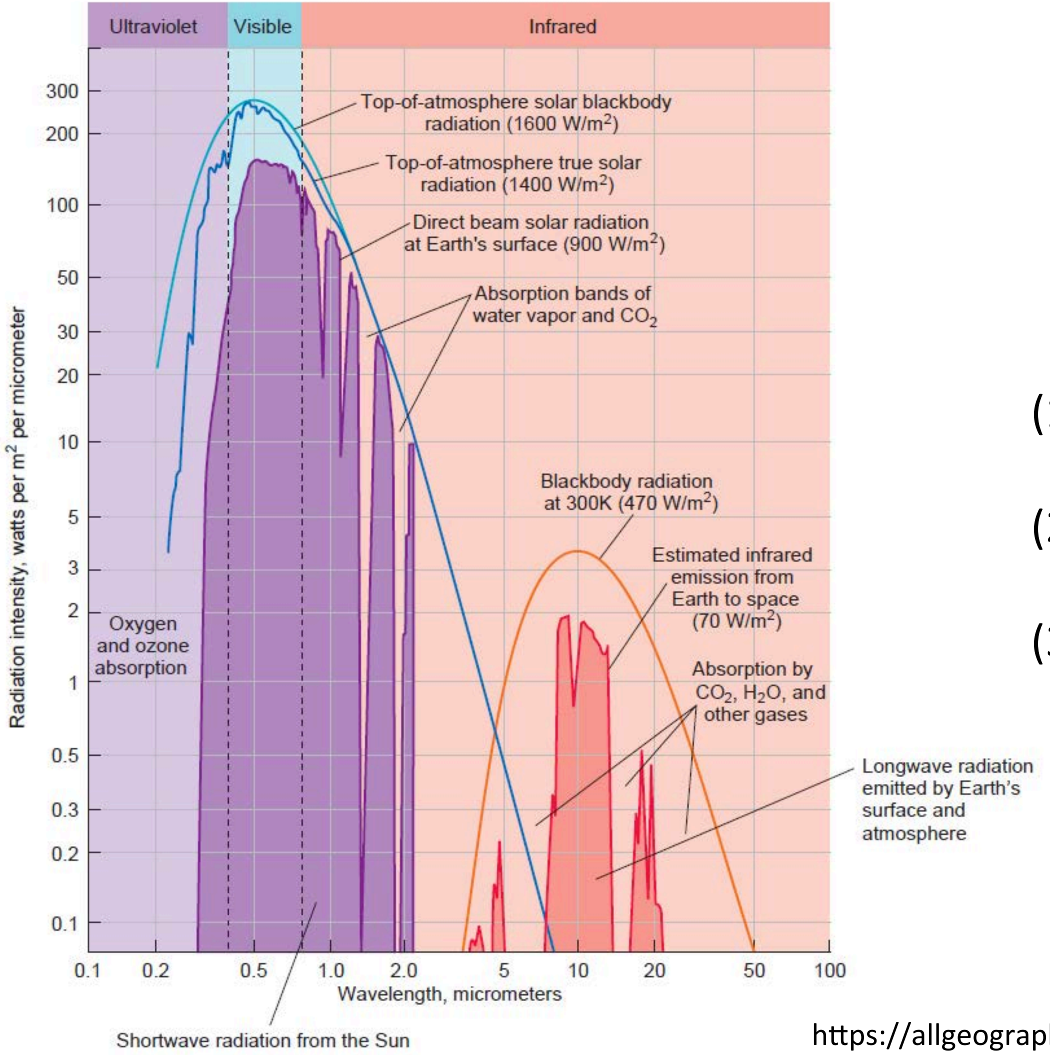
SURFACE TYPE	EMISSIVITY
Water	0.92-0.97
Snow	0.82-0.99
Ice	0.92-0.97
Bare soil	0.84-0.97
Grass (long, 1m)	0.90
Grass (short, 0.02m)	0.95
Agricultural crops	0.90-0.99
Forests	0.97-0.99



Radiation Basics: Shortwave v Longwave

	Sun	Earth
Temperature	5800K	300K
Wavelength of peak	Visible 0.6microns	Infrared 10microns

https://allgeographynow.wordpress.com/2016/02/28/electromagnetic-radiation/



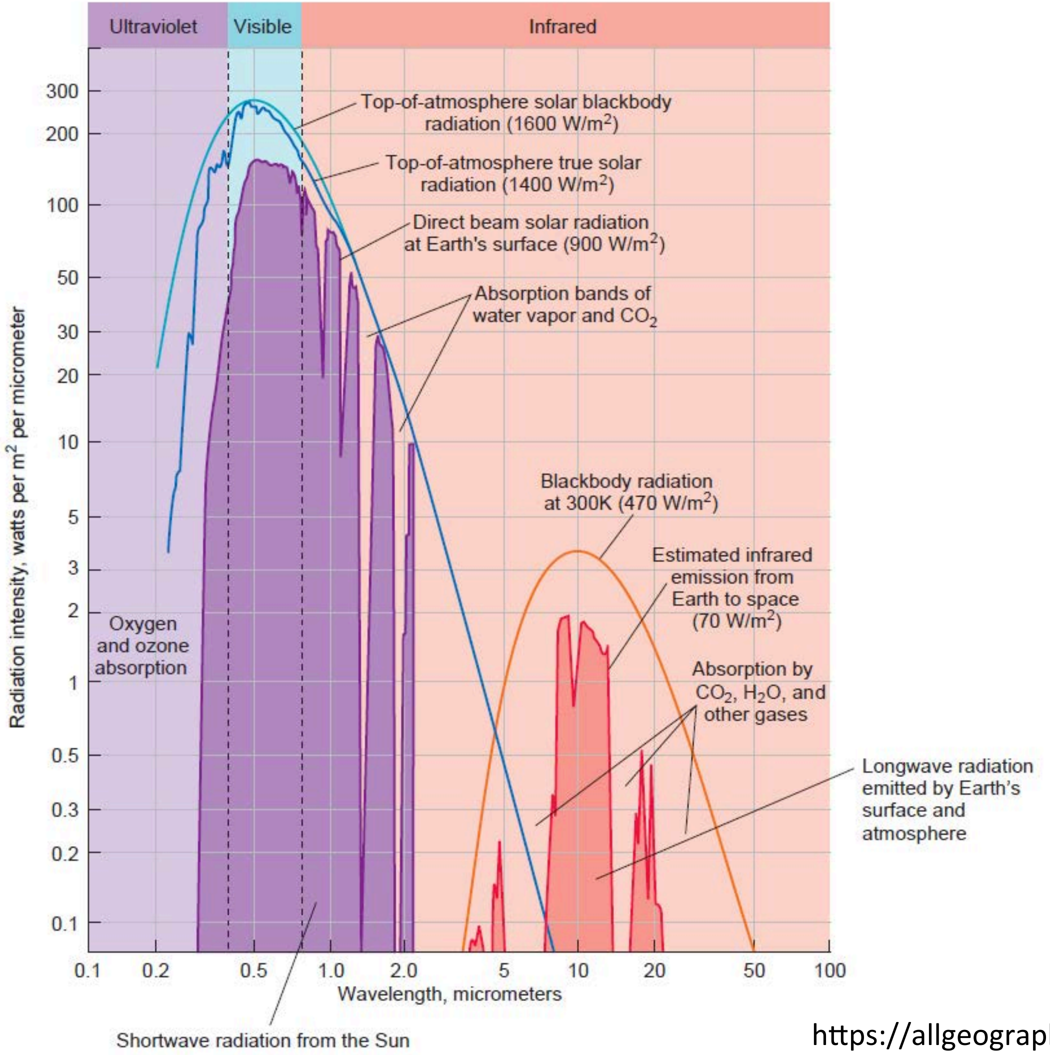
Radiation Basics: Shortwave v Longwave

(1) Little/no overlap

(2) Solar irradiance in UV, Visible and NIR

(3) Earth emits mainly in thermal infrared

https://allgeographynow.wordpress.com/2016/02/28/electromagnetic-radiation/

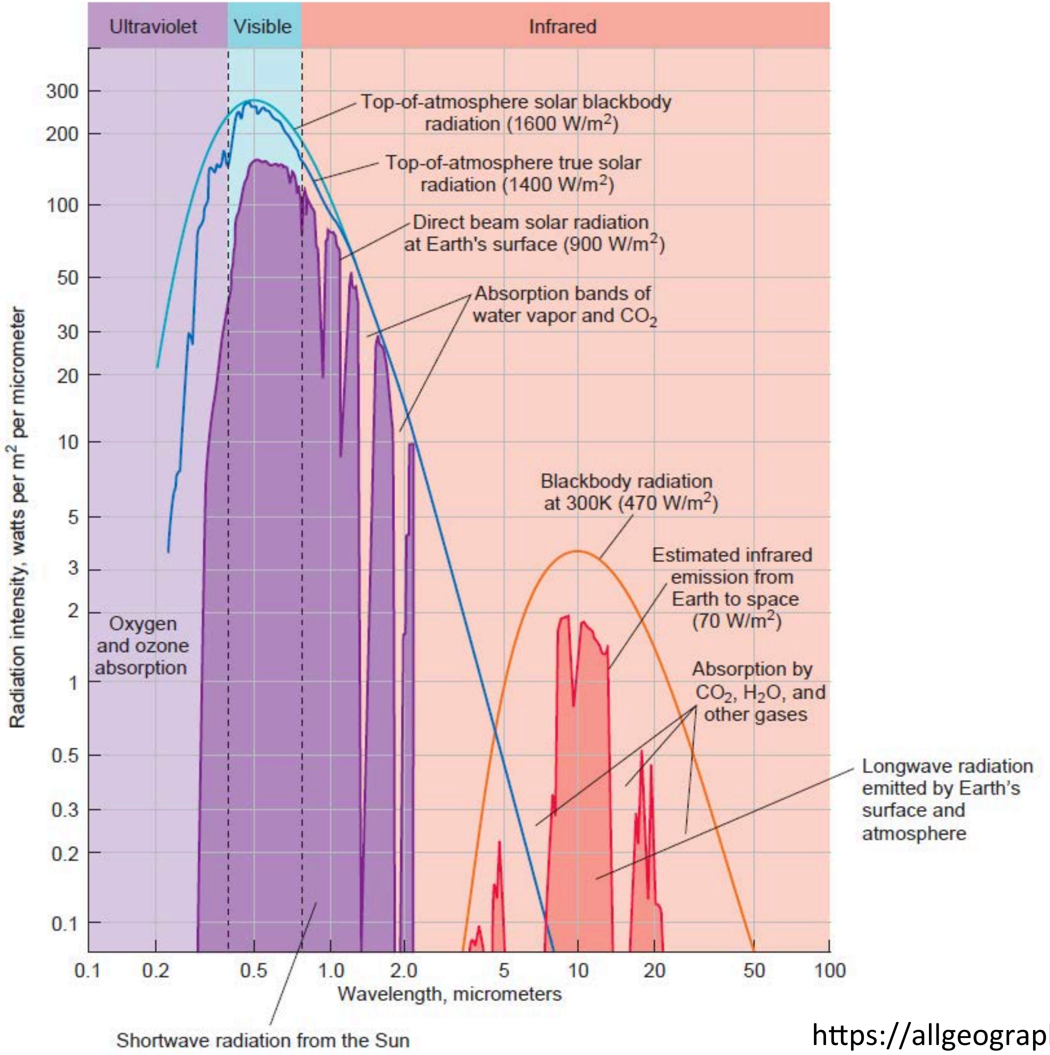


Radiation Basics: Shortwave v Longwave

$$\text{Shortwave: } R_s = \int_{\lambda=0.1\mu m}^{\lambda=4\mu m} R_\lambda \, d\lambda$$

$$\text{Longwave: } R_l = \int_{\lambda=4\mu m}^{\lambda=100\mu m} R_\lambda \, d\lambda$$

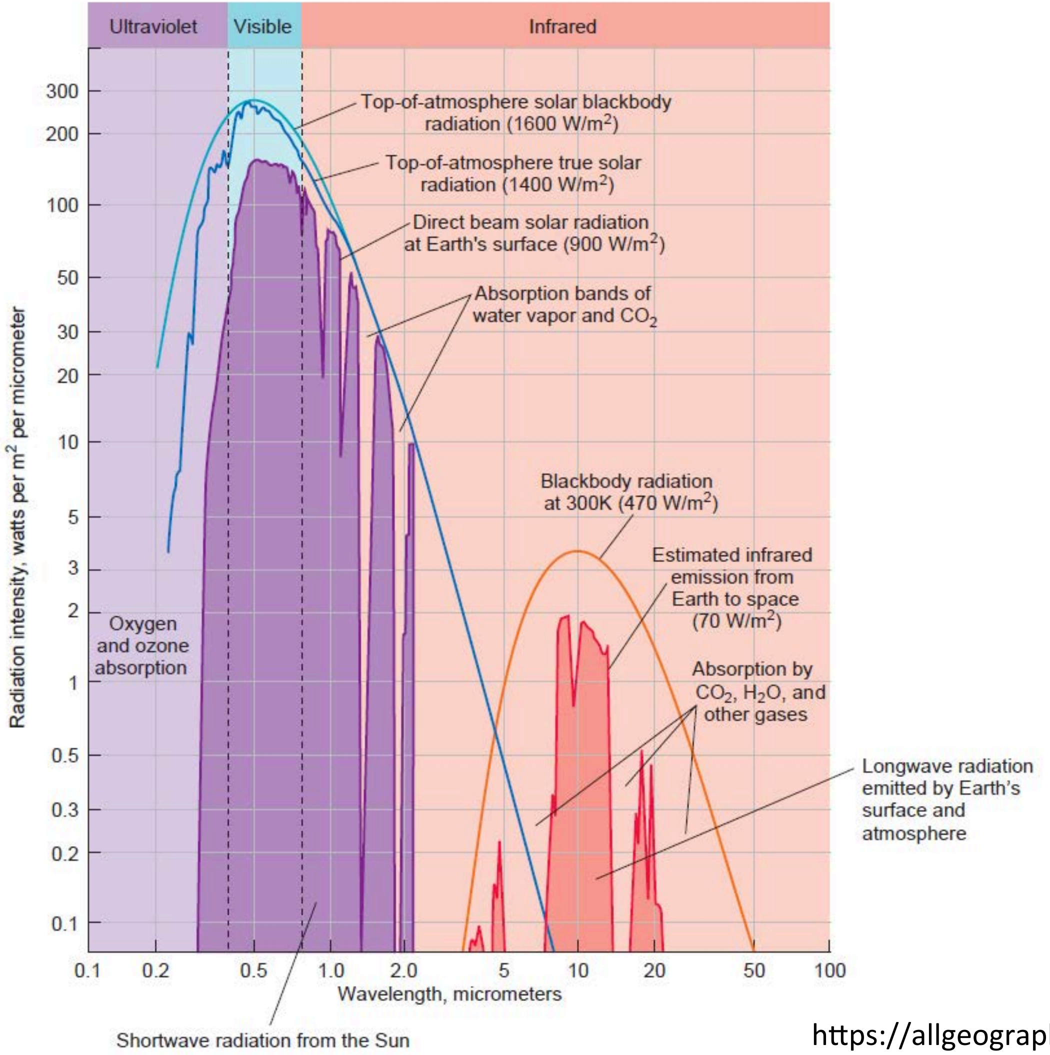
https://allgeographynow.wordpress.com/2016/02/28/electromagnetic-radiation/



Radiation Basics: Shortwave v Longwave

Is the atmosphere a blackbody? Or a graybody?

https://allgeographynow.wordpress.com/2016/02/28/electromagnetic-radiation/



Radiation Basics: Shortwave v Longwave

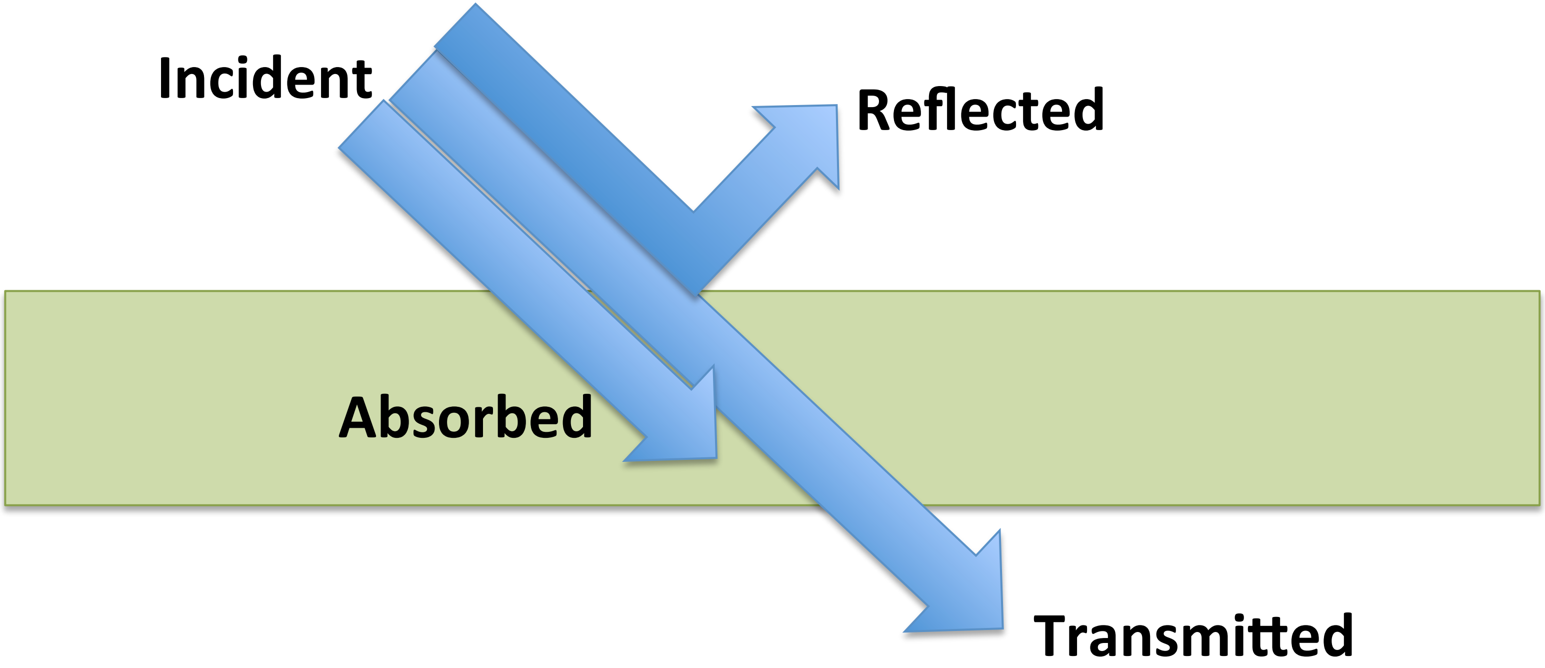
Is the atmosphere a blackbody? Or a graybody?

$$\boxed{\varepsilon = f([H_2O],[CO_2],[CH_4],\ldots)}$$

https://allgeographynow.wordpress.com/2016/02/28/electromagnetic-radiation/

Radiation Basics: Shortwave v Longwave

All incident energy on a given media (at a given wavelength)
is either transmitted, absorbed, or reflected.



Radiation Basics: Shortwave v Longwave

transmissivity + absorption + reflectivity = 1

$$t_\lambda + a_\lambda + r_\lambda = 1$$

Shortwave

$$t_s + a_s + r_s = 1$$

Longwave

$$t_l + a_l + r_l = 1$$

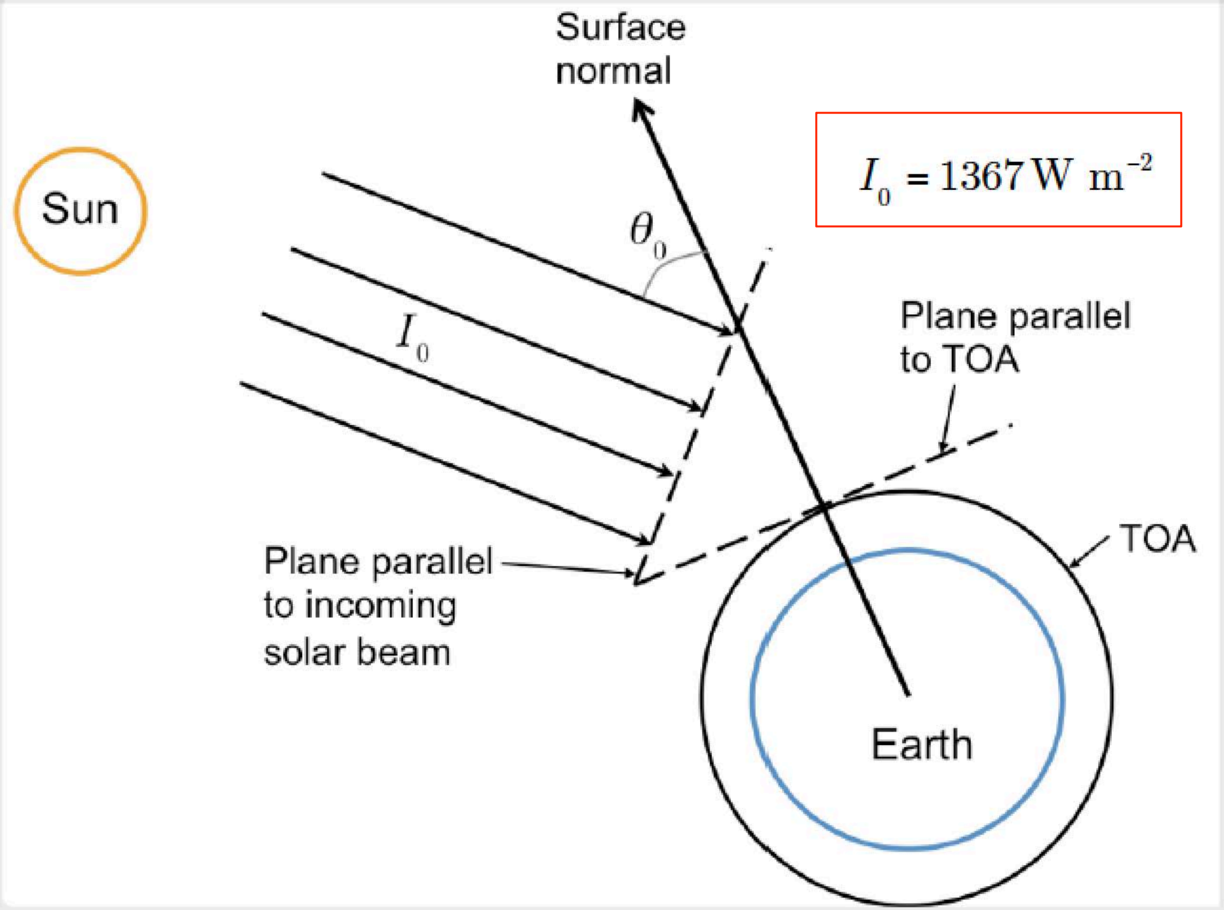
Radiation Basics: Shortwave v Longwave

	Shortwave	Longwave
Atmosphere	$t_s + a_s + r_s = 1$	$t_l + a_l + r_l = 1$
Land	$t_s + a_s + r_s = 1$	$t_l + a_l + r_l = 1$

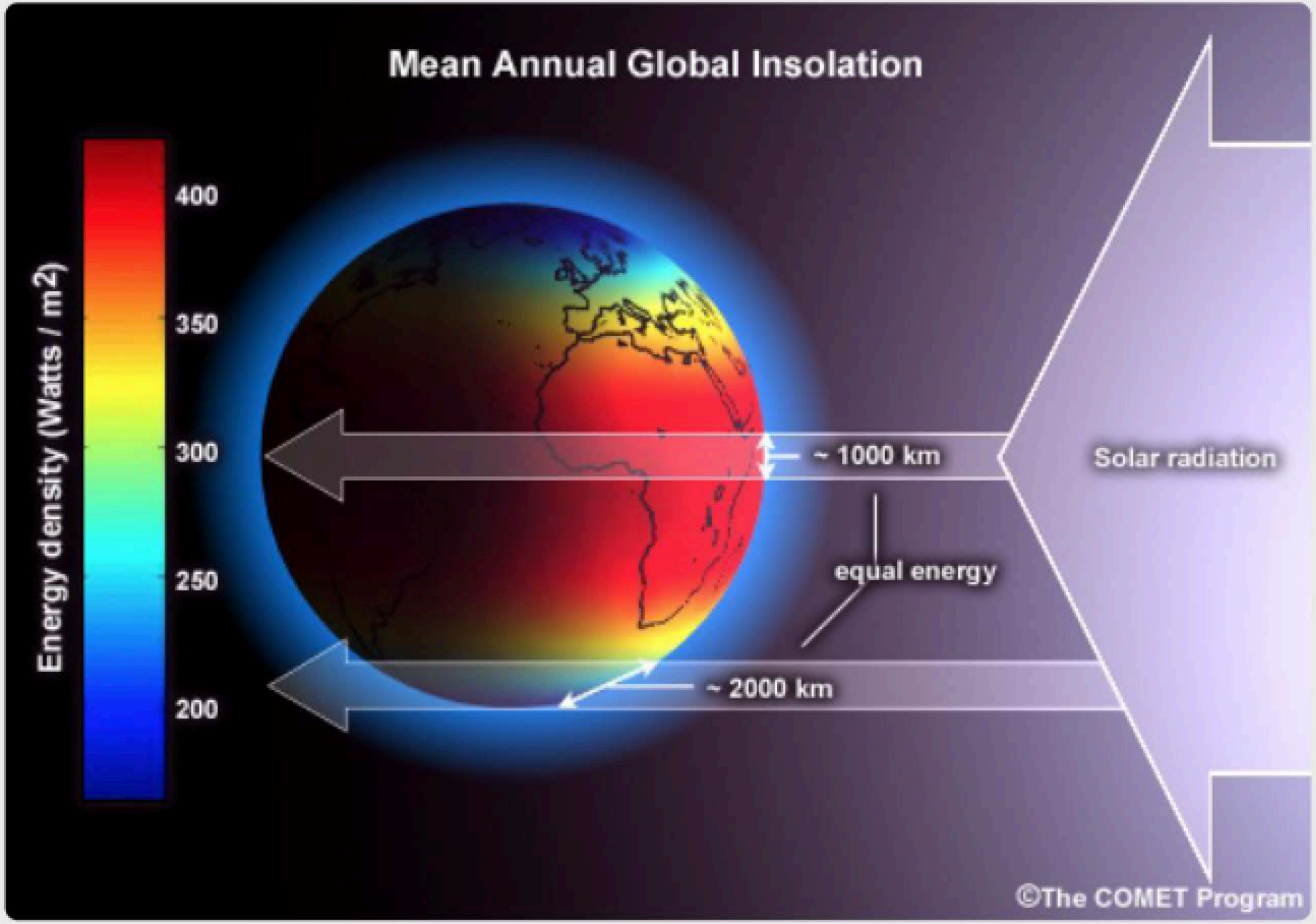
Shortwave Radiation

"Solar constant"
= incoming radiation at top of atmosphere

(the amount of energy that would be intercepted by a surface perpendicular to the incoming beam)



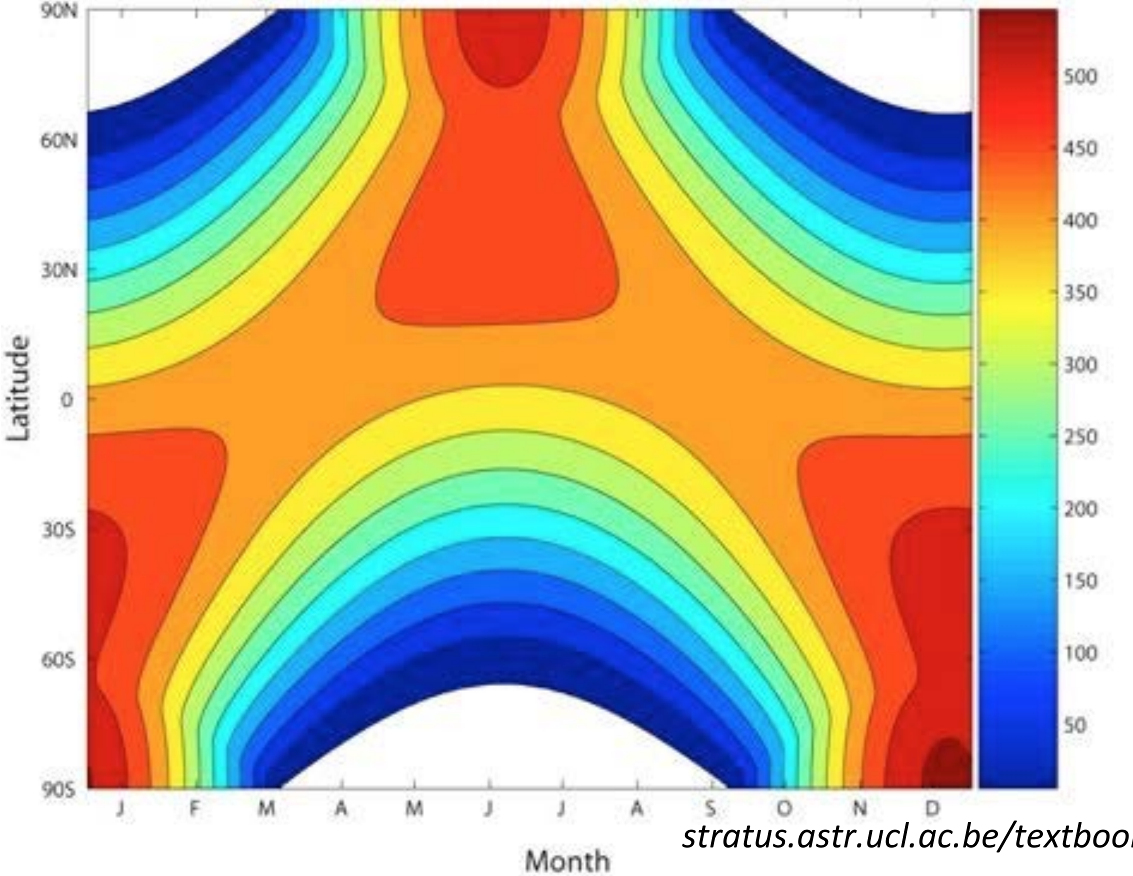
Shortwave Radiation



Equal amount of energy distributed over a larger area as move away from normal to incoming beam

Shortwave Radiation:

Mean daily insolation (W m^{-2})



stratus.astr.ucl.ac.be/textbook/images/image(2).jpg

Shortwave Radiation

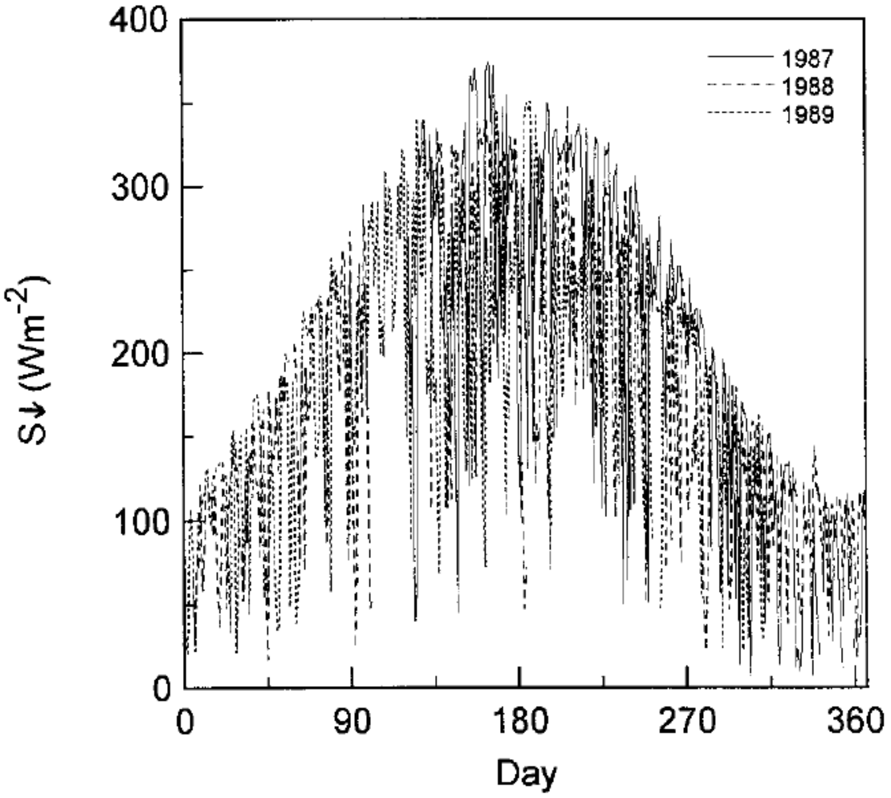
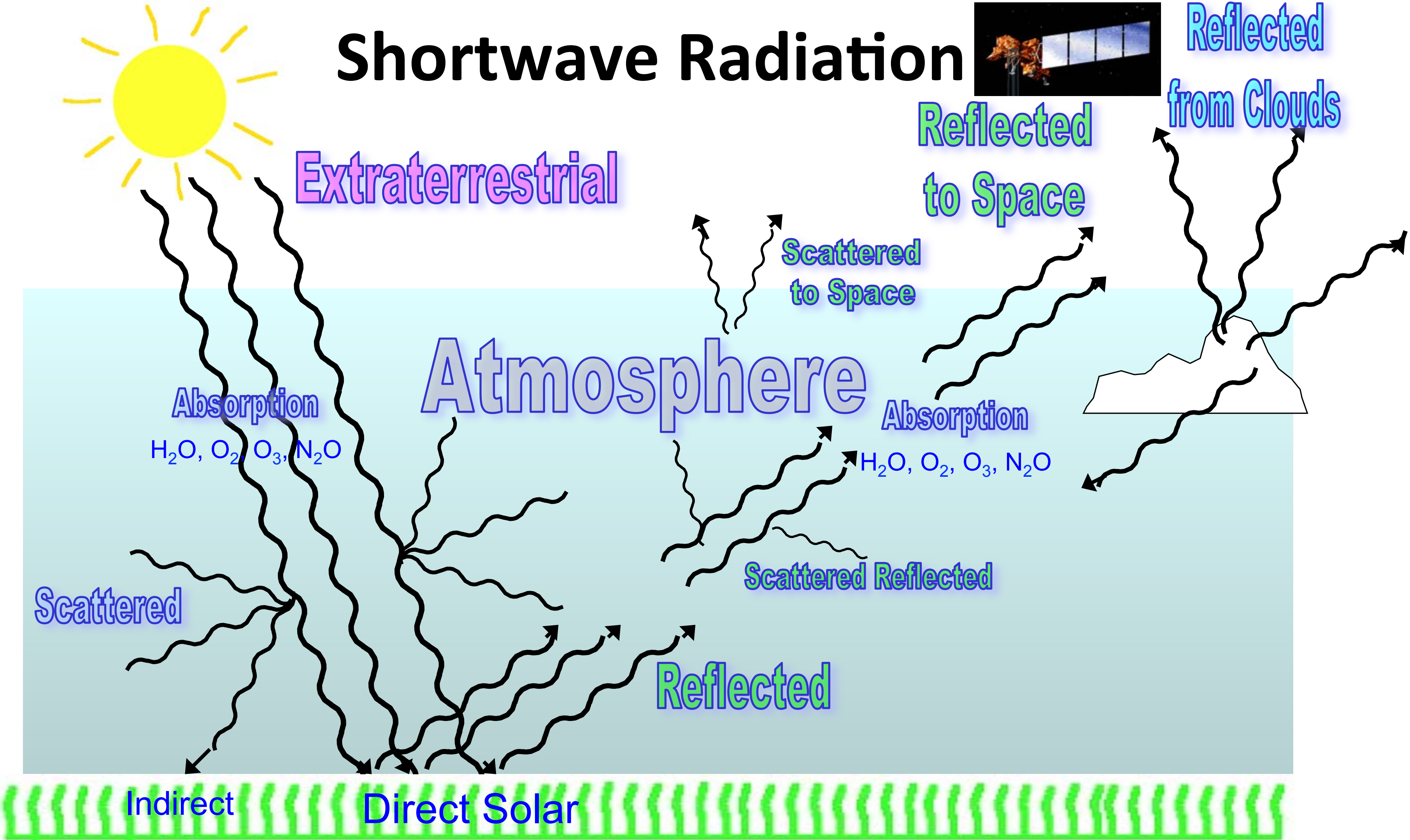


FIG. 3. Daily average incoming solar radiation for the three years (1 May 1987–10 November 1989).

Betts and Ball (JAS, 1998)

Shortwave Radiation



Shortwave Radiation: Surface Albedo

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

$\rho_{s,b}$ = broad band surface albedo

$\rho_{t,b}$ = broad-band top of atmosphere reflectance

$\rho_{a,b}$ = top of atmosphere reflectance

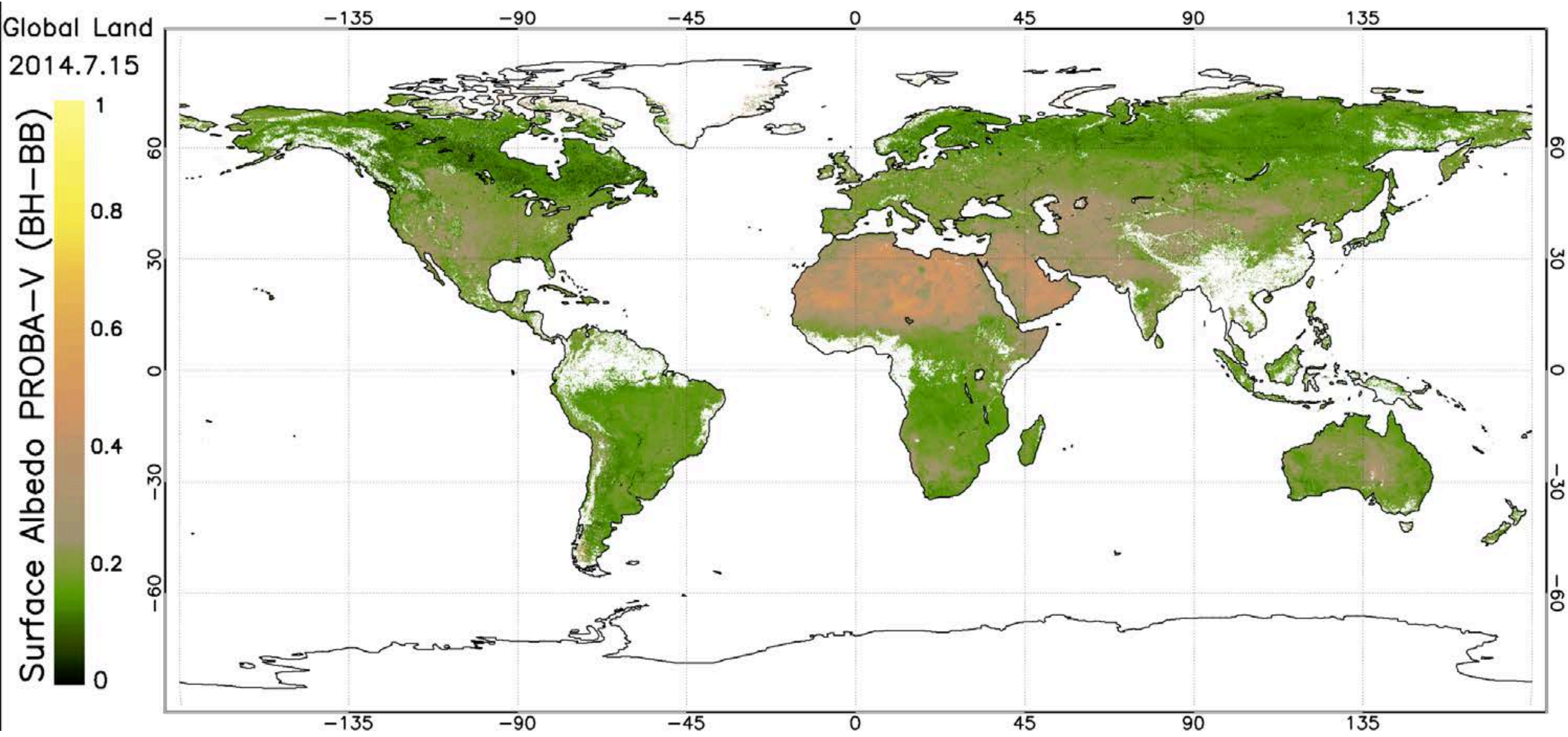
$\tau_{in,b} = \tau_{out,b}$ =single way atmospheric transmittance

Shortwave Radiation: Surface Albedo

TABLE 3.2. TYPICAL BROADBAND ALBEDO FOR VARYING LAND SURFACE TYPES (FROM ARYA, 2001)

SURFACE TYPE	ALBEDO
Water (small zenith angle)	0.03-0.10
Water (large zenith angle)	0.10-1.0
Snow (old)	0.40-0.70
Snow (fresh)	0.45-0.95
Ice	0.20-0.45
Bare soil	0.05-0.40
Grass (long, 1m)	0.16
Grass (short, 0.02m)	0.26
Agricultural crops	0.10-0.25
Forests	0.05-0.20

Shortwave Radiation: Surface Albedo



https://land.copernicus.eu/global/sites/cgls.vito.be/files/gallery/CGLOPS1_AL-BH-BB_PROBAV_20140715.png

Shortwave Radiation: Surface Albedo

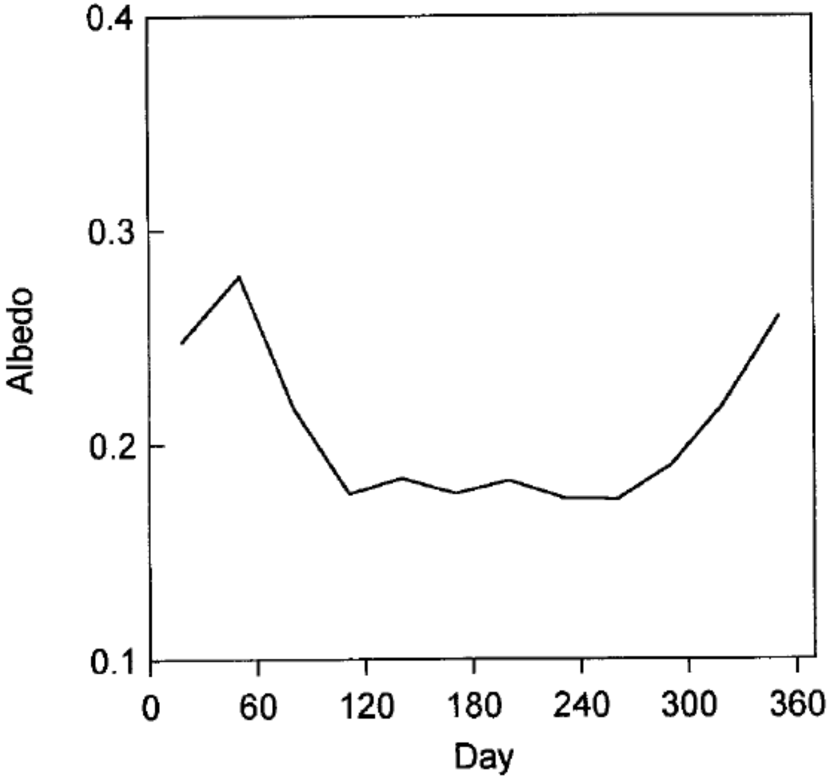


FIG. 4. FIFE site 30-day averaged albedo for 1987–89.

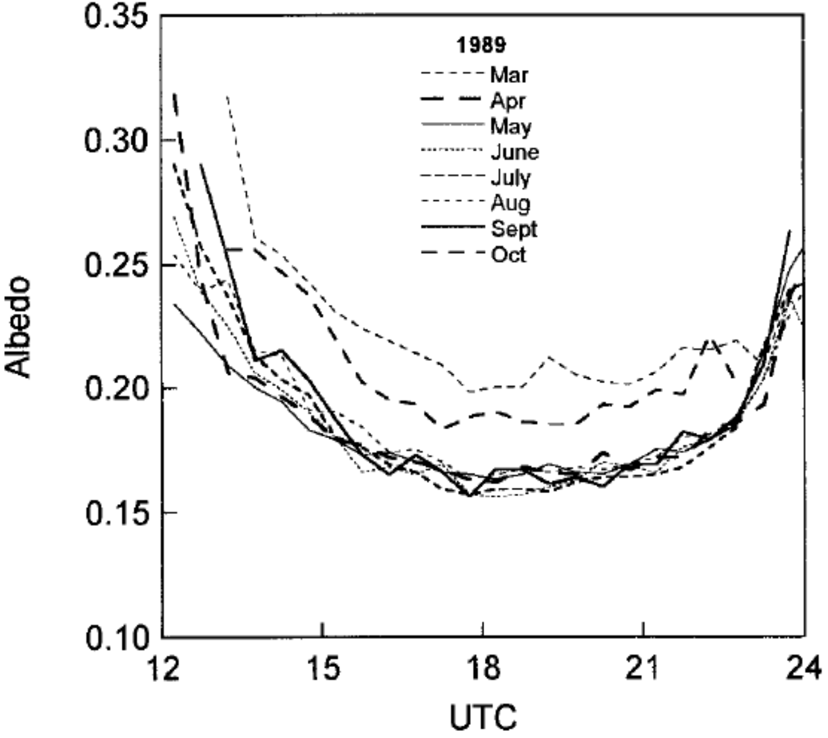
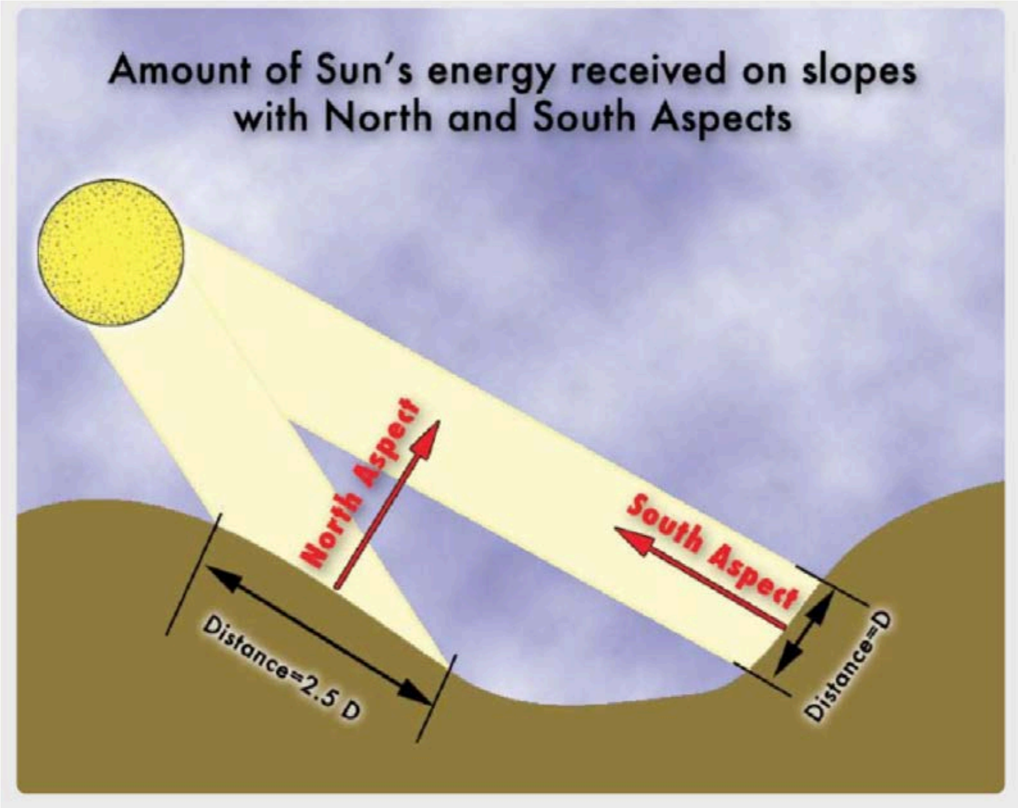


FIG. 5. Daytime albedo for March–October 1989. (Local solar noon is 1820 UTC.)

Betts and Ball (JAS, 1998)

Shortwave Radiation: Slope and Aspect



Shortwave Radiation: Slope and Aspect

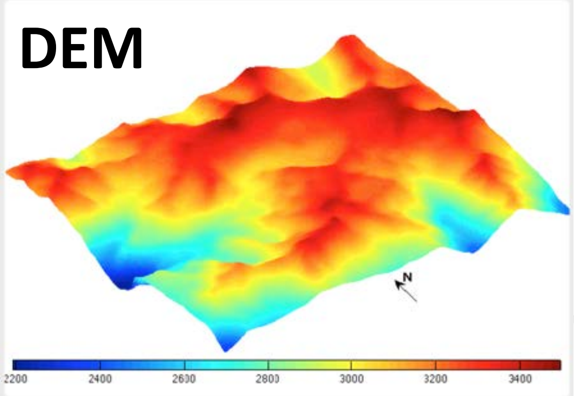


FIGURE 3.16 DEM illustrating the distribution of elevation (in meters) over an example terrain.

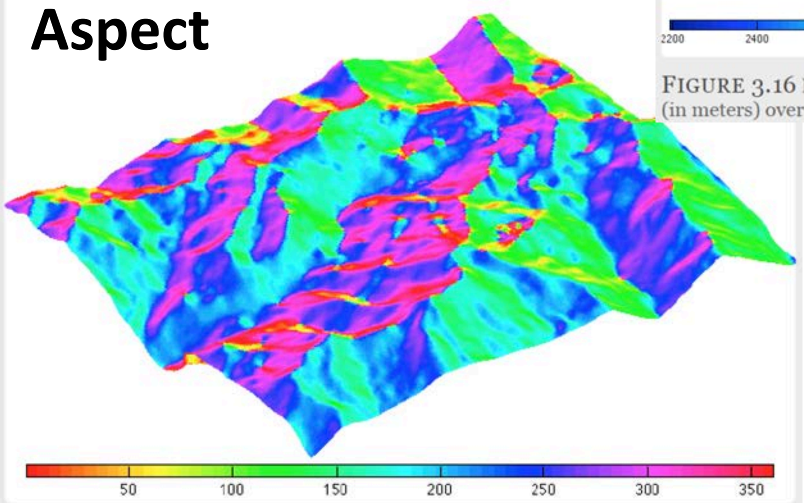


FIGURE 3.18 Distribution of aspect (in degrees) of the terrain represented by the DEM in Figure 3.16.

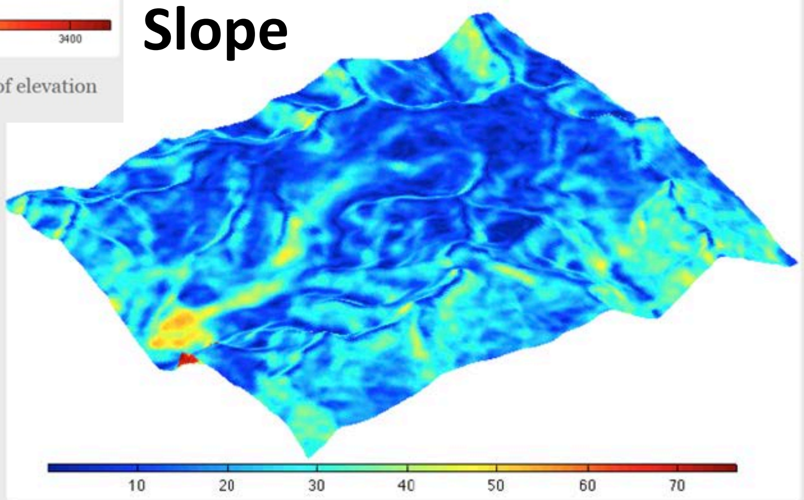
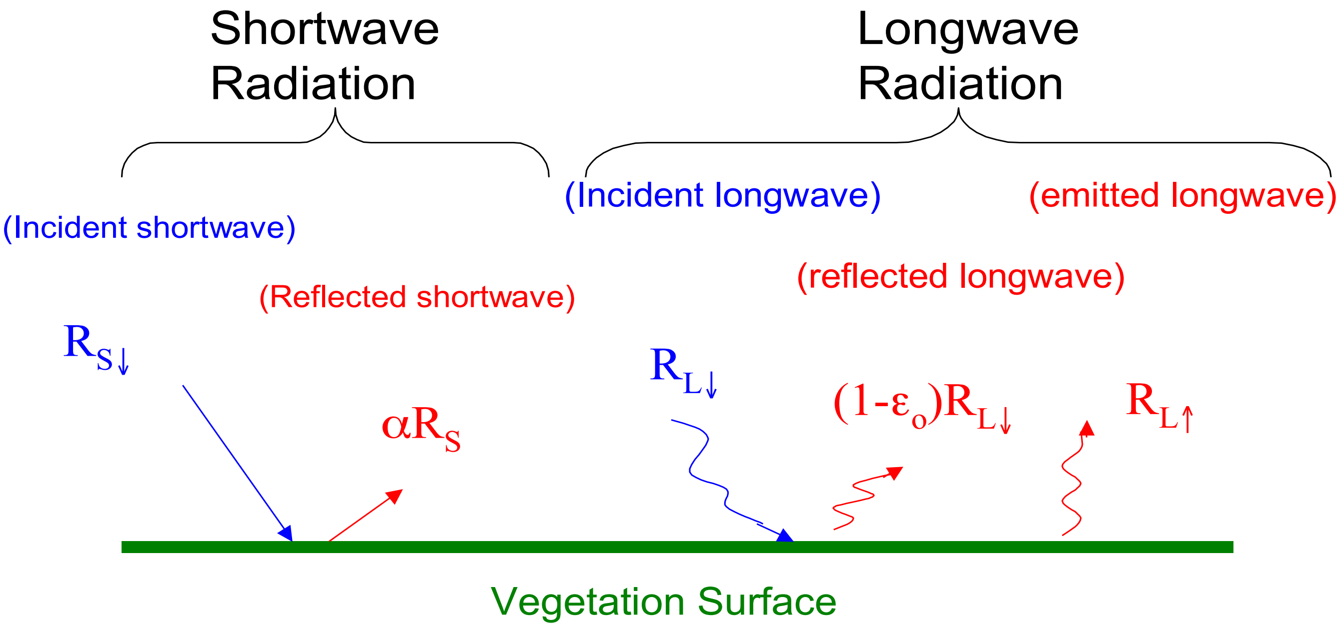


FIGURE 3.17 Distribution of slope (in degrees) of the terrain represented by the DEM in Figure 3.16.

Net Radiation



Net Surface Radiation = Gains – Losses

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

Longwave Radiation from Atmosphere:

$$R_l^{\downarrow} = f\left[\varepsilon([H_2O],[CO_2],\ldots),T(z),\text{clouds}\right]$$

atmospheric composition, temperature, water vapor

$$R_l^{\downarrow} = \varepsilon_a \sigma T_a^4$$

ε_a "effective atmospheric emissivity"

- Based on "clear sky" atmospheric emissivity
- Accounts for cloud using either cloud cover, solar index or some measure of atmospheric water content

Longwave Radiation from Earth Surface

$$R_l^{\uparrow} = \varepsilon_s \sigma T_s^4$$

$\varepsilon_s \equiv$ surface broadband emissivity

$T_s \equiv$ surface temperature

Note: subscript “0” used for in previous diagram

Longwave Radiation from Earth Surface

TABLE 3.1. TYPICAL BROADBAND EMISSIVITIES FOR VARYING LAND SURFACE TYPES (FROM ARYA, 2001)

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Ice	0.92-0.97
Bare soil	0.84-0.97
Grass (long, 1m)	0.90
Grass (short, 0.02m)	0.95
Agricultural crops	0.90-0.99
Forests	0.97-0.99

Net Radiation at the Surface

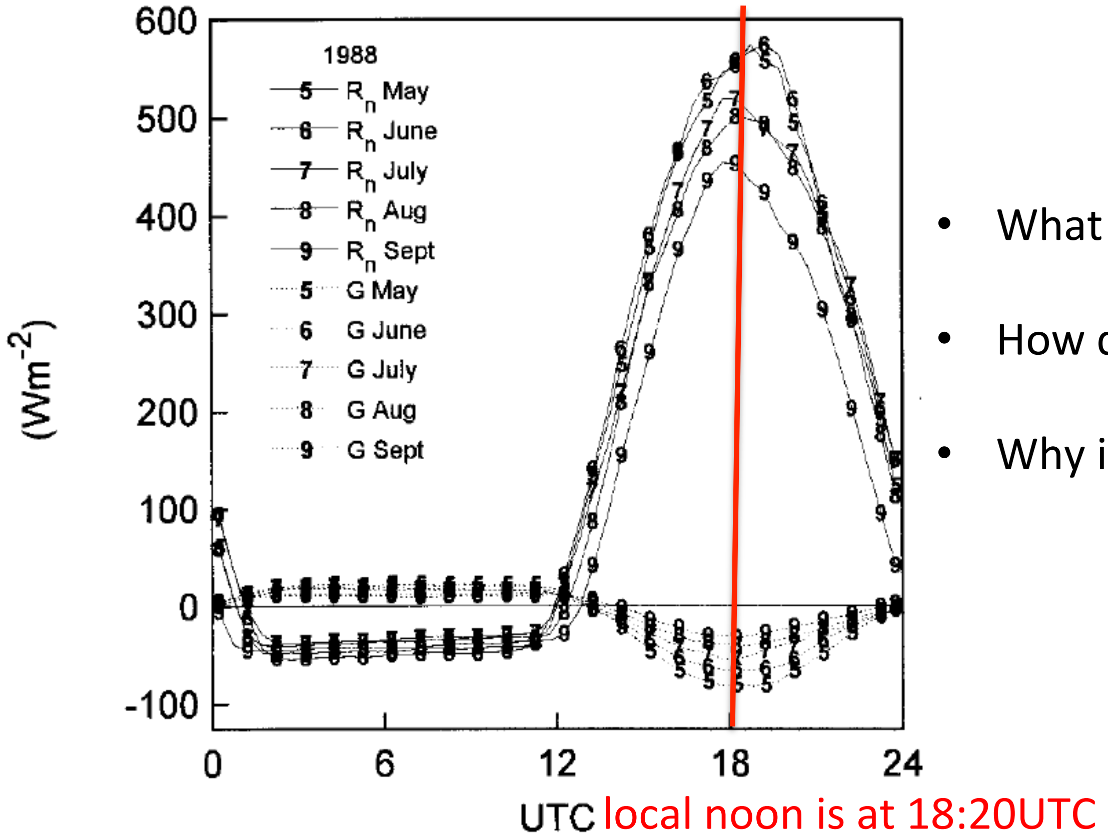
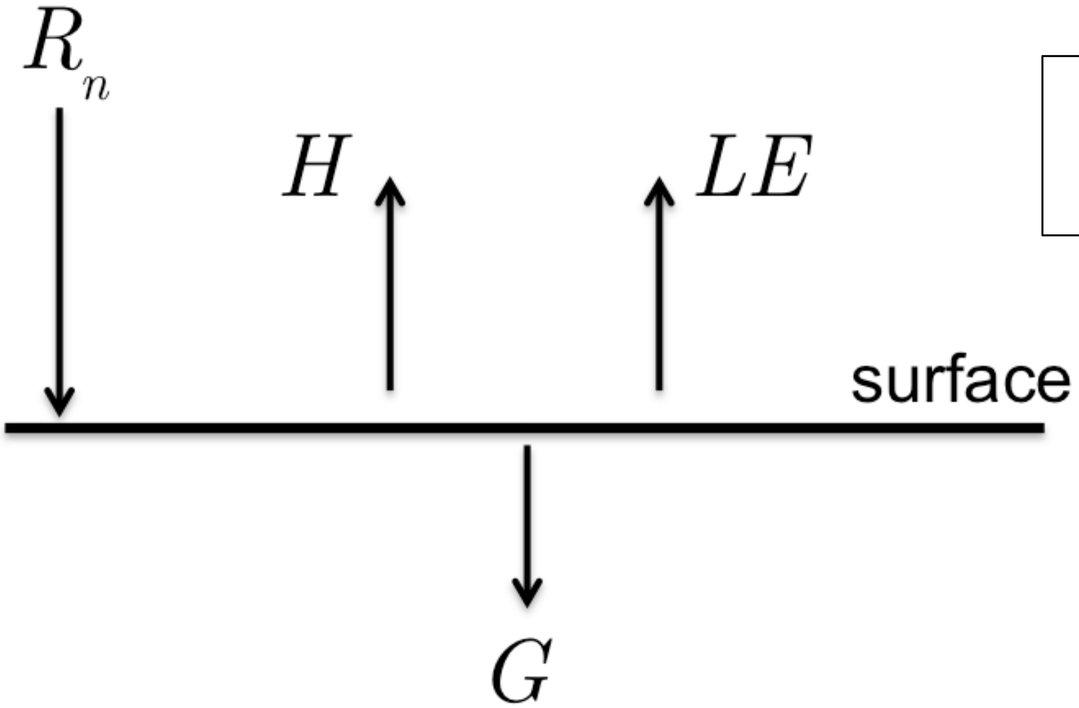


FIG. 9. Diurnal curves of monthly R_n, G for 1988 FLUX data. (May and September are incomplete months.)

- What time of day is maximum net radiation?
- How does maximum change during the year?
- Why is net radiation negative at nighttime?

Surface Energy Balance

Monitor the Surface Energy Balance using Thermal Remote Sensing



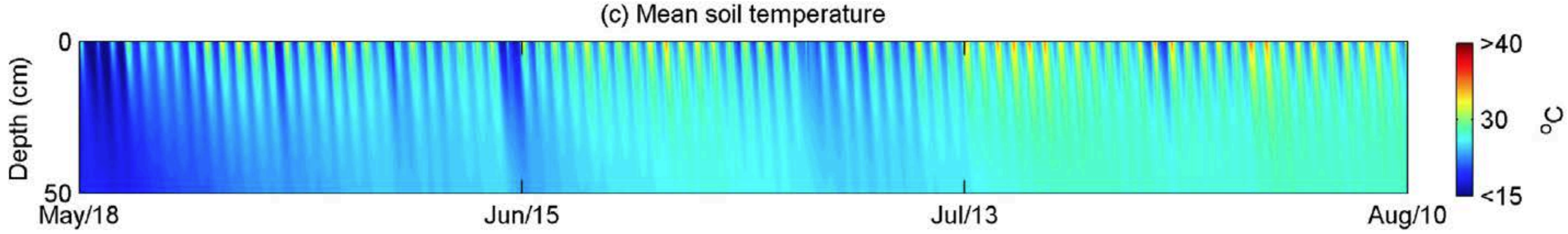
$$\boxed{R_n = LE + H + G}$$

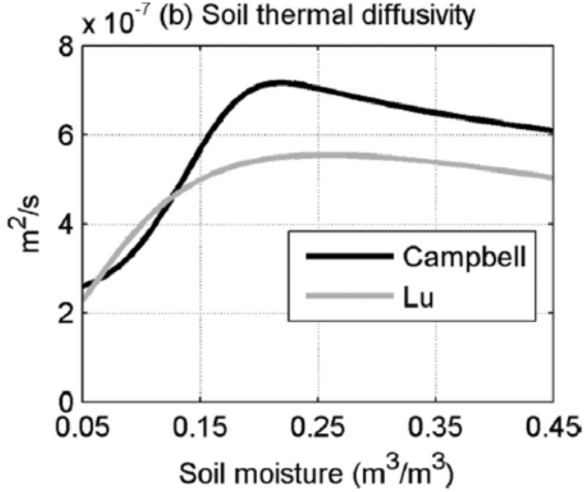
Latent heat flux
(aka Evapotranspiration)

Ground Heat Flux

$$G = D\, c_v \frac{dT}{dz}$$

D is soil thermal diffusivity
c_v is the volumetric heat capacity of soil





[19] The volumetric heat capacity of soil (J m^{-3} K^{-1}) is a simple, well-understood linear function of soil moisture:

$$C = \rho_m c_m = \frac{V_a}{V_t}\rho_a c_a + \frac{V_w}{V_t}\rho_w c_w + \frac{V_s}{V_t}\rho_s c_s$$
$$C = n(1 - S_r)\rho_a c_a + S_r n \rho_w c_w + (1 - n)\rho_s c_s, \quad (2)$$

where the subscripts m, a, t, w, and s denote the bulk soil, air, total, water, and soil solids, respectively; ρ is the density in kg m^{-3}; V represents volume; c is the specific heat capacity; S_r is the relative saturation; and n is the porosity.

Ground Heat Flux

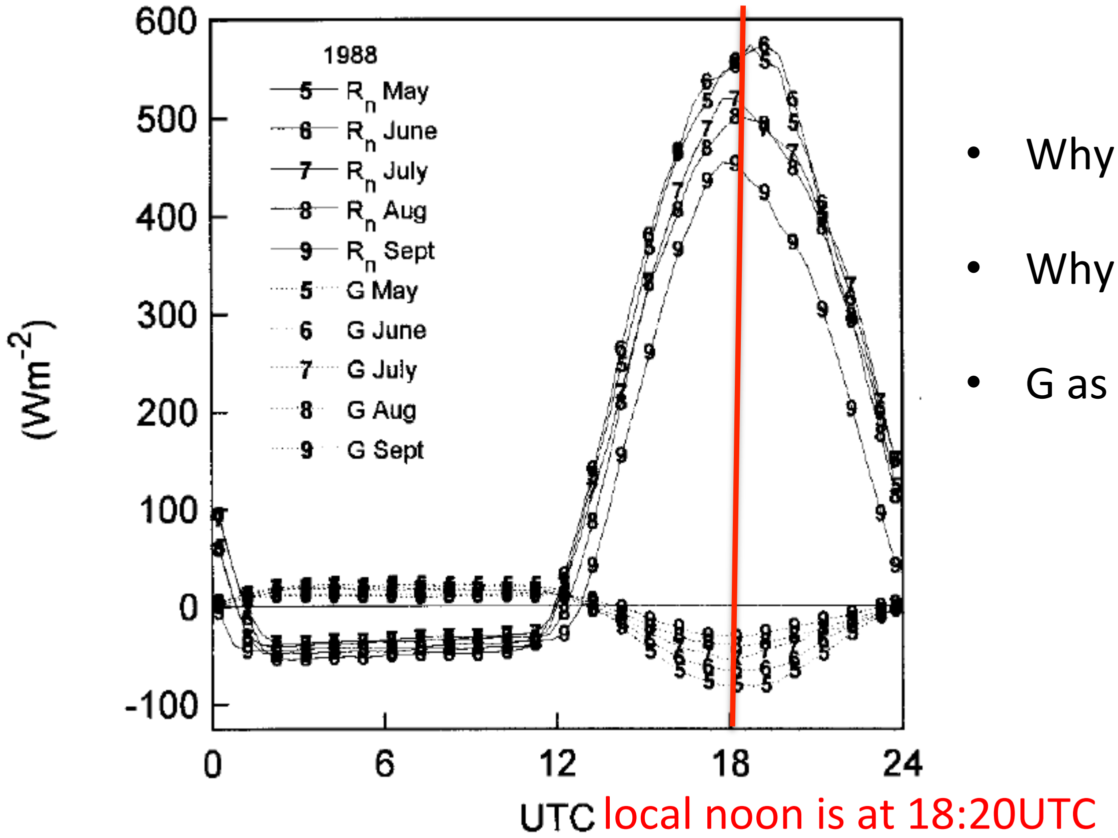


FIG. 9. Diurnal curves of monthly R_n, G for 1988 FLUX data. (May and September are incomplete months.)

- Why is it positive during the day?
- Why negative at night time?
- G as a fraction of net radiation?

Ground Heat Flux

$$G = f\,R_n$$

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

Typical values

f = 0.4 for deserts

= 0.1 for crops

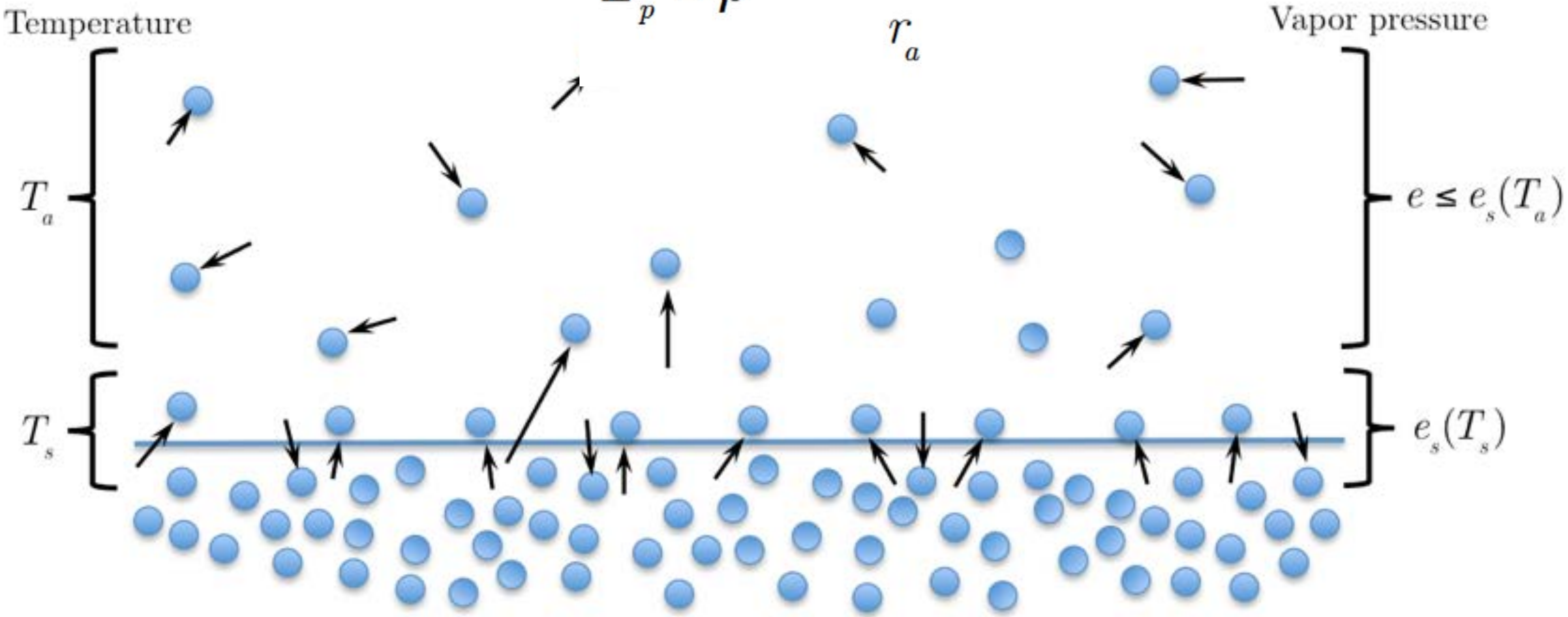
= 0.5 for water bodies

= 0.05 for forests

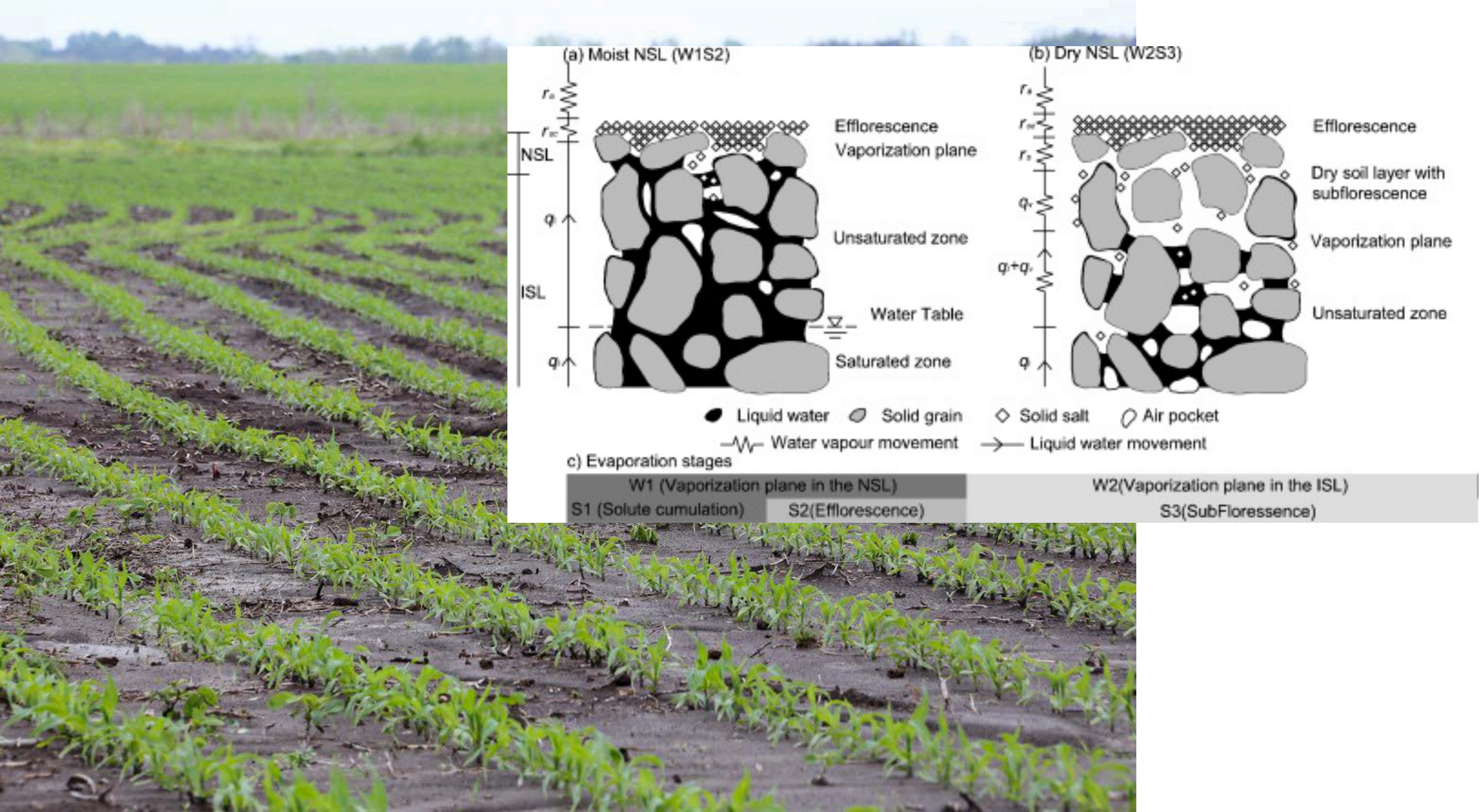
Latent Heat Flux: Evaporation

Open water

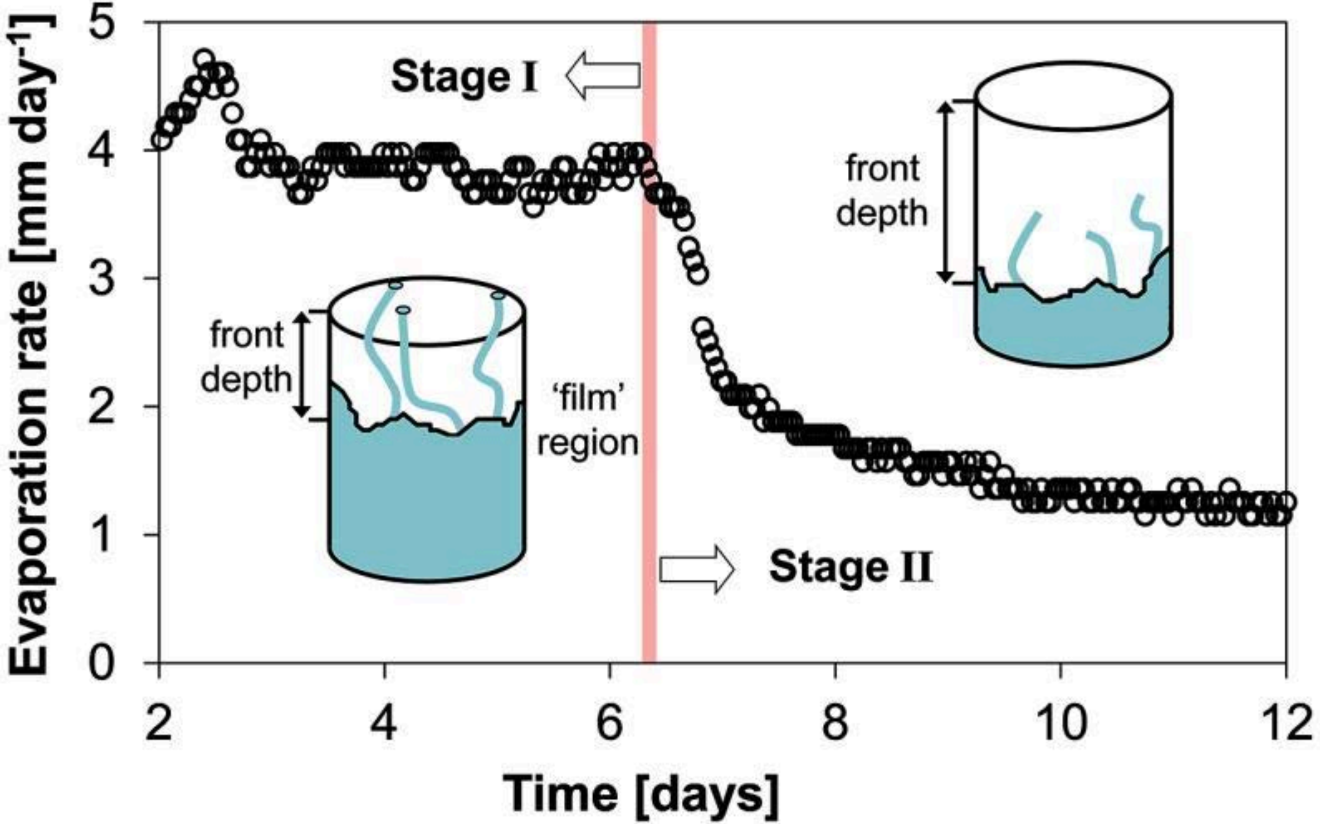
$$E_p = \rho \frac{(q_s(T_{surf}) - q_a)}{r_a}$$



Latent Heat Flux: Bare soil evaporation

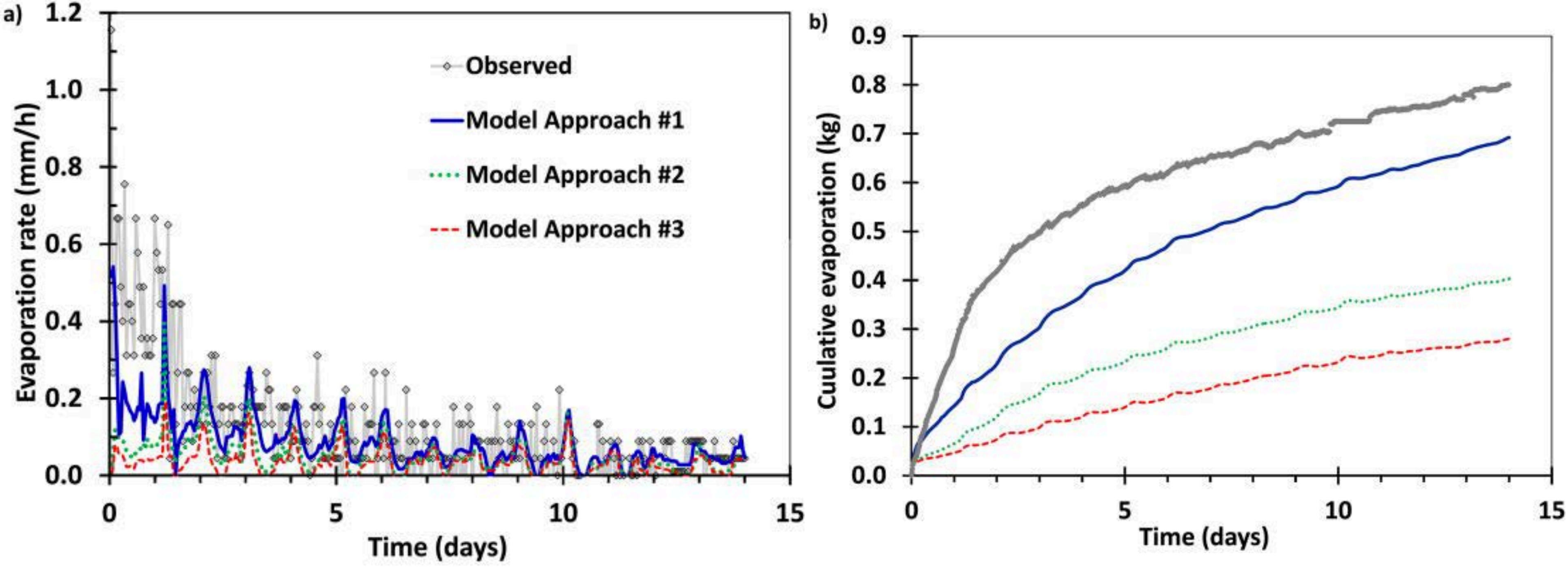


Latent Heat Flux: Bare soil evaporation



Advances in Soil Evaporation Physics—A Review (Or et al. (VZJ 2012)

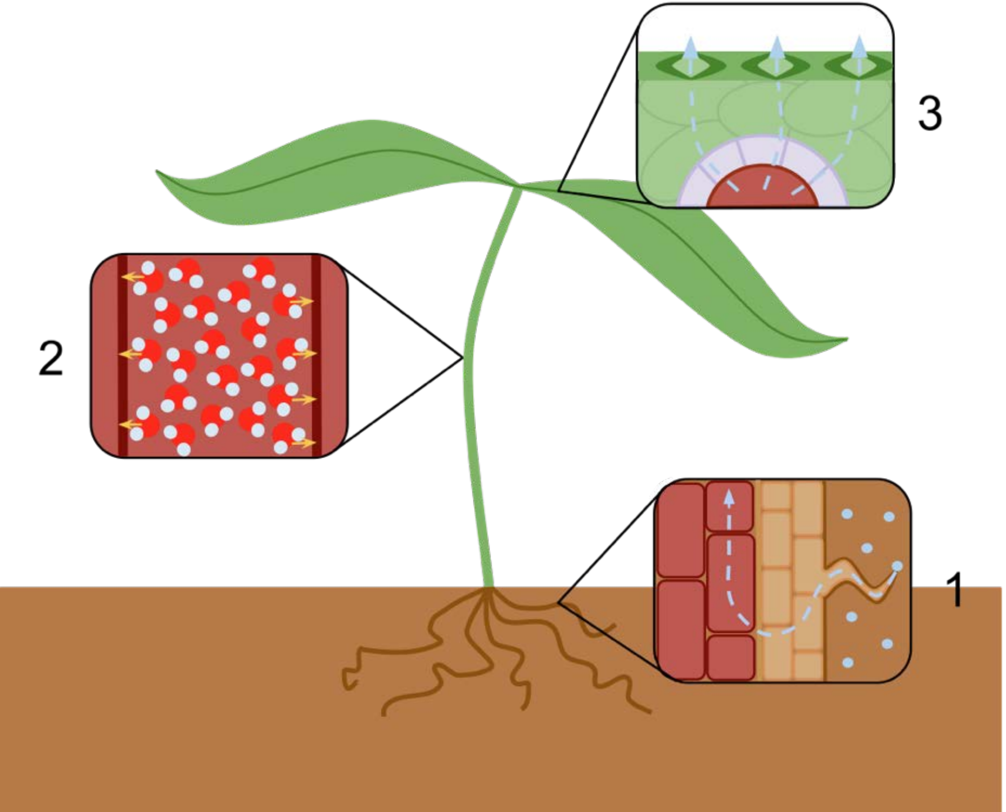
Latent Heat Flux: Bare soil evaporation



Smits et al. 2012 (doi:10.1029/2012WR012113).

Latent Heat Flux: Transpiration

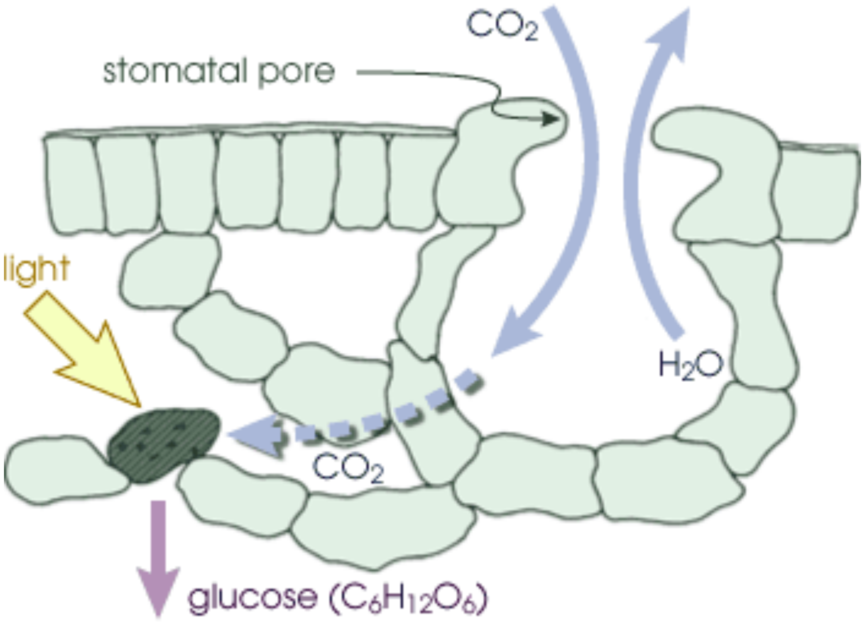
Plant's vascular system



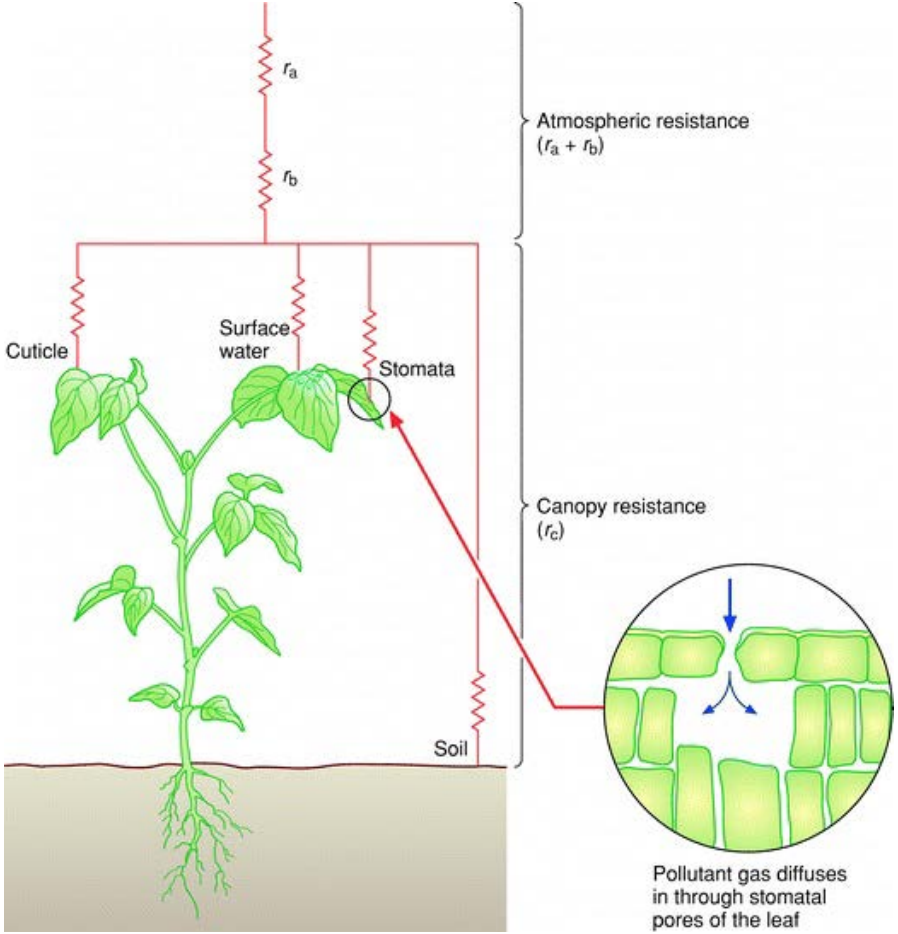
Photosynthesis

$$H_2O + CO_2 \rightarrow CH_2O + O_2$$

Latent Heat Flux: Transpiration



Latent Heat Flux: Transpiration



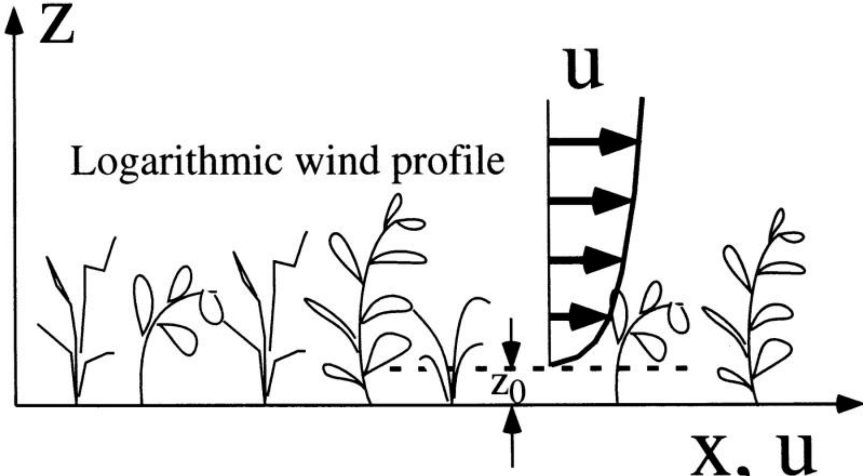
$$E = \rho \frac{(q_{surf} - q_a)}{r_a + r_c}$$

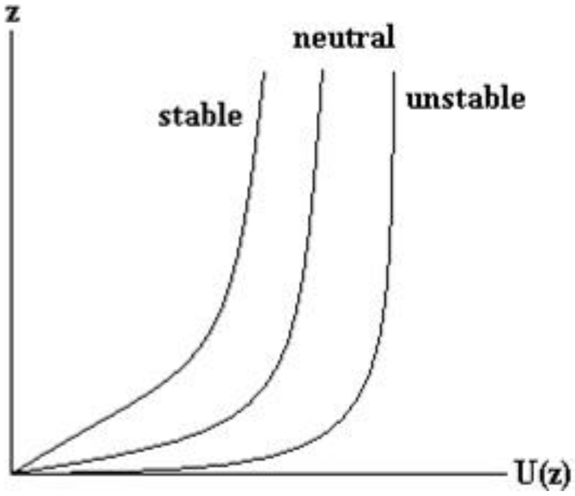
$$r_s = \frac{r_{smin}}{f_{R_s} \cdot f_{T_a} \cdot f_{\delta e} \cdot f_{\theta_{rz}}}$$

$$r_c = \frac{r_s}{LAI}$$

Latent Heat Flux: Transpiration

$$u_{z2} - u_{z1} = \frac{u^*}{k} \ln\left(\frac{z_2}{z_1}\right)$$





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

Latent Heat Flux

Aerodynamic resistance

$$r_a = r_{aN}\phi_m\phi_h$$

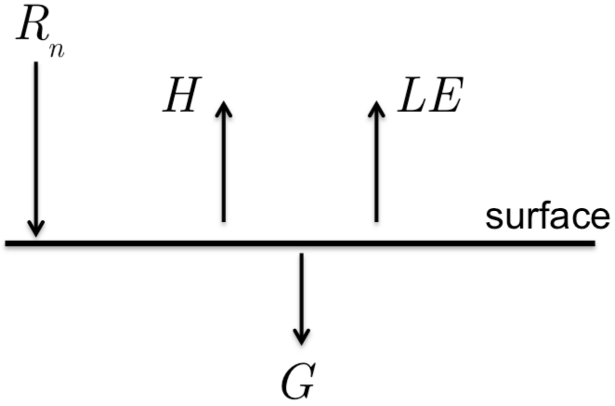
$$\phi_m \equiv \text{momentum stability correction factor}$$

$$\phi_h \equiv \text{sensible/latent heat stability correction factor}$$

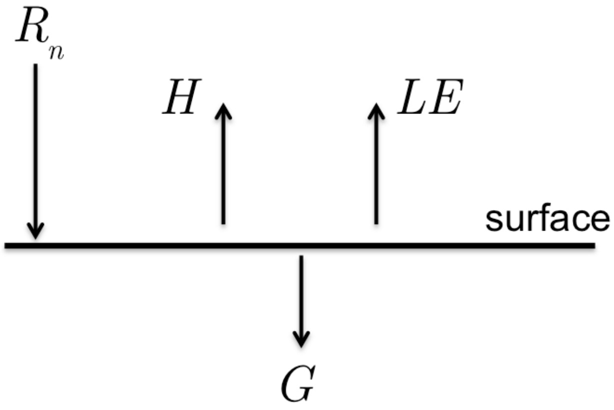
$$r_{aN} = \frac{\left(\ln\left[\dfrac{z-d}{z_0}\right]\right)^2}{\boldsymbol{\kappa}^2 V}$$

Latent Heat Flux

Latent Heat Flux

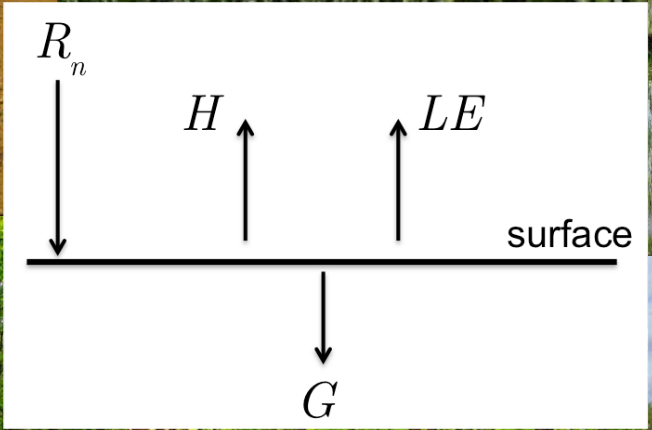


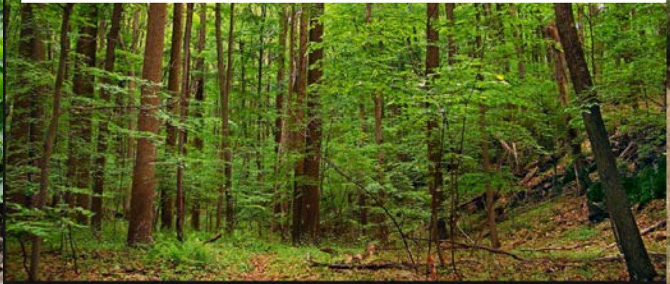
Latent Heat Flux



Tair = ?

Latent Heat Flux





Sensible Heat Flux

$$H = F_z(\text{heat}) = -D_H \frac{d(\rho c_p T_a)}{dz} = -\rho c_p D_H \frac{dT_a}{dz}$$

$$H \simeq -\rho c_p \frac{\kappa^2 V_2^2}{\left(\ln\left[\frac{z_2 - d}{z_0}\right]\right)^2} \frac{(T_2 - T_1)}{(V_2 - V_1)}$$

$$H = \rho c_p \frac{(T_{surf} - T_a)}{r_a}$$

The specific heat of air is: $c_p = 1004 \text{ J kg}^{-1} \text{ K}^{-1}$

Sensible Heat Flux

Aerodynamic resistance

$$r_a = r_{aN}\phi_m\phi_h$$

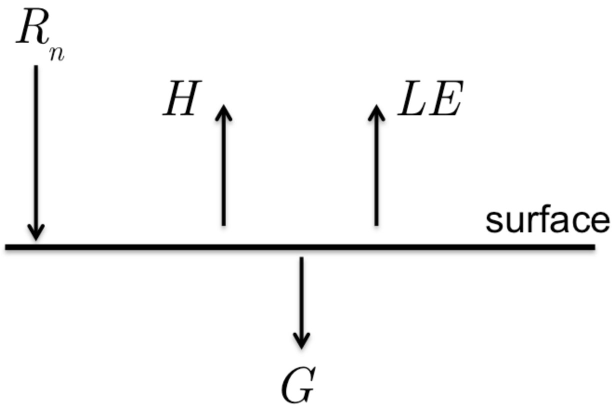
$$\phi_m \equiv \text{momentum stability correction factor}$$

$$\phi_h \equiv \text{sensible/latent heat stability correction factor}$$

$$r_{aN} = \frac{\left(\ln\left[\frac{z-d}{z_0}\right]\right)^2}{\kappa^2 V}$$

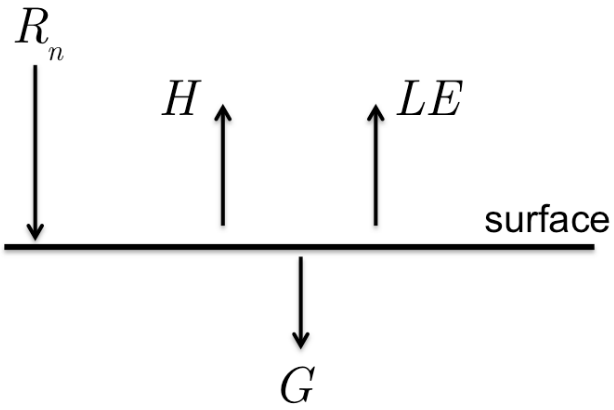
Same as for latent heat flux!

Sensible Heat Flux



Tair = ?

Sensible Heat Flux



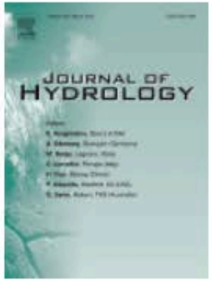
Tair = ?

The SEBAL Approach: Background

ELSEVIER

Journal of Hydrology

Volumes 212–213, December 1998, Pages 198-212



A remote sensing surface energy balance algorithm for land (SEBAL). 1. Formulation

W.G.M. Bastiaanssen [a], M. Menenti [a], R.A. Feddes [b], A.A.M. Holtslag [c]

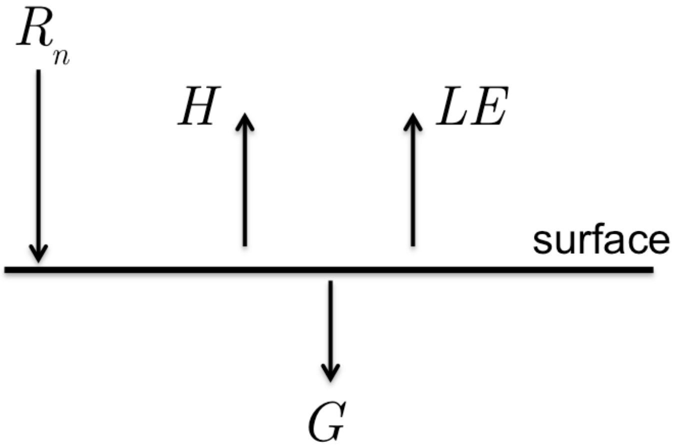
⊞ **Show more**

https://doi.org/10.1016/S0022-1694(98)00253-4

The SEBAL Approach: Background

High Resolution	Low Resolution
DisALEXI	ALEXI
ETLook	ETLook
SSEBop	SSEBop
SEBAL/METRIC	SEBS
S-SEBI	MOD16
EEFlux(Google)	CMRS-ET
	GLEAM

The SEBAL Approach: Methodology



$$\boxed{R_n = LE + H + G}$$

$$\boxed{LE = R_n - H - G}$$

The SEBAL Approach: Methodology

$$\boxed{LE = R_n - H - G}$$

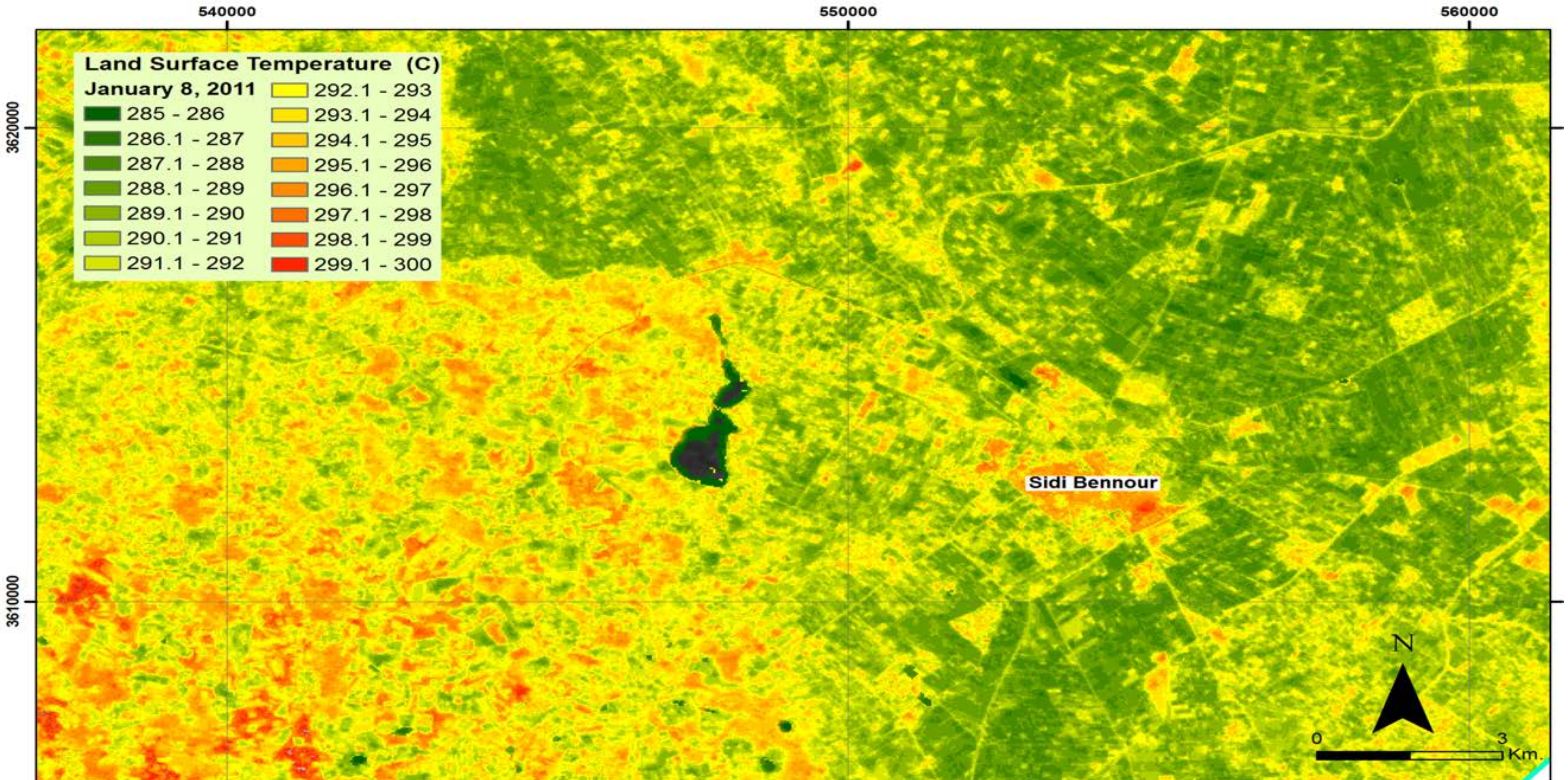
Optical and Thermal Remote Sensing?

The SEBAL Approach: Methodology

Landsat Temperature Data

The SEBAL Approach: Methodology

Landsat Temperature Data



The SEBAL Approach: Methodology

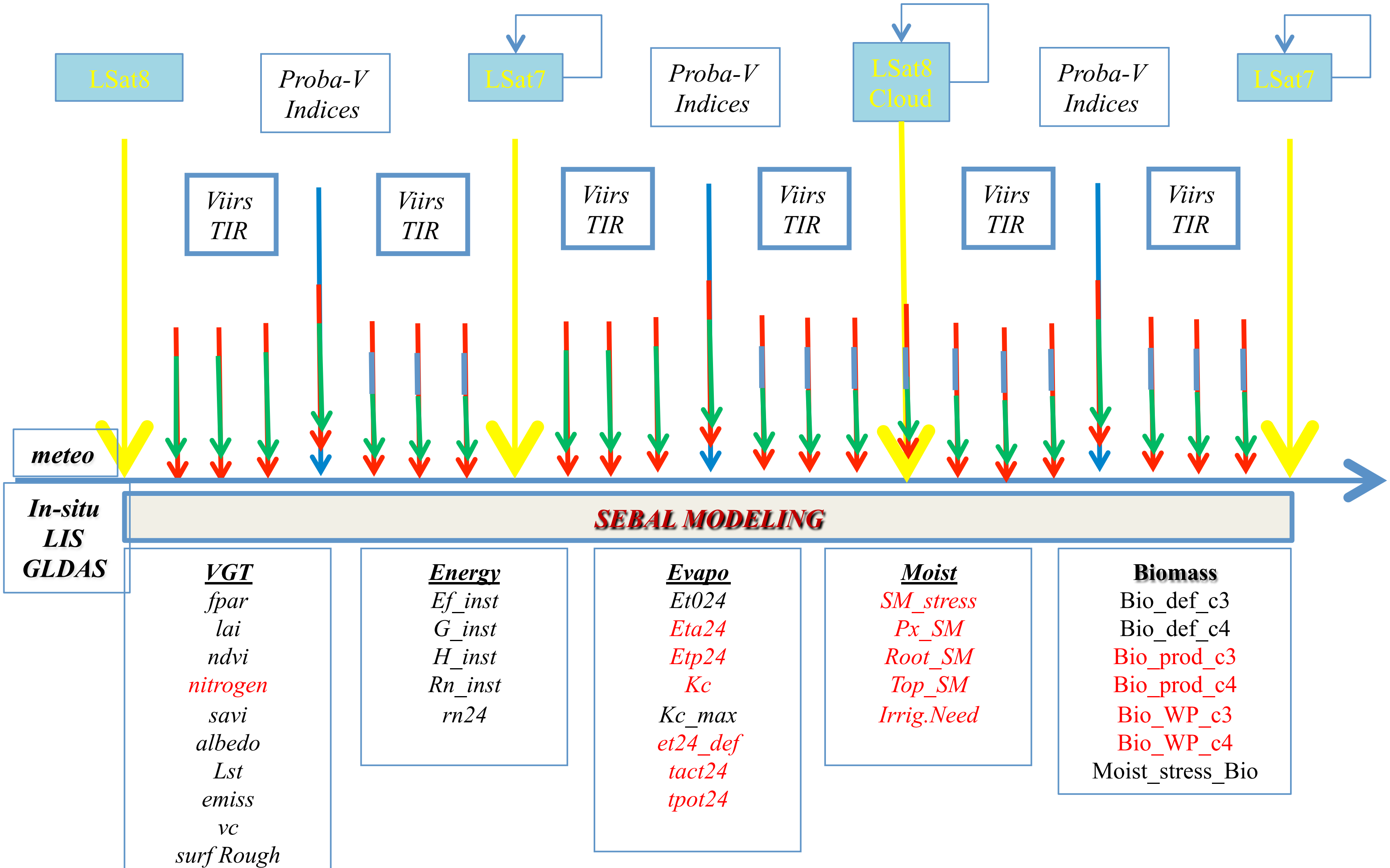
$$LE = R_n - H - G$$

Optical => Albedo => shortwave radiation

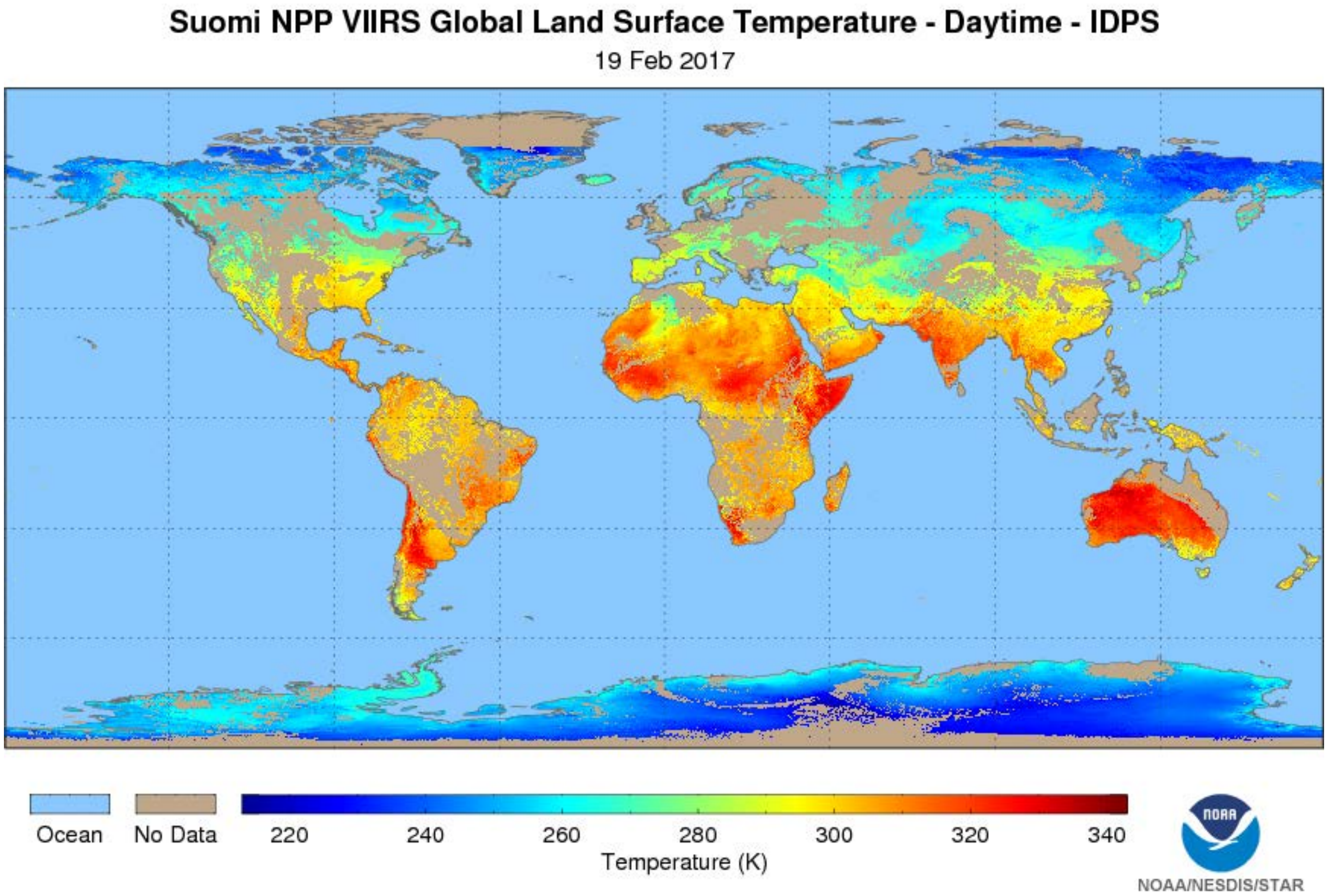
Thermal => surface temperature => longwave radiation
=> cooling ... see hot/cold => H
=> air temperature???

The SEBAL Approach: Methodology

Proba-Vegetation offers 5 day products 100 m


LSat8
Proba-V Indices
LSat7
Proba-V Indices
LSat8 Cloud
Proba-V Indices
LSat7
Viirs TIR
Viirs TIR
Viirs TIR
Viirs TIR
Viirs TIR
Viirs TIR
meteo
In-situ LIS GLDAS
SEBAL MODELING
VGT
fpar
lai
ndvi
nitrogen
savi
albedo
Lst
emiss
vc
surf Rough
Energy
Ef_inst
G_inst
H_inst
Rn_inst
rn24
Evapo
Et024
Eta24
Etp24
Kc
Kc_max
et24_def
tact24
tpot24
Moist
SM_stress
Px_SM
Root_SM
Top_SM
Irrig.Need
Biomass
Bio_def_c3
Bio_def_c4
Bio_prod_c3
Bio_prod_c4
Bio_WP_c3
Bio_WP_c4
Moist_stress_Bio

The SEBAL Approach: Methodology



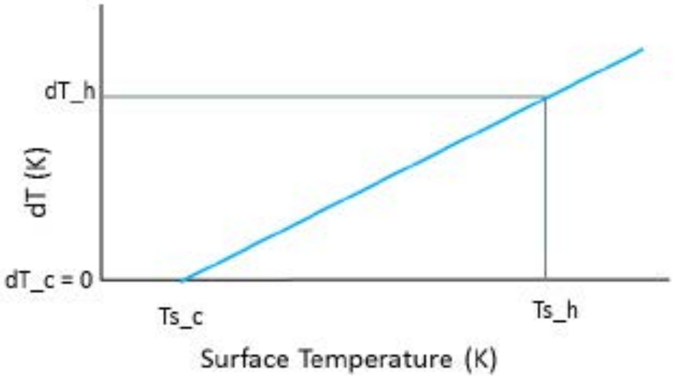
SEBAL Sensible Heat Flux Calculation

- Pixel Selection:

  Hot pixel: $H = R_n - G$

  $dT_{hot} = H_{hot} * r_{ah}/(\rho * c_\rho)$

  Cold Pixel: Wet location $H = 0$, $dT_{hot} = 0$



Relationship between T_s and dT

$$dT = b + a * T_s$$

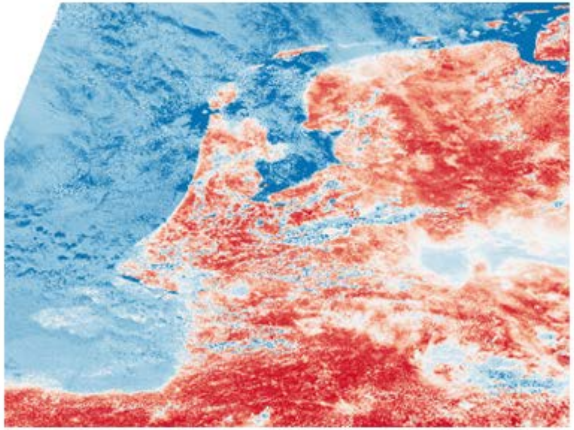
Sensible Heat Flux Calculation

$$H = (\rho * c_\rho * dT)/r_{ah}$$

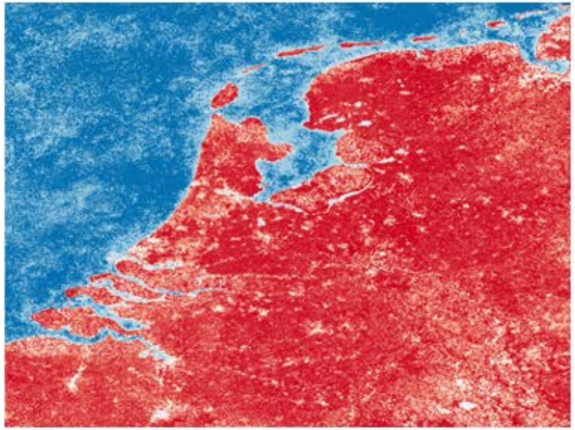
The SEBAL Approach: Methodology

Harmonic Analysis Time Series (HANTS) for cloud removal

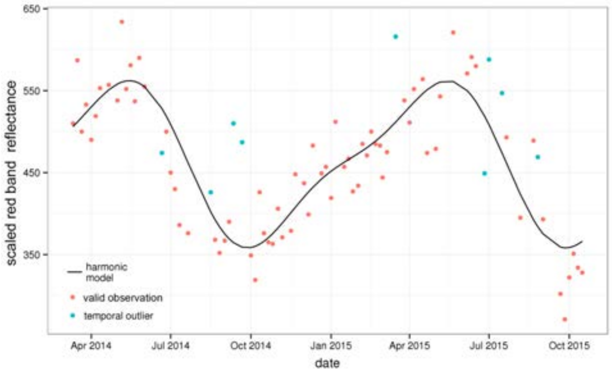
Demonstration of cloud removal capabilities of HANTS in the Netherlands on 20 September 2014 using NDVI maps with vegetation highlighted in red.



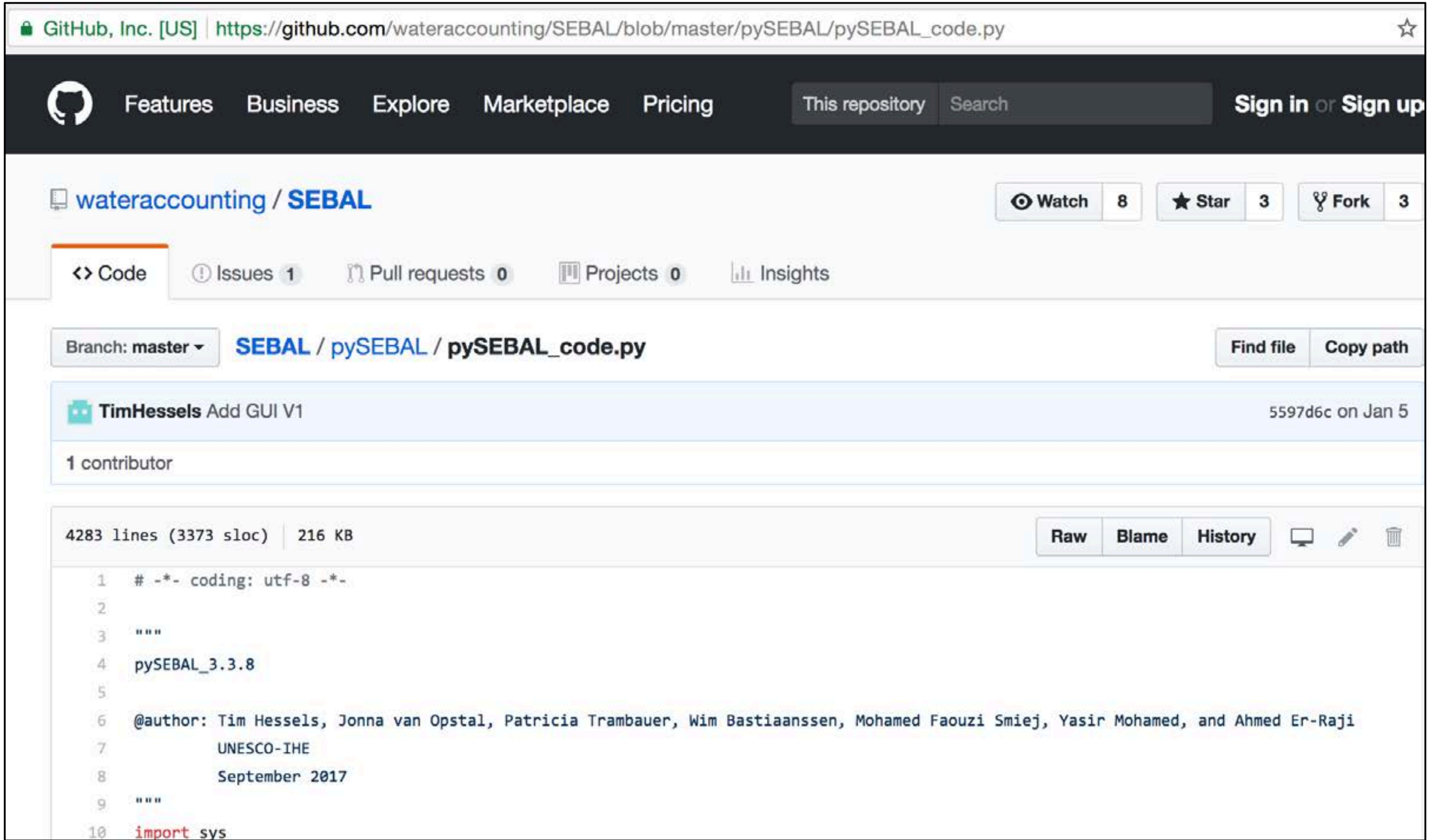
Before HANTS



After HANTS



The SEBAL Approach: Open & Online



Learning Objectives

By the end of today's lecture, you will be able to:

- Explain what **ET** is, and why we need to observe it
- Understand and explain the difference between **shortwave and longwave radiation**
- Understand and be able to estimate the components of **net radiation** from RS
- Be able to estimate ET from RS data as the **residual of the energy balance**

Lecture Outline

- Introduction
- Radiation Basics
- Surface Energy Balance
- The SEBAL Approach
- Guest Lectures: Yang Lu (TU Delft), NEO